MINERAL PROSPECTIVITY ANALYSIS
AND QUANTITATIVE RESOURCE ASSESSMENTS
FOR REGIONAL EXPLORATION TARGETING:
DEVELOPMENT OF EFFECTIVE INTEGRATION
MODELS AND PRACTICAL APPLICATIONS

VOLUME 1

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Publications arising from this thesis


17. Lisitsin V.A. (under revision). Rank-size statistical assessments of undiscovered gold endowment in the Bendigo and Stawell zones (Victoria) and the Mossman Orogen (Queensland, Australia): Comparison with three-part assessment results. Natural Resources Research. (Chapter 7).
Abstract

This thesis discusses various individual tools, methods and approaches which can be useful in an assessment of mineral prospectivity of a region at a scale of tens to hundreds of kilometres, illustrating them by practical applications in Queensland and Victoria. The range of the reviewed approaches include: manual GIS-assisted delineation and ranking of permissive and prospective tracts, knowledge-driven fuzzy logic prospectivity modelling, exploratory spatial data analysis, conceptual mineral system analysis and quantitative mineral resource assessments (using various statistical models of regional mineral endowment).

A major part of the completed research involved a comparative analysis of orogenic gold mineral systems in the Western Lachlan Orogen (Victoria) and Mossman Orogen (Queensland). Its initial step was to compile, review and validate spatial, petrological and gold grade and ore tonnage data on orogenic gold mineralisation in both regions. Spatial and grade and tonnage information for consistently defined ore fields, representing local-scale clusters of genetically similar gold occurrences, is presented in four appendices compiled in Volume 2 of the thesis. This information was extensively used as a major input into subsequent research tasks.

Exploratory spatial data analysis of gold deposit point patterns revealed important properties of the spatial distribution of orogenic gold mineralisation. In both regions, gold mineralisation is characterised by highly uneven distribution at all scales. At a local scale of hundreds to thousands of metres, gold occurrences are strongly clustered into ore fields. At a broader scale, there are richly endowed linear zones (>100 km long, <20 – 40 km wide), containing a disproportionately large number of randomly or regularly distributed ore fields, surrounded by poorly mineralised areas. Finally, at the regional scale, some parts of each province are significantly enriched in gold compared to others.

Conceptual mineral system analysis suggests that the scale and broad regional distribution of gold endowment in each province were largely controlled by the volume of originally hydrous crustal source rocks – limited by crustal architecture, which was in turn defined by the tectonic evolution of each region. The most critical structural mineral system controls are related to crustal block boundaries in the middle to lower crust– the western margin of the Selwyn Block in Victoria and the eastern margin of the Etheridge Province in Queensland. The metallogenic significance of the latter was established for the first time by this research. The deep crustal block boundaries, expressed at surface as broadly coincident boundaries between greenschist and subgreenschist metamorphic zones and
igneous geochemical domains, affected focused crustal-scale flow of mineralising fluids resulting in highly endowed linear metallogenic zones oblique to the surface regional structures. Crustal-scale faults generally provided more local-scale and indirect controls on the spatial distribution of gold deposits.

Quantitative mineral resource assessments indicated that the Mossman Orogen is likely to contain several undiscovered ore fields with >1 t of contained gold, with a total gold endowment of between 1 t and >30 t (1 Moz). In contrast, total undiscovered orogenic gold endowment in the Western Lachlan Orogen is likely to be of the order of 10 Moz to 100 Moz.

The research additionally focused on the problem of uncertainty of mineral prospectivity models. Uncertainty is implicitly present in every dataset, concept and model used to assess mineral prospectivity, propagating into assessment results and affecting their suitability for informed decision making. Part of this thesis discusses main types and sources of uncertainty in mineral prospectivity modelling. A new approach was developed to explicitly define uncertainties of individual model input factors and propagate them through a computational algorithm to evaluate the combined uncertainty of a prospectivity map – the probabilistic fuzzy logic method. This new method was used in regional-scale fuzzy logic prospectivity mapping of western Victoria for hydrothermal nickel deposits.

No single approach or method, when used in isolation, could adequately characterise mineral prospectivity of region. A method, or their combination, should be selected on the basis of the purposes and limitations of an assessment. Subjective GIS-assisted delineation of permissive and prospective tracts may be adequate for a rapid prospectivity mapping for regional land use planning when a more comprehensive analysis is impossible due to time constraints. A quantitative mineral resource assessment is warranted for regional ground selection and land use decisions based on potential economic parametres of undiscovered deposits (such as their likely tonnages and grades). Prospectivity mapping identifies and ranks specific exploration targets within a region deemed to contain potentially economic undiscovered mineral deposits. Exploratory spatial data analysis of deposit point patterns may be a critical precursor of both a systematic quantitative mineral resource assessment and mineral prospectivity mapping, revealing any cryptic metallogenic controls. In any case, a general conceptual mineral system analysis would potentially control bias which may be introduced by invalid assumptions or flawed statistical methods.
Chapter 1

INTRODUCTION

1. Background to the research

Assessments of a relative and absolute attractiveness of specific areas for mineral exploration (often referred to as mineral prospectivity) have long been a significant focus both for the mineral resources industry and government agencies. Traditional approaches, still widely used at present, are often based on the use of direct and indirect detection and a heuristic principle of a proximity to a known target object (a mineral deposit) as an indicator of an elevated probability of occurrence of similar objects. The latter principle is similar to the ‘first law of geography’: “Everything is related to everything else, but near things are more related than distant things” (Tobler, 1970). Relative proximity to known mineral deposits has been often used as a major criterion for area selection for subsequent detailed applications of detection methods. This essentially summarises the philosophy of brownfield exploration aiming to discover extensions of known mineral deposits in a close proximity to known mineralisation. Such traditional approaches, strongly focusing on extensive direct detection in the vicinity of known mineralisation, have been successfully used in the past. However, their effectiveness in replenishing mineral resources depleted by mining has significantly declined in the last 20 years, as indicated by a marked decline in discovery rates, particularly for major and ‘world class’ mineral deposits.

This decline of exploration success is widely interpreted as a result of the continuously increasing exploration maturity of the regions traditionally targeted by mineral exploration. These regions are characterised by the presence of mineral deposits or their indicators exposed at surface, thus enabling efficient applications of detection methods. Probability of new major discoveries of such exposed mineral deposits in established mineral provinces is continually declining due to the effectiveness of past and current exploration in those regions. Inevitably, companies targeting new world-class mineral deposits and provinces have to focus their exploration activities on areas characterised by difficult access, high geopolitical risks, significant thickness of barren cover rocks, or a combination of those factors. Exploring in such frontier regions would significantly increase technical and economic risks and exploration costs compared to traditional near-surface exploration in established mineral provinces. The need for more efficient methods of area selection, required to significantly reduce the ‘search space’ to areas with
a relatively high probability of significant mineral discoveries, has led to the development
d of a wide range of analytical methods for mapping mineral potential.

Another major motivation for mineral prospectivity analysis applied to relatively
large tracts of land has been a need to estimate the scale of undiscovered mineral resources
likely to be available for economic extraction in the medium to long term and to define
their general global and regional distribution. This has been of interest to some national
and regional governments and major resource companies, leading to the development of
methods of quantitative mineral resource assessment (QMRA, Singer, 1993, Singer and
Menzie, 2010).

Government agencies are also increasingly involved in developing land use strategies
and making specific decisions on the allocation of land for a particular preferred or
exclusive use in face of competing land use demands from different sectors of society.
This often requires rapid classification of relatively large areas into tracts with different
levels of probable mineral resource development activities. This task is similar to mineral
prospectivity mapping for exploration targeting for a specific type of mineral deposits but
it has a different general focus and scope and may require a different tract delineation and
classification procedures (Taylor and Steven, 1983; Taylor et al., 1984; VicRFASC, 1999).

Mineral prospectivity mapping and quantitative mineral resource assessments
focus on different aspects of mineral potential. Inevitably, each of those broad types of
mineral prospectivity analysis, and each individual approach and method within them,
has significant limitations, which restricts their effective application to some specific
intended purposes. They essentially represent individual tools which may be best applied
in a combination which would depend on the nature of a problem under consideration.
However, the wide variety of the available methods and a significant complexity of many
of them (in terms of both underlying science, assumptions and methodology and practical
implementation) often lead to arbitrary choices of methods which may be sub-optimal or
even totally inappropriate for an intended task.

2. Research objectives

The main objective of this study was to review and refine relatively common
existing methods of exploratory data analysis and predictive modelling to define their
optimal combination for an improved effectiveness of mineral prospectivity analysis and
exploration targeting at the regional to camp scales. Selected methods were systematically
applied to investigate various aspects of the mineral potential for selected mineral systems
in distinct geological terranes in Victoria and Queensland (Australia). The study also investigated several specific unresolved problems of mineral prospectivity analysis and proposed practical solutions optimising the methods.

Many previous studies performed detailed investigations of specific methods of computer-based mineral prospectivity analysis or compared their relative performance. Notable examples include Harris (1984), Bonham-Carter (1994), Scott (2003), Porwal (2006), Carranza (2009) and Singer and Menzie (2010). In contrast, research discussed in this thesis was not intended either to develop completely new models for mathematical data analysis and integration or to complete an exhaustive comparative analysis of numerous different models and tools. Many alternative methods can be effectively used for mineral prospectivity mapping and quantitative resource assessments. For example, some comparative studies indicated that different mathematical aggregation models applied to the same evidential geological datasets produce comparable maps of mineral prospectivity (Harris and Pan, 1999; Harris et al., 2003; Porwal et al., 2003, 2010; Singer and Kouda, 1999; Agterberg and Bonham-Carter, 2005). At present, major practical limitations of mineral prospectivity analysis probably lie not so much in a lack of suitable mathematical models but in excessively narrow scopes of mineral prospectivity mapping, some conceptual deficiencies of the existing methods and in the nature of the geological data commonly used as inputs for an analysis.

One methodological deficiency shared by most typical applications of mineral prospectivity mapping is the treatment of uncertainty. Uncertainty is an intrinsic property of all the geological datasets used as inputs in mineral prospectivity mapping. It arises from numerous sources and could never be completely eliminated or significantly reduced as part of desktop prospectivity mapping. However, it can be appropriately evaluated and managed. Regardless of a mathematical data integration model, uncertainty of the input factors propagate into the final outputs of prospectivity mapping, resulting in uncertainty of prospectivity maps. However, uncertainty is typically ignored in most practical applications of prospectivity mapping. This results in outputs not suitable for any further risk analysis and even potentially biased results. Part of the presented research focused on the development of a general statistical procedure for efficient assessment of uncertainty of prospectivity maps.

Most primary geological datasets and derivative evidential maps used as inputs in a mineral prospectivity analysis characterize geological objects and associated natural phenomena at a scale of original geological observations. They are also often biased
towards the types of observations typically collected during traditional geological mapping and mineral exploration. A problem of scale is that most direct observations and detailed studies are made at a local scale of up to a few kilometres. Even regional geological maps typically show the distribution of features expressed at a local scale. On the other hand, geological objects which are too small to be individually visualized at a mapping scale (e.g., dykes or veins) are often not adequately reflected in primary geological datasets even when they represent parts of spatially extensive geological features (e.g. dyke swarms).

Spatial distribution of mineral deposits in many geological provinces suggests the presence of regional-scale mineralisation controls which do not have an obvious expression in standard geological datasets (Hronsky et al., 2012). This can be due to a combination of the problem of scale and types of typical geological observations. When such cryptic regional controls are not recognised as distinct geological features in a prospectivity analysis, its outputs would be significantly biased towards the identified features and, possibly, also towards geological characteristics reflecting deposit-scale processes – the most typical scale of geological observations focusing on mineralisation. An indiscriminate use of deposit-scale observations in a regional-scale prospectivity analysis may erroneously highlight local geological properties irrelevant at a regional scale – the problem of scale dependence (Hronsky and Groves, 2008; McCuaig et al., 2010). Systematic analysis of the spatial distribution of known mineral deposits may reveal the presence and characteristics of such regional metallogenic controls with only subtle expressions in standard geological datasets. A significant part of the research presented in this thesis focused on applications of a systematic exploratory spatial data analysis (ESDA) of mineral deposits in central Victoria and north Queensland to identify possible regional-scale metallogenic controls.

A key focus of this research was an attempt to develop and illustrate a comprehensive system of integrated mineral prospectivity analysis – an effective combination of individual methods of exploratory spatial data analysis, prospectivity mapping and quantitative mineral resource assessment, used within a unifying conceptual mineral system framework. The author believes that maintaining a persistent focus on the geological processes which could be critical for a particular mineral system is a prerequisite of a meaningful prospectivity analysis – more important than a choice of specific methods of data analysis and integration. A preference was therefore given to relatively simple and commonly used methods that could be easily implemented in a GIS environment, thus excluding potentially powerful artificial intelligence methods and expert systems (such
as artificial neural networks). Methods of data analysis and integration discussed in this thesis are summarised in Table 1.

**Table 1. Summary of methods described in this thesis.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Individual methods</th>
<th>Purpose</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative mineral potential assessment</td>
<td>Subjective tract delineation</td>
<td>1. Land use planning</td>
<td>Rapid expert-driven GIS-assisted process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. First-pass part of QMRA and prospectivity modelling</td>
<td></td>
</tr>
<tr>
<td>Quantitative Mineral Resource Assessment (QMRA)</td>
<td>1. 3-part assessment</td>
<td>Quantify undiscovered mineral endowment of large tracts</td>
<td>Generally applicable</td>
</tr>
<tr>
<td></td>
<td>2. Regression modelling</td>
<td></td>
<td>Generally applicable</td>
</tr>
<tr>
<td></td>
<td>3. Rank-size (Zipf law)</td>
<td></td>
<td>Relatively mature provinces</td>
</tr>
<tr>
<td>Prospectivity modelling</td>
<td>Fuzzy logic</td>
<td>1. Define and rank exploration targets</td>
<td>Relatively good understanding of prospectivity factors (knowledge-driven)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Assess uncertainty of prospectivity maps</td>
<td></td>
</tr>
<tr>
<td>Exploratory Spatial Data Analysis (ESDA)</td>
<td>1. Regional homogeneity (point density mapping)</td>
<td>1. Assess spatial distribution of known deposits</td>
<td>Relatively mature provinces with many known deposits and occurrences</td>
</tr>
<tr>
<td></td>
<td>2. Centrogram and directional anisotropy (Fry)</td>
<td>2. Identify likely metallogenic factors – to provide inputs and constraints to other methods</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Clustering (summary functions: $K, L, F, G, J$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral system analysis</td>
<td>Review deposit-forming genetic processes – to guide, integrate and interpret outputs of other methods</td>
<td>Essential to minimise potential bias of other methods</td>
<td></td>
</tr>
</tbody>
</table>

### 3. Geological provinces of detailed case studies

Most of the detailed case studies discussed in this thesis (Chapters 4-7) focused on Palaeozoic orogenic gold mineral systems in the Western Lachlan Orogen (Victoria) and the Mossman Orogen (Queensland), eastern Australia (Figs 1-2). Modelling of mineral prospectivity for hydrothermal-remobilised nickel deposits (Chapter 3) focused on the Stawell Zone and the Delamerain Orogen in western Victoria (west of the Moyston Fault, Fig. 1). Reconnaissance GIS-assisted subjective delineation of tracts permissive for various mineral deposit types (Chapter 2) covered central and south-east Queensland, south-east of the Mossman Orogen shown on Fig. 2.
Fig. 1. Regional geology and orogenic gold deposits of the Western Lachlan Orogen (WLO). Lighter shades represent post-Devonian cover sequences. (From Lisitsin and Pitcairn, 2015).
Fig. 2. Regional geology and orogenic gold deposits of the Hodgkinson Province. Areas of post-Carboniferous cover are masked out. (From Lisitsin and Pitcairn, 2015).

4. Structure of the thesis

The thesis is structured as a collection of individual papers published or submitted for publication in major international peer-reviewed journals. Because of this format of the thesis, only brief reviews of individual methods of data analysis and integration used in this research are included in the relevant chapters. Performing a systematic review of the wide variety of methods which have been used or could be used in a comprehensive
mineral prospectivity analysis would be a significant research project in its own right but it was not in the scope of this study.

*Chapter 1* constitutes the introductory part of the thesis.

The main body of the thesis contains six chapters, describing various applications of spatial data analysis and integration and quantitative mineral resource assessment to assess prospectivity of large parts of the states of Victoria and Queensland (Australia) for different types of mineral deposits (*Chapters 2-7*), and one chapter discussing a new method for assessing uncertainty of mineral prospectivity maps developed as part of the research discussed in this thesis (*Chapter 8*).

*Chapter 2* describes an assessment of general mineral prospectivity of south-east Queensland for government land-use planning and policy development. The assessment was carried out using a rapid, GIS-assisted subjective analysis. The main purpose of the study was to delineate areas in south-east Queensland with a relatively high potential for mineral resource development activities in the medium term (10 to 20 years). Outputs of this study were used to define areas with potential land use conflicts and contributed to the development of a regional land use plan for south-eastern and central Queensland, released by the Queensland government in 2013.

*Chapter 3* describes modelling of mineral prospectivity of western Victoria for hydrothermal-remobilised nickel deposits. The study involved a review of hydrothermal nickel mineral systems and definition of a conceptual model for hydrothermal-remobilised nickel mineral systems associated with mafic-ultramafic magmatic complexes. The conceptual model was translated to a fuzzy logic inference engine, used to implement a fuzzy logic mathematical model of data integration in a GIS environment. This chapter has been published in Ore Geology Reviews (*Lisitsin et al.*, 2013b).

*Chapter 4* discusses comprehensive exploratory spatial data analysis of point patterns representing orogenic gold deposits in the Hodgkinson Province of north Queensland and in the Bendigo and Stawell zones in central Victoria. Individual methods described in this chapter were used as an integrated suite of complementary methods of spatial data analysis. Most of the individual methods had been applied in previous published research into spatial distribution of mineral deposits in isolation from each other, investigating only very specific and limited aspects of their spatial patterns. A systematic combination of the previously disparate methods resulted in much more detailed and substantiated insights into likely regional metallogenic controls on orogenic gold mineralisation in two regions. An important aspect of the approach was to use spatially defined ore fields (as opposed
Chapter 1

to individual mineral occurrences, mines, etc.) as an analysis unit. This is a common approach in quantitative mineral resource assessments (Singer and Menzie, 2010) but not in traditional mineral occurrence-focused spatial data analysis and mineral prospectivity mapping. Outputs of the spatial data analysis for north Queensland were used as inputs in regional metallogenic analyses and quantitative mineral resource assessment described in the following Chapters 5 and 6. Chapter 4 has been published as a paper in Ore Geology Reviews (Lisitsin, 2015).

Chapter 5 describes a comparative mineral system analysis of the orogenic gold mineral systems in the Hodgkinson Province of north Queensland and the Western Lachlan Orogen in central Victoria. It links crustal architecture with a conceptual model for Phanerozoic orogenic gold mineral systems and discusses likely reasons of major differences in the scale of gold endowment of those regions. The paper has been published in Ore Geology Reviews (Lisitsin and Pitcairn, 2015), in the special issue on Australian mineral systems.

Chapter 6 applied the insights gained from exploratory spatial data analysis discussed in Chapter 4 and a general comparative mineral system analysis reviewed in Chapter 5 to a quantitative mineral resource assessment, integrated with regional mineral prospectivity mapping of orogenic gold mineral systems in the Mossman orogenic gold province of north Queensland. The chapter has been published as a paper in Mineralium Deposita (Lisitsin et al., 2014a).

Chapter 7 applies rank statistical analysis based on ‘Zipf’s law’ as an alternative statistical model to assess undiscovered gold endowment in central Victoria and north Queensland. This chapter analyses implicit assumptions of Zipf’s law applied to mineral resource assessments and discusses their implications for assessment results and their uncertainty. The chapter has been submitted for publication in Natural Resources Research (Lisitsin, under revision).

Chapter 8 introduces the method of probabilistic fuzzy logic modelling – a novel approach to expressing and assessing uncertainty of mineral prospectivity maps. This approach modifies traditional GIS-based fuzzy logic prospectivity mapping to include Monte Carlo simulations as an implementation of a fuzzy inference engine. This approach has a general applicability and can be used to implement any fuzzy logic prospectivity model to assess uncertainty of its final outputs. The approach was first introduced and used in practice in the analysis of mineral prospectivity of western Victoria for hydrothermal
remobilised nickel deposits discussed in Chapter 3. The chapter has been published as a paper in Mathematical Geosciences (Lisitsin et al., 2014b).

Chapter 9 constitutes the concluding part of the thesis and contains a general discussion of the main insights and lessons learnt as part of this research. This includes a general analysis of relative strengths and limitations of the individual methods of mineral prospectivity analysis discussed in the previous chapters. The discussion outlines regional mineral prospectivity analysis as a comprehensive synthesis of a metallogenic analysis, exploratory spatial data analysis, mineral prospectivity mapping and quantitative mineral resource assessments. Those individual areas of research are often developed and practised in a relative isolation from each other. It is proposed that using such an integrated framework of currently isolated fields of research would ultimately lead to more robust practical exploration targeting outcomes.

A major component of this research comprised a comprehensive compilation, review and processing of data characterising orogenic gold mineral occurrences in the Western Lachlan Orogen (Victoria) and the Mossman Orogen (Hodgkinson and Broken River provinces, Queensland). Validated primary mineral occurrence data was processed and aggregated to characterise consistently defined larger metallogenic objects – ore fields. Compilation of spatial and grade and tonnage properties for orogenic gold ore fields in Victoria, originally published in government departmental reports (Olshina and Lisitsin, 2011a, b, c), are included in Volume 2 of this thesis as Appendices 1-3.

References


Chapter 1


Lisitsin V.A. (under revision). Rank-size statistical assessments of undiscovered gold endowment in the Bendigo and Stawell zones (Victoria) and the Mossman Orogen (Queensland, Australia): Comparison with three-part assessment results. Natural Resources Research.


This chapter illustrates the author’s contribution to an unpublished regional prospectivity assessment.

1. Introduction

This chapter provides a brief outline of the process and results of a rapid regional mineral prospectivity mapping of the Darling Downs and Central Queensland administrative regions of south-east Queensland, covering an area of 285,000 km². It illustrates a simple form of GIS-assisted mineral prospectivity mapping. While various more sophisticated and effective methods of prospectivity modelling are available, their use may not be justified in all situations. The assessment discussed in this chapter is an example of such a situation when a simple expert-driven GIS-based approach was deemed most suitable for the purpose, given the requirements and limitations of the assessment. The assessment was performed in 2012 by a team of geologists from the Geological Survey of Queensland, including Vladimir Lisitsin (team leader), Courteney Dhnaram, Patrick Carr and Dominic Brown. Ian Withnall and Paul Donchak assisted with ranking of the relative likely economic significance of different deposit types in the region (Table 2).

The purpose of the assessment was to delineate areas of elevated mineral and extractive resource potential where potentially economic deposits may be present. The generated mineral prospectivity and exploration potential maps are of a regional-scale reconnaissance nature. Their main intended use was to facilitate informed decision making on land use strategy development for south-east Queensland and planning for broad areas of possible conflicting or incompatible land uses. They can also be of assistance as an input into province to district-scale exploration targeting in the region. However, the outputs of this project are not designed to be used for prospect-scale exploration targeting, or for detailed development project planning for individual land properties. A more detailed and better constrained subdivision of the assessment area into smaller blocks with different levels of mineral prospectivity would require a substantially more extensive geological assessment, possibly involving field investigations.
2. Assessment methodology

2.1. Overview

Much of the mineral resources identified in the region are likely to be exhausted after 5 to 15 years of mining. The medium to long term future of the mining industry in the region largely depends on the major discoveries of new mineral resources. The new resources are likely to occur not only in the vicinity of the current or past mineral project areas but also in areas with no history of large-scale mining activities. The assessment area has not been exhaustively explored and the available information is insufficient to precisely identify the locations of undiscovered mineral resources. Therefore, this regional prospectivity assessment focused on the delineation of the areas with a relatively high mineral potential as indicated by relevant regional geological information – not restricted to the areas of known mineralization.

Due to the limited timeframe and resources available for the assessment, GSQ could not perform a comprehensive full-scale quantitative mineral resource assessment (e.g., as described by Singer (1993), Barton et al. (1995), Singer and Menzie (2010) and applied by Lisitsin et al. (2007, 2010)), or an automated GIS-based prospectivity mapping (e.g., Bonham-Carter, 1994; Carranza, 2009; Lisitsin et al., 2013). The approach used in this study employed qualitative GIS-assisted techniques previously used for similar purposes by the United States Geological Survey (Marsh et al., 1984; Taylor and Steven, 1983; Taylor et al., 1984) and Geoscience Australia (VicRFASC, 1999). Levels of certainty in tract prospectivity classifications were not assessed as part of this study.

2.2. Process

The first stage of the assessment involved identification of mineral deposit types which could be of a potential economic significance in the region. This was largely based on the types of deposits already discovered in the region. The assessment was then performed separately for each deposit type (or sometimes a group of closely related deposit types). Zones (or tracts) with different levels of estimated potential for each deposit type were delineated on the basis of detailed geological maps, geophysical data and the distribution of known mineralisation. In the majority of cases, known mineralisation was only used to fine-tune boundaries of geological tracts deemed prospective for a particular deposit type, so the tracts were mostly defined on the basis of their assessed geological permissiveness (Singer, 1993; Singer and Menzie, 2010). Deposit tracts were subjectively classified using
five categories of mineral potential: high, moderate to high, moderate, moderate to low and low. The general principles used in classifying deposit tracts are as follows.

**High potential.** Available data clearly indicates that mineralisation exists within the tract. The tracts include known deposits and occurrences of a significant past or likely future economic significance. Future exploration and possible subsequent mine development within the tracts are considered highly probable.

**Moderate to high potential.** The tracts are defined as highly favourable metallogenic zones. Known mineral deposits and occurrences are common but may be relatively minor. Future exploration and possible subsequent mine development within the tracts are considered probable.

**Moderate potential.** The tracts are defined as favourable metallogenic zones. The tracts may contain smaller zones of a higher potential or even known deposits and occurrences but the available information is insufficient for a more detailed tract delineation. Future exploration and subsequent mining is possible in some portions of the tracts, but are often likely to be of a small to medium scale.

**Moderate to low potential.** The tracts are defined as geologically permissive zones, based on general geological considerations, such as the presence of rocks which may host mineral deposits. Significant undiscovered mineral deposits may exist but the boundaries of the tracts are relatively poorly defined so the tracts may include zones of low prospectivity. There may be geological factors complicating future exploration and mining activities (for example, the presence of significant barren cover rocks). The probability of future large-scale resource development in most parts of the tracts is considered relatively low.

**Low potential.** The tracts are geologically permissive but the available information suggests that the probability of the presence of significant undiscovered economic deposits is low.

To facilitate consolidation of individual mineral prospectivity maps created for each deposit type, the subjective prospectivity ratings were assigned numeric scores (Table 1), adopting the scale used by Geoscience Australia in their regional prospectivity assessments (VicRFASC, 1999).
Table 1. Prospectivity scores assigned to qualitative prospectivity classes.

<table>
<thead>
<tr>
<th>Mineral prospectivity class</th>
<th>Prospectivity score</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>18</td>
</tr>
<tr>
<td>Moderate to high</td>
<td>12</td>
</tr>
<tr>
<td>Moderate</td>
<td>6</td>
</tr>
<tr>
<td>Moderate to low</td>
<td>2</td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
</tr>
</tbody>
</table>

A GSQ expert panel ranked the identified deposit types in terms of their potential economic significance in the region and assigned numeric ‘weights’ (Table 2), which were used to calculate weighted prospectivity scores to enable comparison between identical prospectivity classes for different deposit types. For example, conceptually, it is logical to conclude that a tract of land assigned a high prospectivity for epithermal gold and silver mineralisation (major high-value deposits of which are known in the region but which are generally rare and difficult to find) should be given a higher priority compared to a tract of land considered highly prospective for relatively minor polymetallic base metal vein deposits.

Table 2. Deposit type weight factors.

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epithermal Au-Ag</td>
<td>7</td>
</tr>
<tr>
<td>VHMS (Zn, Pb, Cu, Ag, Au)</td>
<td>6</td>
</tr>
<tr>
<td>Magnesite</td>
<td>6</td>
</tr>
<tr>
<td>Porphyry Cu-Mo</td>
<td>5</td>
</tr>
<tr>
<td>Lateritic Ni</td>
<td>5</td>
</tr>
<tr>
<td>Limestone</td>
<td>5</td>
</tr>
<tr>
<td>Marble</td>
<td>5</td>
</tr>
<tr>
<td>Bauxite</td>
<td>4</td>
</tr>
<tr>
<td>Skarn</td>
<td>4</td>
</tr>
<tr>
<td>Clay (bentonite, kaolin)</td>
<td>4</td>
</tr>
<tr>
<td>Oilshale</td>
<td>3</td>
</tr>
<tr>
<td>Zeolite</td>
<td>3</td>
</tr>
<tr>
<td>Orogenic gold</td>
<td>3</td>
</tr>
<tr>
<td>Silica sands</td>
<td>2</td>
</tr>
<tr>
<td>Hydrothermal Sn-W-Mo</td>
<td>2</td>
</tr>
<tr>
<td>Heavy mineral sands</td>
<td>2</td>
</tr>
<tr>
<td>Ultramafic-associated PGE</td>
<td>2</td>
</tr>
<tr>
<td>Polymetallic veins (Zn, Cu, Ag, Au, As, Bi)</td>
<td>1</td>
</tr>
</tbody>
</table>
3. Assessment results

3.1 Aggregated mineral prospectivity maps

The individual mineral prospectivity maps for specific mineral deposit types included in the analysis were aggregated into combined maps showing aggregated mineral prospectivity of the region. The weighted cumulative mineral prospectivity map (Fig. 1) provides a broad indication of the relative potential of the land blocks within the assessment area for a variety of mineral deposits. It was created as index overlay of the individual prospectivity maps, calculating a weighted arithmetic sum of the individual prospectivity scores for each cell within the assessment area. For example an area classified as highly prospective (prospectivity score of 18) for base metal and gold VHMS deposits (deposit weight of 6), moderately prospective (prospectivity score of 6) for porphyry Cu deposits (deposit weight of 5) and moderately prospective (prospectivity score of 6) for orogenic gold (deposit weight of 3) would receive a weighted cumulative prospectivity score of:

\[ P_w = 18 \times 6 + 5 \times 6 + 6 \times 3 = 156 \]

To simplify the presentation of the results and to minimise risks of inadvertent misinterpretation, the resultant cumulative potential map was reclassified into three categories – high, moderate and low prospectivity. The high prospectivity was assigned to 5% of the total assessment area with the highest weighted cumulative prospectivity scores, the medium prospectivity – to another 5% of the area with lower weighted cumulative prospectivity scores and the low prospectivity – to the remaining 90% of the assessment area (Fig. 1). The cumulative prospectivity map provides a simple way to represent the overall mineral potential of land tracts within the region.

However, caution should be exercised interpreting the results for land use planning. Some areas currently classified as of moderate or low cumulative prospectivity are actually highly prospective for a single deposit type with a relatively low deposit weighting factor (Table 2) – such as clay. The cumulative prospectivity map is thus likely to be biased towards the areas of overlapping individual prospective tracts.

To minimise the risk of a biased interpretation, a composite mineral prospectivity map has been produced (Fig. 2). The map shows the highest level of mineral prospectivity for any of the assessed deposit types. The two mineral prospectivity maps can to be used in a combination when assessing the possible distribution of future mining and exploration activities.
3.2. Current and potential mineral resource activities

The mineral prospectivity maps created as part of this study represent the current level of understanding of the mineral potential of the region defined largely on the basis of general metallogenic considerations. While this may be used as an indication of the likely distribution of long-term future mineral exploration and development activities, it is also important for land-use planning purposes to take into account the distribution of the actual current activities. Some of those current activities focus on mineral deposit types not included in the prospectivity assessment due to time constraints. Some activities also take place outside the areas classified at the moderate to high prospectivity levels in the current study – possibly because companies conducting the work have access to more detailed local information which was not evaluated by the authors of this rapid regional-scale assessment. The distribution of current mining, development and exploration permit areas may be used as an indicator of general locations of likely significant short- to medium-term activities. For land-use planning purposes, the areas under current mining and development tenure or application are classified as having a high level of current and potential mineral resource activities (the score of 18) and the areas within exploration permits are classified as having a moderately mineral resource activity level (the score of 6). An overlay of the mineral tenure areas over the composite mineral prospectivity map can be used as a map of current and potential mineral resource activities (Fig. 3). The overlay combination method used the Fuzzy OR operator (Zimmerman, 1991; Bonham-Carter, 1994; Porwal et al., 2003; Carranza, 2009) which selects the highest numerical mineral prospectivity or resource activity value (Table 1) at each location. The areas of high and moderate to high potential for mineral resource activities cover 8% of the total assessment area and the areas of estimated moderate potential cover an additional 17%. This map is recommended for the use in regional policy development and land-use planning.
Fig. 1. Weighted cumulative mineral prospectivity map. The map shows the sum of all individual prospectivity scores for each assessed deposit type, weighted by corresponding deposit weigh factors (Table 2).
Fig. 2. Composite mineral prospectivity map, showing the highest estimated level of mineral potential for any of the assessed deposit types.
Fig. 3. Current and potential mineral resource activities.
4. Examples of reviewed conceptual deposit models and delineation of permissive tracts

Porphyry Cu-Mo

Deposit model references

Tectonic setting
Subduction-related continental and island magmatic arcs along convergent continental margins. In South-East and Central Queensland, known deposits and occurrences are apparently restricted to magmatic complexes associated with continental magmatic arcs.

Age
In the assessment region, Silurian to Cretaceous. Most known porphyry Cu-Mo deposits and occurrences in the assessment area are of the Permo-Triassic age. Late Carboniferous epithermal deposits and occurrences are known in the Connors-Auburn province (e.g., at Cracow). In the coastal area extending from north of Rockhampton to Townsville (to the north of the assessment area), most porphyry Cu-Mo occurrences are Cretaceous and a few – Late Carboniferous to Early Permian (Horton, 1978, 1982; Bookstrom et al., 2010).

Assessment Criteria – Central and South-East Queensland

Permissive rocks
Regions of magmatic arcs, containing significant I-type, oxidised, alkaline and calc-alkaline igneous and associated volcano-sedimentary rocks. While porphyry-type mineralisation is genetically associated with I-type intrusive magmatism, any rock types within magmatic arcs which formed before the emplacement of (typically late-stage) mineralising intrusions may host porphyry Cu-Mo deposits associated with minor outcropping and ‘blind’ intrusions. Individual porphyry intrusions genetically related to porphyry Cu-Mo mineralisation are often less than 200 m across. Permissive rocks covered by less than 1 km of post-mineralisation cover were included in permissive tracts.

Evidence of potential presence of porphyry Cu mineral systems
- Known porphyry Cu-Mo-Au occurrences;
- Known epithermal occurrences;
○ Distribution of permissive rocks (I-type oxidised alkaline and calc-alkaline magmatic rocks) – exposed, intercepted by drilling and interpreted from geophysics;
○ Presence of potentially associated deposit types (preferably displaying metallogenic zonation) – magnetite skarns, polymetallic veins, Au-Sb veins;
○ Geochemical anomalies (Cu, Mo, Au, Zn, Ag, Sb);
○ Regional and more localised alteration types characteristic for porphyry-Cu mineralisation (distal propylitic, phyllic, potassic, argillic);
○ Characteristic ‘bull’s eye’ and ‘doughnut’ magnetic anomalies (deposit-scale).

**Preservation factors**

Presence of contemporaneous epithermal mineralisation and widespread volcanic and high-level sub-volcanic igneous rocks and hydrothermal breccias may suggest preservation of any existing porphyry Cu mineralisation in that area.

**Guidelines for defining permissive tracts**

Generalised, buffered outlines of permissive rocks within late Palaeozoic to Cretaceous magmatic arcs (including extensions under less than 1 km of post-mineralisation cover, as interpreted from geophysical datasets and indicated by drilling). In the assessment area, buffering distance was set at 2 km.

**Permissive and prospective tracts**

In the assessment area, regions with regional-scale prospectivity for porphyry Cu-Mo-(Au) deposits are associated with exposed and near-surface magmatic arc complexes of the New England Orogen. Three prospective regions are defined in this study: the coastal magmatic belt, the Retreat Batholith and the Texas region.

Most of the prospective areas occur in the coastal region of the Rockhampton, Gladstone and Banana councils (encompassing the Calliope, Connors-Auburn, Yarrol, Wandilla and Gympie tectonic provinces). This region includes almost all of the porphyry Cu-Mo deposits and occurrences currently known in the assessment area. The permissive region is defined as a broad area of Carboniferous to Triassic magmatic and associated volcano-sedimentary rocks (including their likely extensions under a relatively shallow cover). The tract is extended into the eastern margin of the Bowen Basin to include the documented Cretaceous intrusions and extensions of the Permo-Triassic permissive rocks under shallow cover. This permissive tract (outside areas of known mineralisation and active exploration) has been assigned a moderate level prospectivity.
Two other regions with a possible potential for porphyry Cu-Mo mineralisation include the areas of Permo-Triassic intrusives in the Texas and Silverwood provinces in the south-east and the Retreat Batholith in the north-east.

Known mineralisation associated with the intrusives in the Texas Province is dominated by Sn-W and W-Mo veins. The intrusions (dominated by extensive Early to Middle Triassic Stanthorpe and Ruby Creek granites) are mostly highly evolved, felsic to leucocratic, often only weakly oxidised I-type granites. The region is likely to have only low to moderate prospectivity for porphyry Mo±Cu mineralisation.

PorCuMo1_H – Delineation of this tract is based on the distribution of permissive magmatic complexes (both mapped and interpreted from geophysics) known to host porphyry Cu-Mo mineralisation. Highly prospective Permo-Triassic magmatic complexes occur in the central part of the coastal magmatic belt. The tracts are defined by a 2 km buffer around outcropping permissive rocks, and/or their extent defined by the geophysics (whichever incorporates a larger area) to include their subsurface extensions. This tract contains the majority of the porphyry Cu-Mo deposits and occurrences identified in the assessment area.

PorCuMo2_H-M – This tract includes the areas within 2 km from the other permissive Carboniferous to Cretaceous intrusive rocks in the coastal magmatic belt not included in PorCuMo1_H. This also includes documented mineralised permissive rocks within the Texas region.

PorCuMo3_M – The rest of the mostly exposed coastal magmatic belt. Prospectivity of this tract is related to potential small mineralising intrusions not identified in the existing datasets.

PorCuMo4_M-L – This tract is defined as an interpreted extension of the coastal magmatic belt completely under the relatively shallow cover of the Surat and Clarence-Moreton basins in the OAKEY, JANDOWAE and BARAKULA 1 : 100,000 mapsheets. This covered belt lies along the regional strike of the exposed Auburn Province. The prospectivity of the tract is inferred on the basis of the likely general similarity with the exposed parts of the New England Orogen immediately to the north and south which are included in the tract PorCuMo3_M. General estimates of Cranfield et al. (2001 – Yarraman report) indicate cover thickness of up to several hundred metres. Because of a lack of reliable direct indicators of the presence of porphyry copper mineral systems in this unexplored tract, uncertainties with regards to the cover thickness and difficulties of exploration under cover, this tract has been assigned a moderate to low prospectivity.
Sn and Sn-W vein and greisen deposits

Deposit model references

Tectonic settings
Sediment-dominated parts of convergent continental margins, intruded by late orogenic to post-orogenic granitoids.

General description
Quartz-cassiterite+-wolframite veins and stockworks within or in a close proximity to felsic intrusive rocks.

Permissive rocks
Fractionated, reduced felsic meso-zonal and hypabyssal plutons and adjacent rocks (normally meta-sedimentary).

Age
Typically Palaeozoic and Mesozoic, but generally may be of any age.

Depositional environment
In and above apical parts of felsic plutons.

Known deposits and occurrences
The vast majority of known deposits and occurrences are located in the Stanthorpe tin field in the Texas region, within the Stanthorpe Granite, Ruby Creek Granite and above their extensions under the Carboniferous sedimentary Texas Beds.

Assessment criteria
1. Distribution of fractionated, felsic to leucocratic, reduced granites (including their sub-surface extensions)
2. Distribution of known tin occurrences
3. Distribution of tungsten and poly-metallic veins proximal to prospective granitic intrusions

Permissive and prospective tracts
Sn1_M-H – Delineation of this tract is based on the distribution of the Stanthorpe, Ruby Creek and Ballandean granites and known Sn occurrences. The tract includes all but one recorded occurrences in the Texas region. It is assigned moderate to high prospectivity.
Sn2_L-M – This tract outlines potential sub-surface distribution of reduced granites of the New England Batholith in the Texas region, immediately to the north of tract Sn1_M-H, as inferred from geophysical datasets. This tract includes one minor tin occurrence. The nature and tin-bearing potential of inferred sub-surface granites is not known. Also, any substantial tin mineralisation, if present, is likely to be blind. Therefore, the tract is assigned low to moderate prospectivity.

Sn3_L-M – Crows Nest Granite (reduced felsic granite, hosting 3 known tin occurrences).

Sn4_L - This tract outlines potential sub-surface distribution of reduced granites of the New England Batholith under the cover of the Surat Basin, immediately to the west of the Texas region. The nature and tin-bearing potential of inferred sub-surface granites is not known and their depth is poorly constrained. Therefore, the tract is assigned low prospectivity.

References


Chapter 3

REGIONAL PROSPECTIVITY ANALYSIS FOR HYDROTHERMAL - REMOBILISED NICKEL MINERAL SYSTEMS IN WESTERN VICTORIA, AUSTRALIA

Ore Geology Reviews, v. 52, pp. 100-112

Abstract

Fuzzy logic mineral prospectivity modelling was performed to identify camp-scale areas in western Victoria with an elevated potential for hydrothermal-remobilised nickel mineralisation. This prospectivity analysis was based on a conceptual mineral system model defined for a group of hydrothermal nickel deposits geologically similar to the Avebury deposit in Tasmania. The critical components of the conceptual model were translated into regional spatial predictor maps combined using a fuzzy inference system. Applying additional land use restrictions and depth of post-mineralisation cover, downgrading the exploration potential of the areas within national parks or with thick barren cover, allowed the identification of just a few potentially viable exploration targets, in the south of the Grampians-Stavely and Glenelg zones. Uncertainties of geological interpretations and parameters of the conceptual mineral system model were explicitly defined and propagated to the final prospectivity model by applying Monte Carlo simulations to the fuzzy inference system. Modelling uncertainty provides additional information which can assist in a further risk analysis for exploration decision making.

1. Introduction

Effective regional exploration targeting for major mineral deposits and camps in poorly explored areas is one of the most significant challenges for the mineral exploration industry. Defining and ranking regional targets is often done subjectively, on an intuitive level, which mainly draws from specific deposit models and past exploration experiences of the targeting geologist. This results in an Introduction of systemic uncertainties (Porwal et al., 2003; McCuaig et al., 2010) resulting from the targeting geologist’s subjective proclivity for a specific conceptual deposit model or past exploration experience. GIS-
based prospectivity analysis has been developed in the last 30 years in an attempt to complement expertise of exploration geologists with objective tools more suitable for efficient and repeatable processing and integration of vast amounts of data from numerous information sources. However, these approaches generally do not incorporate uncertainties resulting from inadequacies in the primary data (e.g., imprecision, inconsistent coverage etc.) or from subsequent data processing (e.g., interpolation).

In recent years, prospectivity analyses have increasingly used the mineral systems approach (Wyborn et al., 1994; McCuaig et al., 2010; Czarnota et al., 2010). This approach is based on breaking down the geological processes which may lead to the formation of mineral deposits into several groups of critical processes. While individual mineral system models vary in details of the break-down, common groups of critical processes include: 1) sources of metals and fluids; 2) geological features and processes responsible for transporting and focusing mineralising fluids; 3) metal deposition mechanisms.

The purpose of this study is to apply the mineral systems approach to perform a systematic regional prospectivity analysis for hydrothermal nickel deposits in western Victoria. On a broad regional scale, the region has been previously identified as having a potential for hydrothermal nickel deposits (Seymon, 2006; Champion et al., 2009). There has been only limited exploration for Avebury-style nickel mineralisation in recent years (Beaconsfield Gold, 2008; Evans and Cuffley, 2008; Weber and Guzel, 2009), with no deposits discovered to date. This study is based on the current understanding of the essential characteristics of the hydrothermal nickel mineral systems, specifically of the Avebury style (see Section 3) and of the presence of the critical mineral system components in the region. It utilises GIS-based fuzzy prospectivity modelling techniques to identify ore field / camp-scale areas with enhanced mineral prospectivity and exploration potential. It builds upon the previous prospectivity analysis of hydrothermal nickel deposits in Tasmania (González-Álvarez et al., 2010) and ongoing research into the genetic aspects of hydrothermal nickel mineral systems. In addition, we attempt to quantify uncertainty in the resulting prospectivity maps using Monte Carlo techniques. The outputs are therefore not only potential exploration targets but also confidence in each target.
2. Methodology

2.1. Overall approach

On a high conceptual level, semi-automated GIS-based methods of prospectivity modelling can be subdivided into data-driven, knowledge-driven and hybrid categories (Bonham-Carter, 1994; Porwal et al., 2003; Carranza, 2008). Data-driven methods are based on empirical spatial statistical associations between known mineralisation and ‘mappable’ geological features. These methods are most suitable for mineral provinces with a reasonably large number of known deposits. Popular data-driven methods include weights of evidence, logistic regression and neural networks. Knowledge-driven and hybrid methods, on the other hand, rely on subjective expert opinions or more structured conceptual models defined by experts. These methods (including fuzzy logic, applications of probability and Dempster-Shafer belief theories and various structured expert systems) can be used in poorly explored terranes with few or no known deposits.

There are only a few minor nickel occurrences known in the study area. Also, hydrothermal nickel deposits are relatively rare worldwide and remain poorly characterised and understood. This precludes an effective use of empirical data-driven prospectivity modelling techniques. We considered fuzzy logic modelling to be the most appropriate knowledge-driven method of prospectivity analysis for this study. Its additional advantage is that it can be used to explicitly define, propagate and express uncertainty, which is important in the current study, as further discussed below.

The prospectivity analysis in this study involved the following steps:

○ Review of hydrothermal nickel deposits worldwide, undertaken to identify essential geological characteristics of deposit groups with possible analogues in western Victoria.

○ Definition of a conceptual model of hydrothermal Ni mineral systems applicable to western Victoria. A particular emphasis was made on the identification of likely critical components of the hydrothermal nickel mineral system(s) that operate at an ore field / camp scale and are essential for practical exploration targeting.

○ Translation of the critical mineral system components into spatially defined regional prospectivity criteria in western Victoria.

○ Definition of a fuzzy logic inference system reflecting likely interactions between the critical prospectivity criteria, consistent with the conceptual mineral system model.

○ Prospectivity modelling, combining individual ‘mineral system components’ maps into a single mineral prospectivity map using the fuzzy logic inference system.
2.2. Fuzzy prospectivity modelling

A generalised fuzzy model for GIS-based mineral prospectivity mapping can be defined as follows. If \( X \) is a set of \( n \) predictor maps \( X_i \) (where \( i = 1 \) to \( n \)) with \( r \) map classes, denoted as \( x_j \) (where \( j = 1 \) to \( r \)), then \( n \) fuzzy sets \( A_i \) in \( X \), containing favourable indicators for the targeted mineral system, can be defined as:

\[
\tilde{A}_i = (x_j, \mu_{A_i}) | x_j \in X_i
\]

where \( \mu_{A_i} \) is the membership function for estimating the fuzzy membership value of \( x_j \) in the fuzzy set \( \tilde{A}_i \). The fuzzy membership function \( \mu_{A_i} \) can be linear, Gaussian or any other appropriate function (Bonham-Carter, 1994; Porwal et al., 2003; Carranza, 2009).

A typical fuzzy model is implemented in two steps: defining fuzzy membership values for all map classes of the input predictor maps and combining the predictor maps to produce a prospectivity map.

2.2.1. Estimation of fuzzy membership values of predictor classes

The following linear function has often been used to estimate fuzzy membership values (e.g., Porwal et al., 2003; González-Álvarez et al., 2010):

\[
\mu_{\tilde{A}_i} = \frac{m_i \times w_j \times cf_j}{1000}
\]

where \( m_i \) is the map weight, \( w_j \) is the class weight and \( cf_j \) is the confidence factor. Map weights and confidence factor are often subjectively assigned a value between 1 and 10 based on expert knowledge. Class weights are also assigned values between 1 and 10. Map weight and class weight, respectively, indicate the perceived importance of a predictor map and a class on the predictor map. The confidence factor is assigned to a predictor map based on the degree of directness, that is, how closely it represents an exploration criterion. The predictor map gets a higher confidence factor if it directly maps the exploration criteria and a lower confidence factor if it is based on mapping the indirect response of the exploration criterion. Confidence factor is also used to account for the uncertainties in the primary dataset that was used to create a particular predictor map.

2.2.2. Combining predictor maps and evaluating uncertainty

In fuzzy modelling, predictor maps are combined using a fuzzy inference engine. It constitutes a number of parallel and/or serial networks that sequentially combine predictor maps through fuzzy set operators (see Bonham-Carter, 1994, p. 301 and Porwal et al., 2003 for details). The design of an inference engine should be consistent with the
mineral system model under consideration. The output of an inference engine is a fuzzy prospectivity map for the targeted mineral system.

Geological understanding of the hydrothermal nickel mineral system is still evolving and there are significant uncertainties on the critical components of the mineral system, their relative importance and details of their possible relationships. There are also major uncertainties involved in the translation of the inferred critical components of the mineral system into ‘mappable’ prospectivity criteria (McCuaig et al., 2010). For example, evidence of likely critical processes of a mineral system is rarely accurately and precisely represented in existing geological datasets. Even in the best-case scenario, when there is a direct correspondence between a critical process and a mappable criterion (e.g., a particular rock type), the spatial distribution of that criterion is mostly interpretative by nature – e.g., interpolation between, or extrapolation beyond, the observation points, or non-unique interpretations of geophysical datasets. When critical processes can only be recognised indirectly by proxy, there is an additional uncertainty of the representativeness of the proxies.

These numerous uncertainties are often made implicit, by making a series of ‘best-guess’ decisions, on the basis of information available to prospectivity modelling analysts at the time of analysis. Information on uncertainty of the individual decisions is usually ignored, leading to final prospectivity models and maps which may indicate an inappropriately high level of confidence. In effect, typical applications of knowledge-based prospectivity modelling techniques (including fuzzy logic models) are thus based on essentially deterministic models of mineral prospectivity, which accept a single set of geological interpretations and one specific conceptual model. Prospectivity maps derived on the basis of such deterministic models may have significant predictive power in successfully highlighting and ranking prospective areas. However, they do not clearly indicate uncertainty of the predictive models, while such information may be critical in exploration decision making. In this paper, we have attempted to simulate a probabilistic prospectivity model, indicating sensitivity of final model outputs to uncertainties of input data and concepts.

On a high conceptual level, various sources of uncertainty can be subdivided into the stochastic (data) and systemic (model) categories (Porwal et al., 2003). In the current study, significant sources of uncertainty were associated with:

1. The geological character and geographical distribution of geological features indicative of critical components of the mineral system. These uncertainties
arouse from interpolation of point data, incomplete data coverage and conflicting interpretations of the available data.

2. Fuzzy membership values of individual prospectivity parameters derived from primary geological datasets – systemic uncertainties of the strength of relationships between particular exploration targeting criteria and a likelihood of the presence of mineralisation.

3. Conceptual mineral system model – systemic uncertainties of the relative and absolute importance of individual prospectivity parameters and the nature of their inter-relationships.

Uncertainties of the first two types were modelled by defining statistical distributions deemed representative of likely variability of the estimated parameters. The uncertainties were then propagated through the fuzzy logic inference system by applying Monte Carlo simulations and the inference system combination rules to the defined statistical distributions. These procedures are illustrated in Section 5.

3. Hydrothermal nickel deposits – essential characteristics of the “Avebury style”

3.1. Non-magmatic primary nickeliferous deposits – a global overview

Non-orthomagmatic nickeliferous deposits are relatively rare compared to their orthomagmatic counterparts. They display a broad variety of geological characteristics, which can due to the wide variety of environments in which nickel can be mobilised, transported and deposited by mineralising fluids. For example, the genesis of some deposits has been linked to hydrothermal remobilisation of nickel from pre-existing magmatic nickel sulphide deposits (e.g., Fortaleza de Minas, Brazil, Brenner, 2006; Almeida et al., 2007), sedimentational, exhalative and diagenetic processes (e.g., Nick Horizon, Canada, Hulbert et al, 1992; Talvivaara, Finland, Loukola-Ruskeeniemi and Heino, 1996; Loukola-Ruskeeniemi, 1999), or processes related to circulation of metamorphic fluids and basinal brines (Kalumbila/Enterprise, Zambia, Steven and Amstrong, 2003). Hydrothermal nickeliferous deposits remain poorly understood and insufficiently constrained, which adds significant complexity to the definition of practical exploration targeting models (González-Álvarez et al., 2010).
To define exploration models potentially applicable to western Victoria, considering different geological properties of deposits and genetic processes involved in their formation, non-magmatic nickel deposits could be broadly grouped as: (1) stratiform black shale-hosted deposits (e.g., Lower Cambrian black shales of southern China, Lott et al., 1999; Mao et al., 2002; Jiang et al., 2007); (2) volcanogenic massive sulphide deposits (e.g., Outokumpu, Finland, Gaál and Parkkinen, 1993; Loukola-Ruskeeniemi and Heino, 1996; Loukola-Ruskeeniemi, 1999; Peltonen et al., 2008); (3) poly-metallic veins (cf. “five-element” Ag-U-Co-Ni-As-Bi veins, Bastin, 1939; Kissin, 1993; Lefebure, 1996, e.g., Zalesi, Czech Republic, Dolniček et al., 2009); (4) Ni rich veins in peripheral parts of large igneous provinces (e.g., Khovu-Aksy, Altai, Russia, Borisenko et al., 2006; Dobretsov et al., 2010; Tretiakova et al., 2010); and (5) ultramafic-mafic altered suites associated (e.g., Avebury, Australia, Keays and Jowitt, 2013; Bou Azzer, Morocco, Ahmed et al., 2009). Importantly, deposits in different groups listed above can share some common features due to possible overlapping or/and overprinting processes.

The hydrothermal Ni deposits associated with altered ultramafic/mafic suites are characterised by an apparent close spatial association with altered ultramafic to mafic rocks, widely considered to be the source of nickel (e.g., Leblanc and Billaud, 1983; Auclair et al., 1993; Hoatson et al., 2006; Peltonen et al., 2008; González-Álvarez et al., 2010). Many of these deposits are hosted by ultramafic rocks, often along their contacts with country rocks (e.g., Jumbo Mountain, USA, Mills, 1960). They also tend to be spatially and, possibly, genetically associated with fractionated granitic intrusions. One of the most representative examples of such deposits is the Avebury deposit in Tasmania (Australia; Hoatson et al., 2006; Keays and Jowitt, 2009, 2013; Lygin et al., 2010a).

For practical reasons and based on the geological characteristics and history of western Victoria, this study is focussed on the exploration targeting model for the ultramafic-mafic-associated granite-related hydrothermal-remobilised group of deposits, loosely referred to as the “Avebury-style” deposits.

**3.2. Characteristics of the Avebury nickel deposit**

The Avebury deposit was discovered by Rio Tinto Exploration Ltd in 1998 (Hoatson et al., 2006 and references therein) and is currently owned by Minerals Mining Group (MMG). The deposit contains 29.3 Mt ore at an average global nickel grade of 0.9%, for a total of 263.7 kt of contained Ni (MMG, 2014).
The Avebury deposit is hosted by the Eocambrian-Cambrian mafic-ultramafic McIvor Hill complex (Lygin et al., 2010). This mafic-ultramafic Complex was emplaced and mainly affected by two tectonic-metamorphic events: (1) the Tynnean Orogeny (~510 Ma) during the collision of a passive margin in the West and an intra-oceanic arc in the East (Crawford and Berry, 1992), and (2) the Tabberabberan Orogeny at ~390 Ma (Black et al., 2005) that originated NW-trending faults and granitic intrusions. One of these intrusions, the Late Devonian Heemskirk granite is interpreted to be the heating-fluid source associated that triggered the formation of the Avebury deposit (Keays and Jowitt, 2009; Lygin et al., 2010a).

The nickel sulphide mineralization is mainly confined to the ultramafic body and locally developed diopside - actinolite - tremolite skarns (Lygin et al., 2010b). The host ultramafic rocks belong to the Neoproterozoic to Cambrian mafic-ultramafic McIvor Hill complex (Seymour et al., 2007). Several mineralized areas have been identified within the ultramafic intrusion: North Avebury, Viking, Burbank (Green and Taheri, 2004) and Saxon and Bison (Allegiance Mining N.L., 2007). The orebodies lie in the contact aureole of the Late Devonian Heemskirk granite.

Avebury is a nickel sulphide deposit characterized by low Cu and PGE, and enriched in W, Pb, Bi, Mo, Sn, Sb and Au (Lygin et al., 2010b). The mineralisation is distributed in veins and coarse grained disseminations made of dominantly pentlandite, minor pyrrhotite, and rare millerite, mackinawite, niccolite, gersdorffite and maucherite, with up to 18% magnetite associated (Keays and Jowitt, 2009). The mineralized serpentinized ultramafics do not display primary magmatic minerals but largely distributed Cr-spinels (Lyngin et al., 2010b). Based on the geochemistry and petrology of the deposit, Avebury is interpreted as a hydrothermal nickel deposit, formed as a result of heating and metasomatism related to the intrusion of the Heemskirk granite (Hoatson et al., 2006; Keays and Jowitt, 2009; Lygin et al., 2010a; Keays and Jowitt, 2013).

Nickel in the Avebury has been suggested to be sourced from a magmatic Ni-Cu-(PGE) sulphide deposit at depth. This is based on trace element ratios of PGE-Au, that were affected by metasomatic fluids may have removed Cu, Au, Pd, Pt and Rh from the original magmatic sulphides but not Ir (Keays and Jowitt, 2013).

### 3.3. Conceptual mineral system model

The conceptual model for this specific hydrothermal nickel deposit style was developed specifically for the purpose of greenfield exploration targeting. It aimed to
identify critical elements of this distinct mineral system associated with ultramafic-mafic complexes and felsic intrusions, similar to the Avebury deposit, at the regional scale of this prospectivity analysis.

Hydrothermal systems in general are characterised by circulation of mineralising fluids heated by igneous events or metamorphism (Pirajno, 2009). The temperature and properties of these fluids affect their metal complexation capacity and in many cases the fluids can extract, transport and accumulate particular metals. In any hydrothermal nickel mineral system, three groups of factors are considered to be essential: (1) availability of a nickel source; (2) presence of favourable parameters of circulating fluids enhancing nickel mobility; and (3) favourable conditions for localised deposition of nickel.

### 3.3.1. Availability of a nickel source

Nickel is a relatively abundant metal in the continental crust, with the average crustal abundance estimated between 20 ppm and 50 ppm (Shaw et al., 1967; Taylor and McLennan, 1984, 1995; McDonough and Sun, 1995; Hu and Gao, 2008; Rudnick and Gao, 2003). Olivine-rich ultramafic rocks (peridotites, dunites) are strongly enriched in Ni (2000-3000 ppm), compared to pyroxenites (~500 ppm), mafic magmatic rocks (~100-300 ppm) and intermediate to felsic rocks (~50 ppm). High Mg concentrations in intrusive suites generally indicate high olivine content and therefore can be used as an indicator of elevated nickel content. Ultramafic-mafic associated hydrothermal nickel deposits are generally considered to result from fluid-rock interaction in ophiolitic suites and/or ultramafic intrusions (e.g., Avebury, Australia; Keays and Jowitt, 2013; Jumbo Mountain, USA; Mills, 1960; Bou Azzer, Morocco; Ahmed et al., 2009; Epoch, Zimbabwe; Pirajno and González-Álvarez, personal communication).

Exploration proxies: (1) presence of ophiolitic packages, ultramafic intrusions, picritic suites (>12% MgO) and previous magmatic nickel sulphide deposits.

### 3.3.2. Nickel release and transport

Combination of different fluids (meteoric, sea-water, magmatic), at a wide variety of temperatures (~50°C - 600°C) produced by intrusive suites or tectonic events (e.g., different type of granites), with a diverse chemical compositions (alkaline, organic content, Cl rich, CO₂) and redox conditions (oxidizing to slightly reducing) are able to complex Ni, releasing it from the primary host minerals (olivine, pyroxene) and transporting it along
a pipe-line system (complex structural settings, shear zones, faults, permeable units; for a summary see González-Álvarez et al., 2010).

Magmatic sources of fluids can be associated with fractionated felsic intrusions. Felsic intrusions, broadly coeval with mineralisation, are often (but not always) found in the vicinity of hydrothermal Ni deposits (e.g., Avebury). A magmatic source of fluids (or, possibly, basinal brines) is supported by high-salinity fluid inclusions at Bou Azzer and Cobalt (Marshall et al., 1993; En-Naciry et al., 1997).

Different granite types have different volatile solubility, the initial volatile content of a melt and the onset of fluid formation, and a variety of metalliferous fertility that is represented by the metallic associations produced in the metamorphic and alteration halo (e.g., western Tasmania with strongly fractionated and evolved I-type granites; Heemskirk granite, Avebury; e.g., Sial et al., 2011).

High-salinity fluids are likely to be a more effective Ni-transporting medium – in both Cl and CO₂ complexes. Consequently, the presence of evaporitic straigraphic units can become a key component of hydrothermal Ni ore formation.

Exploration proxies that can be used to indicate a potential for hydrothermal nickel deposits include: (1) presence of intrusion and/or volcanic activity; (2) metamorphic facies between greenschist and amphibolite facies; (3) orogenic belts; (4) presence of organic sedimentary units, carbonates and evaporitic units (NaCl); (5) S source associated to sedimentary units, intrusive fluids or/and magmatic nickel sulphide deposits; (6) presence of shear zones, faults or permeable sedimentary units; (7) alteration halo/deposit fingerprints of possible metallogenically “fertile” granitic intrusions, represented by Sn, Zn, Pb and B anomalies; (8) presence of skarns indicating fluid mobility and metal transport; (9) depth and volatile content in the granitic intrusions (e.g., a tourmaline halo); (10) Sn (±W) with Sb, Pb, Zn metals associated to felsic and more fractionated and reduce (magnetite-free) granites; (11) low gravity associated to fractionated granites; (12) low magnetics associated to reduced granitic intrusions; (13) relative stronger radiometrics associated to more fractionated granites; and (14) high conductivity response due to possible metal-S combination after intrusion emplacement.

### 3.3.3. Ni accumulation

Nickel is easily fixed by sulphide-rich sedimentary units (e.g., black shales; Lower Cambrian black shales of South China; Mao et al., 2002; Jiang et al., 2007). Several hydrothermal Ni deposits seem to be located in the irregularities of the intrusive source of
the Ni with the sedimentary package at irregularities (Jumbo Mountain, USA) and along the fluid pathway cross-cutting the Ni source (Epoch, Zimbabwe). Distance from source varies widely from contact with the source to >2 km (Rathbun, Canada; Schandl, 2001) to direct contact by leaching of the deposit (Fortaleza de Minas; Brenner, 2006). Several hydrothermal Ni deposits display high concentration of magnetite due to ultramafic alteration processes (e.g., Avebury, Tasmania).

Exploration proxies include: (1) S-rich sedimentary units; (2) contact source-faults; (3) contacts between the sedimentary package and the intrusion; (4) dilation zones in tectonic structures shear zones, crosscutting structures for fluid mixture; (5) positive magnetic anomalies associated to massive magnetite due to the alteration.

**Fig. 1.** Conceptual hydrothermal Ni mineral system presenting: (1) Ni sources, such as ultramafic–mafic suites and magmatic Ni deposits; (2) Ni mobilisation and transport factors, including (a) energy and fluid sources (e.g., intrusions), (b) additional ligand sources (evaporates, C$_{org}$, S- and carbonate-bearing units), and (c) a plumbing system to facilitate the focused flow of mineralising fluids (e.g., faults and/or permeable sedimentary units); (3) Ni deposition factors (e.g., physical traps in dilational zones associated with faults and folds, chemically reactive rocks) (from González-Álvarez et al., 2010).
4. Geological setting of western Victoria

The regional geological setting of western Victoria and its geological history has been discussed in many detailed reviews (e.g., Vandenberg et al., 2000; Cayley and Taylor, 2001; Morand et al., 2003; Birch, 2003; Champion et al., 2009). Significant new insights into the crustal architecture of the region have been produced by interpretation of recent deep seismic surveys (Cayley et al., 2011a, b). However, some details of the tectonic evolution of this poorly explored region in the Palaeozoic remain controversial. This brief review only focuses on the major geological events and factors likely to be related to the critical components of potential hydrothermal nickel mineral systems, as discussed in the previous section.

Western Victoria represents parts of the Delamerian and Western Lachlan orogens of the Tasman Orogenic Belt, formed along the eastern margin of the Australian continent in the Neoproterozoic and Palaeozoic. The complex geological history of the region during that period included continental rifting, opening of the palaeo-Pacific ocean, passive margin sedimentation, initiation of subduction, several collisional orogenic events, accompanied by regional metamorphism, and syn- to post-orogenic magmatism. Large parts of the Western Lachlan Orogen and the vast majority of the Delamerian Orogen are covered by Meso-Cainozoic sedimentary rocks of the Otway basin in the south and the Murray basin in the north and by Cainozoic alluvial sediments and basalts of the Newer Volcanic Province.

The Glenelg Zone, in the west of the Victorian part of the Delamerian Orogen, is dominated by the Lower Cambrian sedimentary rocks of the Moralana Supergroup and their highly metamorphosed equivalents in the Glenelg River Metamorphic Complex (Vandenberg et al., 2000; Morand et al., 2003; Vandenberg, 2009). The sedimentary rocks are mostly represented by deep-water turbidites (including carbonaceous shales), with minor carbonate-bearing rocks (calcitic and dolomitic shales and limestones). The sedimentary sequence was deposited in the extensive Stansbury Basin, in a passive margin setting.

The mafic Truro Volcanics and associated minor intrusions, formed prior to the Delamerian Orogeny (~515 Ma), with the isotope geochronology results indicating the age between ~560 Ma and 525 Ma (Vandenberg et al., 2000; Morand et al., 2003; Campion et al., 2009), occur as narrow belts and isolated fault-bounded blocks within the Moralana Supergroup. They are composed of submarine tholeiitic to picritic basalts and minor andesites and related mafic to ultramafic and intermediate intrusions. The analysed volcanic rocks range in composition from rift-related within-plate basalts to MORB-like...
magmatic rocks. The Truro Volcanics are interpreted to represent progressive rifting of the passive continental margin and formation of the oceanic crust (Vandenberg et al., 2000; Crawford et al., 2003; Champion et al., 2009).

The Grampians-Stavely Zone includes widespread magmatic rocks of the Dimboola Igneous Complex and Mount Stavely Volcanic Complex, stratigraphically overlain by, and in places structurally intercalated with, the sedimentary Nargoon Group (including the Glenthompson Sandstone). The Dimboola Igneous Complex represents an extensive magnetic mafic-ultramafic ophiolite sequence, interpreted as part of an Early to Middle Cambrian intra-oceanic fore-arc – arc complex, possibly analogous mafic-ultramafic complexes of western Tasmania (Vandenberg et al., 2000; Morand et al., 2003; Champion et al., 2009). The Mount Stavely Volcanic Complex is represented by calc-alkaline intermediate to felsic volcanics, interpreted as a Late Cambrian post-collisional volcanic complex, broadly equivalent to Mount Reed Volcanics in western Tasmania.

Ultramafic rocks are relatively rare in western Victoria. They are usually represented by cumulates in mafic-dominated magmatic complexes (Truro Volcanics in the Glenelg Zone, the Dimboola Igneous Complex in the Grampians-Stavely Zone), isolated narrow fault slices and sometimes – more extensive belts (Hummocks Serpentinite along the Hummocks Fault, etc.). More extensive belts and blocks including ultramafic magmatic rocks have been recognised under sedimentary cover in rare boreholes and through the interpretation of geophysical datasets (Vandenberg et al., 2000; Betts, 2008). All currently known nickel occurrences in western Victoria are associated with ultramafic rocks.

The Delamerian Orogen, as well as western parts of the Stawell Zone of the Lachlan Orogen, were affected by the Delamerian Orogeny (~515 – 500 Ma), accompanied by regional metamorphism and emplacement of granitic intrusions. A later phase of intrusive magmatism affected the region in the Early to Middle Devonian (represented by widespread S-, I- and A-type granite intrusions). The age of Cambrian to Early Ordovician intrusions has been defined by U/Pb SHRIMP and Ar-Ar dating to be in the interval of 484-505 Ma (Vandenberg et al., 2000; Morand et al., 2003), broadly coeval with the Mount Stavely Volcanics in the Grampians-Stavely Zone and the Mount Reeds Volcanics and Murchison Granite in Tasmania. Devonian granites have typical U/Pb SHRIMP ages of 400-410 Ma and Ar/Ar ages of 380-400 Ma (Vandenberg et al., 2000) – broadly coeval with the oldest intrusions in eastern Tasmania, but older than the Late Devonian Heemskirk Granite in western Tasmania.

The Cambrian rocks of the Delamerian Orogen are in places overlain by the post-
cratonic Silurian sedimentary sandstone-dominated Grampians Group and Early Devonian felsic Rockland Volcanics.

![Fig. 2. Simplified geology of western Victoria. Total magnetic intensity shown for the areas of Permian to Cainozoic cover.](image)

5. **Prospectivity analysis**

5.1. **Fuzzy inference system**

The conceptual mineral system model discussed in Section 3.3 formed the basis of the fuzzy inference system used in this study. The system identified GIS proxies deemed representative of the critical mineral system components (Table 1) and defined relationships between individual proxies used to combine input GIS datasets and produce the final fuzzy prospectivity map (Fig. 3). The selection of mineral system components and their representative GIS proxies used in this analysis was strongly affected by the factors of scale and availability. The relative significance of different exploration targeting elements depends on the scale of prospectivity analysis (McCuaig et al., 2010). For example, local factors that represent critical controls on the spatial distribution of mineralisation at the orebody to deposit scale (e.g., small dilational structures, or thin beds...
of chemically reactive rocks) may be less important or even irrelevant at more regional scale, and vice versa. Additionally, information on the spatial distribution of detailed controls or indicators of the presence of specific mineral system components is typically extremely heterogeneous in regional-scale geological datasets with a strong sampling bias towards specific areas (e.g., geochemistry).

This study was conducted at the regional to camp scale and focused on a poorly explored region with limited available information on small-scale geological features. Therefore, the targeting elements represented by detailed GIS proxies with likely high spatial variability exceeding the resolution and not compatible with the scale of this analysis were not included in the fuzzy inference system. Specifically, the deposition factors and some detailed fluid transport factors and their GIS proxies (e.g., fold-related fault and fracture meshes, rheological contrasts, lithological contact and structural complexity densities) were not included in the fuzzy inference engine and prospectivity modelling. This omission is likely to result in a general bias of final fuzzy prospectivity values and a loss of additional information that could allow a more detailed differentiation and relative ranking of the identified prospective areas.

**Table 1.** Conceptual model of Avebury-style hydrothermal-remobilised nickel mineral systems in western Victoria – critical components, targeting elements and GIS proxies.

<table>
<thead>
<tr>
<th>Critical components / processes</th>
<th>Source - Metal</th>
<th>Release</th>
<th>Transport</th>
<th>Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent components / processes</td>
<td>Ni-rich rock types (including possible magmatic Ni deposits)</td>
<td>Energy</td>
<td>Fluids</td>
<td>Ligands</td>
</tr>
<tr>
<td>Targeting elements</td>
<td>1. Magmatism</td>
<td>1. Fractionated granites</td>
<td>1. Granites</td>
<td>1. Faults</td>
</tr>
<tr>
<td></td>
<td>2. Regional metamorphism</td>
<td>2. Metamorphic fluids</td>
<td>2. Rocks with elevated Cl, CO(<em>2), mobile S and ( C</em>{org} )</td>
<td>2. Fold-related fractures</td>
</tr>
<tr>
<td>GIS proxies</td>
<td>1. Average Ni content</td>
<td>1. Proximity to granites</td>
<td>1. Proximity to granites</td>
<td>1. Proximity to granites</td>
</tr>
<tr>
<td></td>
<td>2. Proximity to high-Ni rocks</td>
<td>2. Metamorphic grade</td>
<td>2. Metamorphic grade</td>
<td>2. Average content of S, ( C_{org} ), CO(_2)</td>
</tr>
</tbody>
</table>
Fig. 3. Fuzzy inference engine. The deposition factors and some fluid transport control factors were not included in this scheme, largely due to a lack of sufficiently detailed data with a reasonably consistent regional coverage.
5.2. Estimation of expected fuzzy membership values for individual predictor maps

Expected fuzzy membership values of the predictor maps representing GIS proxies for exploration targeting elements were subjectively estimated, following a general procedure described in Section 2.2. For the nickel source predictor maps, individual lithological complexes identified in western Victoria were assigned nickel source fuzzy membership values as a proportion of their inferred average nickel content:

$$\mu_{0\text{Ni}} = \frac{\text{Ni}}{3000}$$  \hspace{1cm} (3)

For the multi-class predictor maps indicating proximity to certain geological features (Ni-rich mafic and ultramafic rocks, granites, faults), the assigned fuzzy membership values decreased with increasing distance, following the same functional relationships between fuzzy membership values and distances as those defined in the prospectivity analysis of hydrothermal nickel mineral systems in Tasmania (González-Álvarez et al., 2010):

$$\mu_x = \mu_0 x d_x$$  \hspace{1cm} (4)

where $d_x$ is a distance decay coefficient ($0 \leq d_x \leq 1$), generally consistent with expert estimates of distance class membership values in Gonzalez-Alvarez et al. (2010).

Fuzzy membership values assigned to different classes of the predictor maps used in this analysis are summarised in Table 2.

5.3. Estimation of uncertainty of fuzzy membership values

The expected fuzzy membership values (Section 5.2) represent ‘best-guess’ expert point estimates with significant implicit uncertainties. For example, the Ni source membership values for each analysis cell were defined as a function of proximity of the cell to Ni-rich ultramafic and mafic rocks and the average Ni content within the cell. However, neither the average Ni content of a particular broadly defined rock type nor a relationship between the distance to Ni-rich rocks and a probability of occurrence of hydrothermal Ni mineralisation could be determined with any certainty. For example, the nickel content of ultramafic rocks, can vary between <500 ppm for pyroxenites and >3,000 ppm for dunites (McDonough and Sun, 1995; Rudnick and Gao, 2003). To evaluate these uncertainties, we first estimated likely minimum and maximum fuzzy membership values for each predictor class (Table 2).

Fuzzy membership ranges for individual lithological complexes (the Ni source factor) were calculated (using Equation 3) from their likely minimum and maximum Ni contents, estimated on the basis of Ni assay results for the corresponding rock types from western
Victoria and similar rocks elsewhere. For the predictor classes indicating proximity to geological features, the ranges for the distance decay coefficients $d_i$ (Eq. 4) were first estimated on the basis of subjective judgement, guided by alternative power distance decay functions (e.g., linear and inverse distance squared). Fuzzy membership values were then evaluated through Monte Carlo simulations in Oracle Crystal Ball™ using Equation 4, assuming that both arguments in the equation represent random variables following beta statistical distributions (Krishnamoorthy, 2006; Forbes et al., 2011; Olea, 2011) consistent with the estimated expected fuzzy membership values and ranges (Table 2). Fuzzy membership ranges for categorical predictor classes (e.g., metamorphic grades and depth of post-mineralisation cover) were estimated subjectively.

### Table 2. Fuzzy membership values for individual predictor classes.

<table>
<thead>
<tr>
<th>Map class</th>
<th>Fuzzy membership - expected</th>
<th>Fuzzy membership - minimum</th>
<th>Fuzzy membership - maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ni source</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lithological complex</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultramafics</td>
<td>0.67</td>
<td>0.17</td>
<td>1.0</td>
</tr>
<tr>
<td>Ultramafic or mafic rocks – interpretation uncertain</td>
<td>0.38</td>
<td>0.03</td>
<td>1.0</td>
</tr>
<tr>
<td>Mafic igneous rocks</td>
<td>0.1</td>
<td>0.03</td>
<td>0.13</td>
</tr>
<tr>
<td>Mafic to intermediate igneous rocks</td>
<td>0.07</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>Mafic igneous rocks and sedimentary rocks</td>
<td>0.07</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>Intermediate igneous rocks</td>
<td>0.013</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>Sedimentary rocks – combination of sandstones, shales and rare carbonates</td>
<td>0.013</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>Sedimentary rocks – sandstone dominated</td>
<td>0.0067</td>
<td>0.003</td>
<td>0.01</td>
</tr>
<tr>
<td>Felsic igneous rocks</td>
<td>0.0007</td>
<td>0.0003</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Proximity to ultramafic rocks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km</td>
<td>0.57</td>
<td>0.17</td>
<td>0.94</td>
</tr>
<tr>
<td>2 km</td>
<td>0.27</td>
<td>0.07</td>
<td>0.58</td>
</tr>
<tr>
<td>3 km</td>
<td>0.19</td>
<td>0.05</td>
<td>0.44</td>
</tr>
<tr>
<td>4 km</td>
<td>0.13</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>5 km</td>
<td>0.06</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>6 km</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.002</td>
</tr>
<tr>
<td>Map class</td>
<td>Fuzzy membership - expected</td>
<td>Fuzzy membership - minimum</td>
<td>Fuzzy membership - maximum</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------</td>
<td>----------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Proximity to ultramafic or mafic rocks (interpretation uncertain)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km</td>
<td>0.39</td>
<td>0.03</td>
<td>0.9</td>
</tr>
<tr>
<td>2 km</td>
<td>0.18</td>
<td>0.02</td>
<td>0.49</td>
</tr>
<tr>
<td>3 km</td>
<td>0.13</td>
<td>0.009</td>
<td>0.37</td>
</tr>
<tr>
<td>4 km</td>
<td>0.09</td>
<td>0.007</td>
<td>0.27</td>
</tr>
<tr>
<td>5 km</td>
<td>0.04</td>
<td>0.004</td>
<td>0.12</td>
</tr>
<tr>
<td>Proximity to mafic rocks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km</td>
<td>0.09</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>2 km</td>
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<tr>
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<tr>
<td>Proximity to faults</td>
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</tr>
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</tbody>
</table>
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### 5.4. Compilation of predictor maps from multiple datasets

The geology of the vast majority of the study area could only be interpreted from geophysical datasets, with extremely limited borehole and mapping controls. As a result, multiple alternative interpretations were available for GIS proxies of several critical exploration targeting criteria (e.g., the distribution of granites, Ni-rich rocks and faults). In the current study, we did not attempt to explain and reconcile the differences between alternative interpretations (Moore, 1996, 1997, 2004; Cayley and Taylor, 1997, 2001; Morand et al., 2003; Betts, 2008; McLean, 2010; McLean et al., 2010; GeoScience Victoria, 2011). Nor did we want to choose a single preferred interpretation and disregard all the others. Instead, the alternative interpretations were used to derive combined predictor maps to evaluate additional stochastic uncertainties. The combination for each predictor map was performed through a Monte Carlo simulation (using Oracle Crystal Ball™), randomly sampling fuzzy membership values from beta statistical distributions fitted to estimated expected fuzzy membership values and ranges and assigned to predictor classes in individual interpretations (Fig. 4). The expected combined fuzzy membership values were evaluated as means of the resultant combined distributions.

### 5.5. Generation of the prospectivity maps

Fuzzy prospectivity maps were produced by combining individual predictor maps using the fuzzy inference engine (Section 5.1). The fuzzy membership values for individual predictor maps and classes were represented here by statistical distributions, rather
than point estimates, typical for fuzzy logic prospectivity modelling. This provided an opportunity to evaluate uncertainty of the final prospectivity model - in addition to a map of expected fuzzy logic prospectivity. Overall uncertainty was estimated by propagating uncertainties of individual predictor maps through the inference engine using Monte Carlo simulations (Fig. 4). Additionally, variations of the fuzzy logic inference engine could be used in the sensitivity analysis – alternative scenario testing to evaluate robustness of the final prospectivity model and its sensitivity to variations of model parameters. The fuzzy prospectivity maps are shown of Figures 5-8.
Fig. 4. Combination of predictor maps by using Monte Carlo simulations and the fuzzy inference engine (Fig. 3).
Fig. 5. Fuzzy mineral prospectivity (means) map for Avebury-style hydrothermal Ni deposits in western Victoria.
Fig. 6. Fuzzy mineral prospectivity (P90) map for Avebury-style hydrothermal Ni deposits in western Victoria. Colours correspond to 90th percentiles of fuzzy prospectivity statistical distributions for the individual analysis cells.
Fig. 7. Fuzzy mineral prospectivity (P10) map for Avebury-style hydrothermal Ni deposits in western Victoria. Colours correspond to 10th percentiles of fuzzy prospectivity statistical distributions for the individual analysis cells.
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Fig. 8. Fuzzy exploration potential map. It is based on the mineral prospectivity map (mean – Fig. 5), but it also takes into account land use restrictions and depth of barren cover, which would significantly affect a probability of discovery of a hydrothermal nickel deposit, or even legally preclude any exploration activities in particular areas.

6. Discussion and conclusions

This reconnaissance regional prospectivity analysis highlighted several areas prospective for remobilised hydrothermal nickel mineralisation. One of the most prospective areas highlighted in the southern part of the study area (Figs 5-6, 8) has been partially explored in recent years for Avebury-style hydrothermal nickel mineralisation. Significant exploration results include anomalous soil geochemistry (up to 0.4% Ni) and drilling results (including 4.8 m @ 0.44% Ni, (Beaconsfield Gold, 2008; Seymon et al., 2009). These detailed exploration results were not used as inputs in this prospectivity analysis and thus may indicate a potential predictive power of the generated prospectivity model.

Potential of western Victoria for ‘Avebury-style’ hydrothermal nickel mineralisation has been previously assessed by manual qualitative prospectivity analyses on a broad regional scale (Seymon, 2006; Champion et al., 2009) and a more detailed camp scale
(Seymon et al., 2009), as well as part of a continent-scale weights of evidence modelling (Hill and McCarthy, 2009). Naturally, the regional province-scale analyses, based on the consideration of broad regional factors, highlighted much larger areas with a potential for ‘Avebury-style’ mineralisation compared to the outputs of the current study. As such, they cannot be directly used for efficient camp-scale exploration targeting. Conceptually, manual delineation of camp-scale exploration targets within a large region has significant natural limitations (e.g., extreme difficulties of consistent and repeatable manual processing of large amounts of diverse input data by individual experts and numerous intrinsic human biases - Meyer and Booker, 2001; O’Hagan et al., 2006). In contrast, the semi-automated analysis performed in this study allowed a rapid identification and relative ranking of several prospective areas in a transparent and repeatable manner.

The inclusion of exploration potential criteria in this study (exploration ‘No-Go’ areas, depth of cover) allowed to further discriminate identified prospective areas on the basis of practical considerations. For example, some areas with significant estimated mineral prospectivity in the north of the study area (Figs 5-6) occur within the boundaries of national parks or under significant barren cover, which eliminated or significantly downgraded them as potentially viable exploration targets (Fig. 8).

The regional scale of this analysis, as well as the availability, coverage and spatial resolution of the available geological datasets – precluded the use of some valuable exploration datasets – e.g., geochemistry and detailed structural data. Geochemical datasets could be invaluable to indicate potential deposition sites or fluid pathways and dispersion zones. However, such data is only available for just a few relatively small mostly exposed areas that were subjected to detailed mineral exploration. The use of such incomplete and biased datasets could introduce significant bias to the prospectivity analysis results.

Modelling uncertainty in this study provided much more information for decision making compared to typical fuzzy logic prospectivity analysis. It allowed a finer differentiation between identified exploration targets based on the degree of consistency of spatial patterns at different probability levels. This information can also be used to identify additional subtle high-risk targets or account for geochemical anomalies likely to be unrelated to potentially economic mineralisation (e.g., a group of easternmost targets most prominent at the P10 level, Fig. 7). The uncertainty information can assist in a further risk analysis in support of decision making related to mineral exploration for Avebury-style hydrothermal Ni deposits in western Victoria. A similar procedure could also be incorporated in other prospectivity analysis studies. The authors acknowledge
that perhaps the largest source of uncertainty of the prosectivity model described in this paper is uncertainty of the conceptual mineral system model (Section 3.3) used as the basis of the fuzzy inference engine (Section 5.1) and largely defining the resultant mineral prospectivity maps. This fundamental source of uncertainty was not specifically evaluated as part of this study. This should be taken into account when using its outputs – as well as those of any other knowledge-driven prospectivity analysis based on a single conceptual model – for decision making.

References


Co-Zn-Ni deposits of the Sykesville district, Maryland Piedmont. Economic Geology 84, p. 663-675.


Chapter 4

SPATIAL DATA ANALYSIS OF MINERAL DEPOSIT POINT PATTERNS: APPLICATIONS TO EXPLORATION TARGETING

V. Lisitsin, 2015.
Ore Geology Reviews, http://dx.doi.org/10.1016/j.oregeorev.2015.05.019 (in press)

Abstract

Systematic spatial analysis of mineral deposit point patterns can reveal significant spatial properties of mineral systems, with major implications for regional mineral prospectivity modelling. For valid results, a study area needs to be clearly defined, taking into account permissiveness of the geological units for a particular mineral system and effects of cover. Standard statistical tests assuming an isometric contiguous study area with regionally homogeneous distribution of deposits are likely to produce invalid results. Analysis of regional uniformity of spatial deposit density is required for adequate design and interpretation of tests for clustering. Spatial distribution of orogenic gold deposits in the Hodgkinson Province in Queensland and the Western Lachlan Orogen in Victoria (Australia) indicates the presence of significant regional linear metallogenic zones, probably controlled by deep crustal domain boundaries oblique and not related to any recognised major faults. Within the metallogenic zones in both regions, individual gold occurrences are strongly clustered into ore fields, but the distribution of ore fields is random.

Keywords: exploratory data analysis; $L$ function; nearest neighbour distance; Fry analysis; orogenic gold; Hodgkinson Province; Queensland; Western Lachlan Orogen; Bendigo Zone; Victoria

1. Introduction

Predictive mineral potential modelling (both in forms of prospectivity mapping and quantitative mineral resource assessments) typically uses a combination of knowledge of essential natural processes leading to the formation and preservation of mineral deposits (mineral systems), on the one hand, and empirical evidence of spatial association between mineral deposits and other geological objects or their properties, on the other. However, any predictive modelling is invariably impeded by limited knowledge of mineral systems.
and frequently obscure manifestations of major metallogenic factors - such as sources and zones of focused flow of mineralising fluids. Consequently, there is a significant risk of not recognising some essential mineralisation controls, potentially leading to grossly biased modelling results.

In an area with a relatively large number of known mineral deposits, their spatial distribution can provide critical information on metallogenic processes operating at different scales. For example, significant metallogenic controls may have only cryptic expressions in traditional geological datasets, initially revealing themselves only in the spatial distribution of mineralisation. The latter could also help to validate a common assumption of deposit clustering. Recognising cryptic regional metallogenic controls and establishing whether deposits (particularly large ones) tend to be close or distal from each other have major implications for exploration targeting. For example, major deposits within a province could occur in a relatively narrow richly endowed metallogenic zone (discordant to regional geological structures recognised at surface), surrounded by large geologically similar areas containing only sparse and mostly economically insignificant mineralisation. It is then critical to focus exploration for major deposits on that zone. Similarly, if major deposits tend to be spatially separated from each other by a relatively large distance, then extensive exploration in a close vicinity to a known major deposit may be a flawed exploration strategy if a desired target is another major deposit. Such information can be particularly important at scales of tens to hundreds of kilometres – intermediate between those of a broad regional scale (focusing on regional geodynamic and associated metallogenic factors) and detailed camp to deposit-scale studies (focusing on direct observations over relatively small areas).

Methods of spatial statistical analysis of point patterns are well developed and widely used in social and physical sciences, including applications in geology (Getis and Boots, 1978; Cressie, 1991; Diggle, 2003; Illian et al., 2008). They are appropriate for investigating stochastic processes, manifestations of which can be represented, at the scale of analysis, by a finite set of points. In a regional-scale prospectivity analysis (covering thousands of km²), mineral deposits can be adequately represented by points, which has been almost universally accepted in previous spatial and mineral prospectivity analyses (Bonham-Carter, 1994; Porwal et al., 2003; Carranza, 2008, 2009).

Various techniques of spatial statistical data analysis have been applied to investigate distribution of mineral deposits, mostly involving methods of point pattern and fractal analysis (De Geoffroy and Wignall, 1971; Agterberg, 1984; Harris, 1984; Carlson, 1991;
Kreuzer et al., 2007; Raines, 2008; Ford and Blenkinsop, 2008; Carranza, 2008, 2009; Mamuse et al., 2009, 2010; Singer, 2008; Singer and Menzie, 2010; Singer and Kouda, 2011; Dirks et al., 2013). However, different spatial statistical methods have been mostly used in isolation. As each specific method only characterises a particular aspect of a point pattern, outputs of any individual test could be insufficient to make reasonable inferences about spatial distribution of deposits, potentially leading to erroneous interpretations. Importantly, most traditional spatial statistical tests imply some underlying assumptions (similar to the assumption of the normal distribution in many classical statistical tests). In practice, these assumptions are rarely explicitly stated, analysed and validated, even though they are frequently violated. Formal confirmatory statistical analyses may not adequately characterise spatial distribution of mineral deposits, which in many situations would be more amenable to a suite of complementary methods for exploratory spatial data analysis.

Suitability of specific methods to study patterns of mineral deposits depends on ultimate goals of an analysis. The focus may be on the spatial distribution of the intensity of a metallogenic process (e.g., mapping zones of high or low spatial deposit density), interaction of points with each other (e.g., clustering or dispersion), spatial association between deposits and other features (spatial covariance with one or more explanatory variables), or a combination of the above. This paper describes a joint application of several complementary methods of spatial data analysis, many of which are not commonly used in mineral prospectivity modelling but can provide important insights into the spatial distribution of mineral deposits and underlying regional metallogenic controls. The selected set of methods is far from exhaustive and more powerful alternatives and comprehensive modelling strategies have been developed for some of them in recent years (Diggle, 2003; Illian et al., 2008; Gelfand et al., 2010). The method selection was deliberately biased towards traditional methods which are relatively easy to implement using standard readily available software and outputs of which are amenable to a reasonably straightforward intuitive interpretation. A major goal of this paper is to discuss pitfalls of many traditional spatial statistical methods applied to investigate the spatial distribution of mineral deposits and to illustrate their tentative use as part of comprehensive exploratory spatial data analysis. The reviewed methods include analyses of: centrography and directional distribution, Fry plots, nearest neighbour distances, spatial density and Ripley’s K function. A systematic spatial data analysis, focusing on an effective combination of individual methods, was applied to investigate regional spatial
patterns of orogenic gold deposits in the Hodgkinson Province in north Queensland and the Western Lachlan Orogen in central Victoria (Australia). Outputs of the applications of spatial data analysis discussed in this paper have major implications for mineral resource assessments and exploration targeting in those regions.

2. Methods for spatial analysis of point patterns

2.1. Overview of methods and modelling strategies

A point pattern within a study area can be characterised by statistical measures and properties describing the pattern as a whole, as well as by indicators of more local properties of the spatial distribution of points within the pattern. The former can be described by a series of summary statistics providing information on the geographic centre, spread and directional anisotropy (centrographic and directional distribution spatial analysis) and the average spatial density of the point pattern. Estimates of average spatial mineral deposit densities have been extensively used in quantitative mineral resource assessments to estimate numbers of undiscovered deposits in a study area based on average deposit densities in geologically similar areas (Singer et al., 2001; Singer and Kouda, 2011). In contrast, methods for analysing centrographic and overall directional properties have rarely been applied to investigate mineral deposit patterns (Mamuse et al., 2009).

A wide range of other spatial statistical methods place more emphasis on describing local internal properties of patterns, mostly focusing on the distribution of points in relation to each other. A point pattern (e.g., representing a group of known mineral deposits in a study area) is typically compared to a simple theoretical point pattern to classify the analysed pattern into one of several basic types. Then, inferences can be made about the character of a point process and, possibly, an expected distribution of other points in the study area (such as undiscovered deposits).

Point patterns can be subdivided into several basic types (Getis and Boots, 1978; Diggle, 2003). Firstly, the average point density (the number of points per unit area) can be either uniform throughout a study area (a homogeneous distribution) or significantly vary in space (a non-uniform, or heterogeneous distribution). The latter could be a manifestation of the underlying spatial heterogeneity of major factors controlling point processes. This is commonly observed for mineral deposits (e.g. a major structural corridor controlling the location of a richly endowed metallogenic zone). Secondly, depending on the character of interpoint interaction, point patterns can be described as random, clustered or dispersed (regular).

The character and extent of interpoint interaction in an analysed point pattern is typically determined by comparison with a point pattern of complete spatial randomness (CSR). A pattern
of CSR is generated by a uniform Poisson process, which (i) uniformly operated throughout a
study area at a constant intensity and (ii) was characterised by the independence of the location of
each point in relation to any other points in the area (Diggle, 2003; Isham, 2010).

A significant difference between an observed point pattern and a pattern of CSR, as indicated
by statistical tests, is typically interpreted as evidence of significant interpoint interactions
(clustering or dispersion), assuming a regionally homogeneous point process.

However, significant departures from CSR can be also due to regional-scale variations
of intensity of the point process, with no significant local-scale interpoint interactions, or a
combination of both factors. Unequivocally distinguishing the different interpretations is often
impossible on the basis of any single statistic (Diggle, 2003, 2010). Regional heterogeneity of
point processes is quite typical for many types of geographic environments, including mineral
systems. Distinguishing between regional heterogeneity of mineral deposit density
and more local-scale clustering of deposits could have major implications for regional
exploration targeting, as mentioned earlier. Extensive exploratory spatial data analysis,
using a sequence of various complementary methods, is thus required to make robust
inferences regarding a point process.

2.2. Centrographic and directional distribution analysis

Simple overall measures of the geometric centre and directional anisotropy of a point
pattern can be obtained from centrographic and directional distribution spatial analysis,
which can be easily implemented using various GIS and specialised spatial statistical
software. Common centrographic statistics for a point pattern are the mean centre, median
centre, standard deviational circle and standard deviational ellipse (Ebdon, 1988; de
Smith et al., 2007). The mean and median centres are simple summary statistics of a point
pattern equivalent to the mean and median in the classical statistics. The mean centre \( MC \)
is characterised by geographic coordinates \( \{X, Y\} \) equal to the arithmetic means of the
x- and y-coordinates of all the \( N \) points in a pattern:

\[
MC(X) = \frac{\sum_{i=1}^{N} x_i}{N} ; \quad MC(Y) = \frac{\sum_{i=1}^{N} y_i}{N}
\]

Similar to a non-spatial arithmetic mean, a position of the mean centre can be affected
by the presence of spatial outliers – points located at a relatively large distance from the
dominant main group of points. The centre of minimum distance (often referred to as
the median centre) is an alternative unique measure of central spatial tendency of a point
pattern which is robust in the presence of spatial outliers. Unlike the mean centre, defining
the median centre $\text{MedC}$ requires a much more computationally complex iterative process to find a location that minimises the Euclidean distance $d$ to all the points in a point pattern (Burt and Barber, 1996):

$$\text{MedC}\{x', y'\} \mid \min_i \left( \sum_{i=1}^{N} \left( (x_i - x')^2 + (y_i - y')^2 \right) \right)$$

(2)

where $i$ defines each point in a point pattern, $t$ is an iteration number and $\{x', y'\}$ is a location of an iterative candidate median centre. An important property of a point pattern is the degree of its spatial spread. It can be characterised by the standard distance $SD$, estimated as:

$$SD = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{X})^2}{N} + \frac{\sum_{i=1}^{N} (y_i - \bar{Y})^2}{N}}$$

(3)

where $x_i$ and $y_i$ are the coordinates of point $i\{x_i, y_i\}$, $N$ is the total number of points and $X$ and $Y$ are the coordinates of the mean centre $\text{MC}\{X, Y\}$. The standard distance is typically represented graphically in a GIS environment by a standard deviational circle, centred on the mean centre with the radius equal to standard distance (or its multiple – similar to the usage of the standard deviation in defining confidence intervals in the classical statistics).

While the standard deviational circle gives a useful measure of the spatial spread of a point pattern, its definition does not take into account any directional anisotropy of a point pattern which may be characterised by a much wider spread in a particular direction compared to the others. Identifying such directional anisotropy of the standard distance may be of a critical importance for mineral prospectivity analysis. To address this, a point pattern is better characterised by a standard deviational ellipse (SDE). The centre of SDE is located at the mean centre of a point pattern, while the shape and orientation of SDE characterise degrees of spatial spread and directional anisotropy of a point pattern. Many common GIS packages automate its computationally complex definition (Ebdon, 1988; de Smith et al., 2007) and provide spatial graphic outputs.

A SDE can assist in visual illustration of the main directional trend of a point pattern. However, as a single set of global statistics (or their graphic representations), it cannot adequately characterise point patterns with multiple directional trends operating at different scales, or multi-modal patterns. It can also be strongly affected by spatial outliers. Fry analysis is more suitable to characterise multiple directional trends at various scales.
2.3. Fry analysis

Fry analysis was originally developed as a manual graphic method of spatial autocorrelation analysis of point patterns to assess strain partitioning in rocks (Fry, 1979), later applied to identify trends in the distribution of mineral deposits (Vearncombe and Vearncombe, 1999; Carranza, 2009; Dirks et al., 2013). The manual process of generating a Fry plot is as follows. A sheet of blank tracing paper with a marked point of origin is placed on top of a map showing an analysed point pattern, so that the origin point coincides with one of the points on the map, and all the points are marked on the tracing paper. Then, the tracing paper is shifted, maintaining its original orientation, so that its point of origin coincides with another mapped point and the underlying point pattern is marked on the tracing sheet again. The process is repeated until every point on the original map has been used as the origin point for the tracing sheet. As a result, n points in the original pattern are translated into the Fry plot of \( n^2 - n \) points. A Fry plot visually enhances any directional trends present in an original point pattern. It also facilitates further directional analysis using rose diagrams recording orientation frequencies for the vectors between any two points on a Fry plot.

There is specialised software automating production of Fry plots (e.g., Spatstat, Baddeley and Turner, 2005) and associated rose diagrams (e.g., DotProc, originally developed by SRK Consulting and available as freeware from www.kuskov.com). DotProc software was used to implement Fry analysis in this study.

2.4. Analysis of spatial homogeneity

2.4.1. Quadrat analysis

Quadrat sampling is one of the oldest and easiest to implement methods for characterising point patterns (Getis and Boots, 1978; Diggle, 2003). It has been used to evaluate both regional homogeneity of a point pattern and interpoint interactions (clustering or dispersion). In the simplest form, a study area is subdivided into m equal-sizes sub-regions (cells) of the same shape (typically squares). The number of points within each cell is counted and then the number of cells containing each observed number of points is compared with the number of cells expected assuming a particular point pattern (typically CSR). A significant difference between the observed and expected number of cells was traditionally used to infer significant interpoint interactions (clustering or dispersion). However, it can be also due to spatial heterogeneity of point intensity. This method has
been historically very popular due to its simplicity. However, there are potential significant problems of interpretation related to the choice of cell sizes, as well as ambiguity of distinguishing effects of local clustering from regional heterogeneity. More powerful alternatives to this method have been developed and they will be discussed further in more detail.

2.4.2. Analysis of kernel-smoothed point density

An effective and powerful non-parametric approach to characterising regional homogeneity of a point pattern is to analyse the spatial distribution of kernel-smoothed estimates of point density (Diggle, 1985, 2003; Silverman, 1986; Scott, 1992), which can be easily implemented in a GIS environment or using specialised software for spatial statistical analysis (e.g., Baddeley and Turner, 2005). Kernel smoothing estimates local intensity $\hat{\lambda}_h(u)$ of a point process at each location $u$ within a two-dimensional study area as a sum of $N$ outputs of a kernel function $K$ of the distances between $u$ and each of the $N$ points $x_i$, given a certain smoothing parameter (also referred to as bandwidth, search radius or window width) $h$:

$$\hat{\lambda}_h(u) = \frac{1}{Nh^2} \sum_{i=1}^{N} K\left(\frac{||u-x_i||}{h}\right)$$  \hspace{1cm} (4)

where $K$ is typically a symmetrical non-negative function integrating to 1. Several kernel functions have been proposed (Silverman, 1986; Scott, 1992), including bivariate Gaussian (normal, widely used as a default kernel function):

$$K(u) = (2\pi)^{\frac{1}{2}} e^{-\frac{||x||^2}{2h}}$$  \hspace{1cm} (5)

and bivariate quadratic (Silverman, 1986, p. 76, Eq. 4.5; implemented in ArcGIS 10):

$$K(u) = 3\pi^{-1} (1 - \frac{||u-x||}{h})^2 I(||u-x|| < h)$$  \hspace{1cm} (6)

The choice of a bandwidth $h$ affects kernel smoothing outputs much more than the choice of a particular kernel smoothing function (Silverman, 1986; Scott, 1992; Diggle, 2003). Larger values of $h$ produce smoother, more generalised surfaces, at the expense of ignoring more local-scale variations of intensity. On the other hand, smaller values of $h$ highlight local-scale features but result in more ‘noisy’ high-variance outputs which may complicate the recognition of regional trends of intensity. The choice of $h$ thus involves a trade-off between high variance for smaller $h$ and increasing bias for larger $h$.

Choosing $h$ “optimal” for a given dataset may be assisted by several different types of data-driven automated procedures (Diggle, 1985; Silverman, 1986; Scott, 1992; Jones
Spatial data analysis et al., 1996). Several simple ‘rules of thumb’ aiming to choose \( h \) minimising asymptotic mean integrated squared error have been proposed (Silverman, 1986, pp. 86-87; Scott, 1992, p. 152), with a general form (‘Scott’s rule’):

\[
h_{opt} = C_{Kd} \sigma N^{-(d+4)}
\]

(7)

where \( d \) is dimensionality, \( \sigma \) is the standard deviation of an analysed population (or sample) and \( C_{Kd} \) is a constant, strongly dependant on a kernel type and to a small degree – on dimensionality. For example, for a two-dimensional normally distributed GIS dataset, the normal reference constant for the Gaussian kernel \( C_{G2} = 1 \), while for the bivariate quadratic kernel, \( C_{Q2} = 2.78 \) (Silverman, 1986, p. 87). Silverman (1986) noted that, in the case of a skewed population, setting \( h \) based on normal reference constant values would result in over-smoothing and thus recommended using a “slightly smaller” \( h \).

A corresponding more generally applicable univariate bandwidth selection rule for the Gaussian kernel (Silverman, 1986, p. 48) is widely known as a ‘Silverman’s rule of thumb’:

\[
h_{opt} = 0.9 \min (\sigma, IQR/1.34) N^{-1/5}
\]

(8)

where \( IQR \) is the inter-quartile range. As Eq. 8 was proposed for one-dimensional data, it should be appropriately adjusted (Eq. 7) for bandwidth selection in two-dimensional GIS space.

As different kernels have different variances, a value \( h_1 \) estimated specifically for the Gaussian kernel (e.g., Eq. 8) – or any other kernel \( K_1 \) – should be appropriately re-scaled when selecting an equivalent bandwidth \( h_2 \) for a different kernel \( K_2 \), to achieve an equivalent degree of smoothing, with a scaling parameter approximately equal to a ratio of standard deviations of \( K_1 \) and \( K_2 \) (Scott, 1992, p. 142):

\[
h_2 \approx h_1 \sigma(K_1)/\sigma(K_2)
\]

(9)

For exploratory analysis of point patterns, it is generally recommended to review several kernel-smoothed estimate maps for different \( h \), each focusing at a different spatial scale (Baddeley, 2010). Graphic outputs can highlight regional heterogeneity and directional anisotropy of a point pattern. Interpretations are typically subjective, but formal methods have also been developed (Roeder, 1990; Hazelton and Davies, 2009).

### 2.5. Analysis of point interaction

Several summary statistics and formal statistical tests have been commonly used to assess interpoint interactions for mineral deposits, mostly assuming (often inappropriately) spatial homogeneity of a point process. They can be broadly sub-divided into (i) density-based (quadrat counts, not discussed further) and (ii) distance-based (nearest neighbour...
analysis, multi-distance analysis – $K$ and $L$ functions) (Getis and Boots, 1978; Diggle, 2003; Illian et al., 2008; Gelfand et al., 2010).

### 2.5.1. Nearest neighbour distance analysis

One of the simplest summary measures describing an overall tendency of points for clustering or dispersion is the nearest neighbour index, or ratio, originally introduced by Clark and Evans (1954) and widely used ever since (Getis and Boots, 1978; Cressie, 1991), including recent applications to analysis of the spatial distribution of mineral deposits (Carranza, 2008, 2009; Mamuse et al., 2010). This ratio ($R$) compares the mean observed distance between each point in a pattern and its nearest neighbour $d_{obs}$ to the mean distance $d_{rand}$ between the nearest neighbours expected for a random pattern with the same number of points $N$:

$$ R = \frac{d_{obs}}{d_{rand}} $$

with $d_{obs}$ is calculated as:

$$ d_{obs} = \frac{\sum_{i \neq j} \min ||x_i - x_j||}{N} $$

where $\min ||x_i - x_j||$ is the distance between each point in the pattern and its nearest neighbour, and $d_{rand}$ commonly estimated by default as:

$$ d_{rand} = 0.5\sqrt{A/N} $$

where $A$ is the area of either a specific study region or of a minimum enclosing rectangle including the analysed point pattern. $R$ close to 1 indicates a random distribution of points, while $R < 1$ (with a theoretical minimum of 0) indicates clustering of points and, conversely, $R > 1$ (with a theoretical maximum of 2.149) indicates a dispersed, or regular, pattern. A standard $z$ test of statistical significance of $R \neq 1$ is given as:

$$ Z = \frac{d_{obs} - d_{rand}}{SE} $$

where $SE$ is the standard error of the mean random distance, approximated for a simple rectangular study area by:

$$ SE = 0.26136 \frac{0.26136}{\sqrt{N^2/A}} $$

For a given point pattern, estimated values of $R$ and $Z$ are very sensitive to the definition of the size and shape of a study area. For example, Equations 13-15 are based on the assumption of a geometrically simple and internally contiguous study area and may be
invalid for a highly irregular anisotropic study area with internal ‘holes’ (so called donut polygons). Results may be also biased by edge effects (similar to most other distance-based summary statistics), leading to a positive bias for $R$ in the presence of points close to a study area boundary. In such cases, a more appropriate interpretation of $R$ may be based on results of Monte Carlo simulations randomly placing $N$ points within an actual study area (Donnelly, 1978). In recent years, the nearest neighbour ratio of Clark and Evans (1954) has been essentially deprecated in favour of more powerful summary statistics (such as the $G$ and $F$) evaluating a complete probability distribution of nearest neighbour distances of a point pattern, rather than only its mean (Cressie, 1991; Diggle, 2003; Illian et al., 2008; Gelfand et al., 2010).

$G$ function analysis examines the cumulative distribution function of the distance from each point in a pattern to its nearest neighbour:

$$
\hat{G}(r) = \frac{\sum_{i,j} I(\min \| x_i - x_j \| < r)}{N}
$$

(15)

where $I(\min \| x_i - x_j \| < r)$ is the number of the nearest neighbour distances less than $r$. An estimated observed function $\hat{G}(r)$ is usually compared to a Monte Carlo simulation envelope or the theoretical $G_{\text{rand}}(r)$ of a completely random point process, approximated by:

$$
G_{\text{rand}}(r) = 1 - e^{-\frac{r^2}{2}}
$$

(16)

Closely related empty space $F$ function analysis examines the cumulative distribution function of the distance from each of $m$ arbitrary locations within a study area to its nearest point from an analysed point pattern:

$$
\hat{F}(r) = \frac{\sum_{i=1}^{m} \sum_{j=1}^{N} I(\min \| u_i - x_j \| < r)}{N}
$$

(17)

with an observed function also evaluated by Monte Carlo simulations or comparison with $F_{\text{rand}}(r)$ (Eq. 17).

$J$ function is a useful summary statistic combining $G$ and $F$ functions (van Lieshout and Baddeley, 1996):

$$
\hat{J}(r) = \frac{1 - \hat{G}(r)}{1 - \hat{F}(r)}
$$

(18)

For a completely random point process, $J(r) \equiv 1$, with lower values indicating clustering and higher values – dispersion, or spatial regularity. $J$ function is powerful in highlighting clustering or dispersion tendencies at relatively small distances, getting unstable at larger
distances where it approaches zero, infinity or becomes indeterminable. Unlike \( G \) and \( F \)
function, \( J \) function is insensitive to edge effects (van Lieshout and Baddeley, 1996).

Each of the summary functions and statistics characterise only a partial aspect of a
point pattern so it is generally advised to review them all as part of exploratory spatial
data analysis (Diggle, 2003).

### 2.5.2. \( K \) and \( L \) functions

The \( K \) function (Ripley, 1977, 1981), often referred to as ‘Ripley’s \( K \) function’ was
developed for multi-distance analysis, not limited to k-order nearest neighbourhoods.
This function provides a powerful method to analyse spatial clustering or dispersion of
point events at a range of scales. Various related statistics have been used to represent and
analyse the \( K \) function. In the classical definition (Ripley, 1977), the estimated function
parameter is:

\[
\hat{K}(r) = A \sum_{i \neq j} I(||x_i - x_j|| < r) / N^2
\]

(19)

where \( A \) is the size of the study area, \( N \) is the total number of points, \( I(||x_i - x_j|| < r) \) is the
number of other points \( j \) found within distance \( r \) from each point \( i \).

\( \hat{K}(r) \) is commonly transformed to a linear form (Besag, 1977):

\[
\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}}
\]

(20)

This stabilises variance of the function and simplifies a visual comparison between
an observed pattern and a theoretical pattern of CSR, with the latter represented by a
straight line:

\[
\hat{L}(r) = r
\]

(21)

Significant deviations between the observed line and the line of CSR at a particular
distance can indicate a tendency for clustering or dispersion at smaller distances (as the
function value for each distance is cumulative and is affected by results for all smaller
distances). A substantial complication of a simple visual interpretation of the \( L \) function
is due to the fact that the line of CSR can only be adequately represented by a straight line
in cases of an isotropic contiguous study area with the analysed points only occurring at a
relatively large distance (larger than the maximum scale of analysis) from the boundaries
of the study area. The use of edge correction algorithms is generally suggested to minimise
the edge factor artefacts, both for \( L \) function and other distance-based summary statistics
(Ripley, 1981; Diggle, 2003).
Monte Carlo simulations are normally used to deal with potential subjectivity of the visual analysis and to more rigorously test significance of possible clustering or dispersion tendencies. This is particularly essential in a case of an anisotropic study area with geometrically complex boundaries and internal structure. $L$ function for a random point pattern conforming to a complex geometry of the study area would significantly deviate from a theoretical straight line – totally unrelated to any point clustering or dispersion. Monte Carlo simulations repeatedly generate point patterns of a particular model type (most commonly – random), placing within the study area $N$ points and calculating $L$ function for each simulated pattern. $L$ function results for multiple random permutations are used to construct simulation envelopes which provide a good graphical statistical representation of the null hypothesis of a random distribution of the point pattern. For example, an observed $L$ function plotting entirely inside a pointwise simulation envelope representing minimum and maximum values of $L(d)$ estimated for each d from 99 simulations indicates that the analysed point pattern is not significantly different from a random distribution. Conversely, $L$ function falling outside the simulation envelope indicates a significant deviation from a random pattern. Statistical significance of this deviation from the pointwise envelope can only be precisely determined as $2/(99+1) = 0.02$ for a two-sided test and 0.01 for a one-sided test if a fixed distance was specified before the test, as probability of deviation at any distance is much higher (Baddeley et al., 2014).

In practice, the nearest neighbour and $K$ function analyses can be easily performed using various commercial and open-source software, such as ArcGIS™, Spatstat (Baddeley and Turner, 2005) and CrimeStat (Levin, 2007).

### 2.5.3. Analysis of point interactions for an inhomogeneous pattern

Classical statistics and tests compare a certain measure of an analysed point pattern with the same measure expected for a point pattern of complete spatial randomness (CSR), interpreting significant differences as consequences of point interaction (clustering or dispersion). However, it is important to remember that CSR implicitly assumes that (i) the overall intensity of a point-generating process remains constant in space, and (ii) that the presence of one or more point objects within a cell does not directly affect the probability of occurrence of another object in the same cell (Diggle, 2003). The first assumption is violated if the spatial distribution of point objects within an area is heterogeneous – so that some parts of the area have significantly higher concentrations of points compared
to other parts (e.g., a richly endowed metallogenic zone, or a mineralised trend, within a much less endowed region). Such cases of heterogeneous spatial patterns may be difficult to distinguish from regionally uniform clustered patterns only on the basis of any single summary spatial statistic (Baddeley, 2010; Diggle, 2003, 2010).

So, significant deviations from summary statistics for CSR can only be used as evidence that the spatial pattern is not consistent with a homogeneous Poisson process, rather than a good support for a clustered or dispersed pattern. As most of the traditional methods of statistical analysis of point patterns assume that the point processes are stationary (homogeneous) and isotropic, their applications to investigate strongly heterogeneous and anisotropic processes would be, in a strict sense, invalid and any outputs should be interpreted with great caution and best treated as indicative (exploratory) rather than conclusive. One possible approach to assessing local-scale point interactions in a regionally heterogeneous point pattern is to estimate classical summary statistics (such Clark-Evans ratio, $G$, $F$ and $J$ functions) for smaller domains with relatively constant average point density defined within a total study area. However, any conclusions drawn from such tests would only be applicable to the individual domains rather than an overall point pattern. Alternatively, or additionally to the above, recent modifications of traditional tests specifically developed to investigate point interactions in inhomogeneous point patterns (Baddeley et al., 2000; Waagepetersen and Guan, 2009; van Lieshout, 2011) could be applied.

3. Examples of spatial data analysis of mineral deposits

The objectives of the studies used in this paper to illustrate exploratory spatial data analysis of mineral deposit point patterns were to: (i) establish if the spatial intensity of gold mineralisation significantly varied across each study region; (ii) investigate any spatial clustering of gold mineralisation at different scales; and (iii) in case of a significant regional linear spatial heterogeneity, identify likely major metallogenic controls on the spatial distribution of the orogenic gold mineralisation.
3.1. Orogenic gold deposits in the Hodgkinson Province, north Queensland, Australia

3.1.1. Geological setting and orogenic gold mineralisation

The Hodgkinson Province formed along the convergent Pacific margin of the North Australian Craton in the Silurian to Carboniferous (Champion et al., 2009; Henderson et al., 2013). It is dominated by regionally deformed Siluro-Devonian deep-marine sedimentary rocks, locally with minor basalts and cherts, with shallow-marine limestones present along the western margin. The sedimentary sequences were intruded by Carboniferous to Permian granites with associated felsic volcanic rocks. The Hodgkinson Province is locally covered by Carboniferous to Quaternary sedimentary and volcanic rocks (Fig. 1).

![Fig. 1. Location, regional geology and orogenic gold mineralisation of the Hodgkinson Province.](image)

There are two main styles of orogenic gold deposits in the province. Most deposits are characterised by free gold in quartz veins, with minor sulphides and ferroan carbonates. These deposits have been classified as mesozonal orogenic and, for simplicity, are referred to in this paper as gold-quartz veins (Au-Qtz). The second major style of gold deposits in the region is characterised by the prevalence of refractory, or ultra-fine (usually <10 μm), gold in sulphide grains (arsenopyrite and pyrite) in thin quartz-carbonate veins and stockworks or disseminated in host turbidites along faults. Those deposits, often spatially...
associated with stibnite-quartz veins (a third distinct mineralisation style, relatively minor in terms of associated gold endowment), can be classified as epizonal orogenic and are described in this paper as gold-antimony (Au-Sb) deposits. More detailed discussions of orogenic gold mineralisation in the Hodgkinson Province can be found in Denaro (2013), Lisitsin et al. (2013, 2014), Lisitsin and Pitcairn (2015) and references therein.

3.1.2. Definition of the study area and data representing gold mineralisation

All significant orogenic gold deposits in the Hodgkinson Province are hosted by the Siluro-Devonian volcano-sedimentary rocks (Fig. 1). No significant deposits have been discovered under younger cover, which effectively masked any existing covered deposits from past exploration. No orogenic gold occurrences have been documented in the spatially extensive Carboniferous and Permian magmatic rocks, which were probably emplaced after the bulk of orogenic gold mineralisation (Lisitsin et al., 2014). The study area was therefore defined as a geometrically complex region of the exposed Siluro-Devonian rocks volcano-sedimentary rocks of the Hodgkinson Province.

The primary spatial dataset recording locations of orogenic gold mineralisation in the region is a validated subset (Denaro, 2013) of a state-wide point mineral occurrence database compiled and maintained by the Geological Survey of Queensland. Typical location accuracy is stated as 200 m. Mineral occurrence points represent various geological objects (individual orebodies, mineralised veins or larger composite gold deposits), often only indirectly, recording historic mineral extraction sites (shafts, adits, open cuts). Some of the original three-dimensional contiguous geological objects with a lateral extent exceeding several hundred metres are represented in the point dataset as individual points, while others of a similar size are recorded as multiple adjacent points (sometimes only metres apart). The latter case is largely a consequence of historic small-scale mining, with multiple workings extracting ore from the same deposits or even orebodies – typical for Au-Qtz veins. To at least partially alleviate the inconsistent nature of the recorded points and reduce the artificial effects of local-scale clustering of small workings around historically mined gold deposits (which is of no interest for the current analysis), the point subsets for Au-Qtz and Au-Sb occurrences were first thinned so that no more than one point of each style was present in each 1 km² cell of the study area. As a result, the number of Au-Qtz occurrences was reduced from 833 to 376 and Au-Sb occurrences – from 164 to 114, with no two points of the same style located <500 m
from each other. Most analyses applied to the thinned dataset (described below) were replicated for the total original set, producing comparable results which only indicate stronger local-scale clustering of occurrences (particularly at distances up to several hundred metres) but would not significantly affect major interpretations. Any associated loss of information on actual mineral occurrence clustering at a scale of <500 m was not considered significant for the purposes of this study mostly focusing on more regional scales of several to tens of kilometres. This sample reduction had no effect on analysis results for ore fields.

**Fig. 2.** Orogenic gold occurrences (a) and ore fields (b) in the Hodgkinson Province study area. Stars represent ore fields with >1 of contained gold. Areas outside the province, post-mineralisation cover and magmatic rocks are masked out and excluded from the study area.

A visual examination of the spatial distribution of the recorded gold occurrences in the Hodgkinson Province suggests significant regional spatial heterogeneity of the point patterns and more local-scale clustering of occurrences (Fig. 2a). Because of this likely non-uniform spatial density of gold mineralisation, any evidence of point clustering beyond the deposit to ‘camp’ scale (up to several kilometres) based on summary statistics may be a result of this regional heterogeneity. On the other hand, the apparent prominent local-scale clustering of occurrences may obscure more important for exploration targeting properties of the spatial distribution of occurrence clusters, which are manifested at a more regional scale. It is the latter that would represent new exploration targets away from known deposits. Such occurrence clusters were defined as ore fields (Fig. 2b) –
groups of adjacent mineral occurrences and deposits of the same mineralisation style less than 1.6 km apart (Lisitsin et al, 2013, 2014). Their spatial distribution was a major focus of the spatial data analysis discussed in this paper.

### 3.1.3. Geographic spread and directional anisotropy

The SDEs for orogenic gold occurrences (Fig. 3a) indicate the presence of a preferred north-west to south-east orientation of point patterns for both gold-quartz vein (to 148°) and gold-antimony (to 133°) mineralisation but also suggests substantial differences between the overall spatial distributions of different mineralisation styles. The apparent anisotropy of both gold occurrence point patterns may be partially due to the original asymmetric geometry of the Hodgkinson Province and the effects of subsequent deformations, post-mineralisation magmatism and cover, so that the study area itself is elongated in a north-west to south-east direction (to 159°). However, the geometric centres of both gold-quartz vein and gold-antimony occurrences are located to the south-west of the geometric centre of the study area (Fig. 3a), with substantial differences in the orientations of their SDEs, especially for gold-antimony occurrences, which indicates that the observed anisotropy is dominantly due to factors other than the geometry of the study area.

![Fig. 3](image)

**Fig. 3.** Standard Deviational Ellipses (1 standard deviation) for the gold occurrences and study area grid points in the Hodgkinson Province, for: (a) all occurrences; (b) only occurrences south of latitude 16°20’.

The different orientations of SDEs for gold-quartz vein and gold-antimony occurrences can be due to a relatively large number of the former (~40%) in the northern
half of the province where there are only two documented minor gold-antimony occurrences. This is suggested by modelling the SDEs for gold occurrences located only in the southern half of the province. The SDEs for gold-quartz vein and gold-antimony occurrences strongly overlap (Fig. 3b) and both SDEs have very similar orientations (121° and 127°, respectively). The SDE for grid points representing the study area south of 16°20′ indicates the same orientation as the point pattern (elongation to 122°) but gold occurrences of both styles occur in a much narrower belt, rather than spread out across the region. This suggests that overall spatial distributions of both gold-quartz vein and gold-antimony occurrences in the south of the province were controlled by identical or at least spatially coinciding regional geological factors.

![Fig. 4. Results of Fry analysis for gold occurrences in the Hodgkinson Province. Fry plots for: (a) gold-antimony occurrences; (b) gold-quartz vein occurrences; and rose diagrams for vectors connecting any two points of Fry plots for: (c) gold-antimony occurrences; (d) gold-quartz vein occurrences.](image)

Fry analysis can provide more detailed information on the directional anisotropy in the distribution of gold occurrences and the presence of multiple preferred orientations.
Chapter 4

at different scales. Fry plots for both gold-quartz vein and gold-antimony occurrences clearly show a dominant regional south-easterly trend (Figs. 4a, b), with an apparent secondary north-south trend for gold-quartz vein occurrences (Fig. 4b). Rose diagrams showing orientations of all the vectors connecting any two points in the Fry plots (Figs. 4a, b) confirm the presence of a single preferred orientation for gold-antimony occurrences (120° – 130°, Fig. 4c), compared to two south-easterly (140° – 145° and 125° – 130°) and one north-south (180°) orientations for gold-quartz vein occurrences (Fig. 4d).

As noted in the earlier discussion of directional distribution analysis, the presence of a relatively large proportion of gold-quartz vein occurrences in the north of the province (where gold-antimony mineralisation is almost absent) may have affected apparent regional directional trends for that mineralisation style. It is noted that the dominant regional structures change orientation from northeast-southwest in the southern part of the province to north-south in the north. This change of regional structural trends may account for the presence of the north-south preferred orientation for gold-quartz vein occurrences. Fry analysis for the occurrences located only in the southern half of the Hodgkinson Province indicates that both gold-antimony and gold-quartz vein occurrences in that area have very similar dominant south-easterly trends (to 120° – 130°, with maximum frequencies at 123° and 126°, respectively, Figs 5a-d). In contrast, gold-quartz vein occurrences in the north of the province have a dominant southerly trend (177°, Fig. 5e-f).

Results of Fry analysis for the geometric centres of ore fields each containing >0.1 t of gold (derived from Lisitsin et al., 2013) confirm the presence of the dominant south-easterly trend for significant mineralisation of both gold-antimony and gold-quartz vein styles (Fig. 6).

Analysis of the geographic spread and directional anisotropy of gold occurrences in the Hodgkinson Province suggests that, while global measures of directional anisotropy (SDEs) indicate substantial overall differences in preferred orientations between gold-quartz vein and gold-antimony mineralisation, this is largely due to a wider spread of gold-quartz veins extending into the northern part of the province where mineralisation is characterised by different structural trends compared to the southern part. In the south of the province, occurrences of both styles have almost identical regional spatial distributions, suggesting spatially coincident or even identical regional-scale metallogenic controls.
Fig. 5. Results of Fry analysis for gold occurrences in the southern (a-d) and northern (e, f) parts of the Hodgkinson Province. Fry plots for: (a) gold-antimony occurrences; (b) gold-quartz vein occurrences – south; and rose diagrams for vectors connecting any two points of Fry plots for: (c) gold-antimony occurrences; (d) gold-quartz vein occurrences – south; (e) gold-quartz vein occurrences – north, all vector lengths; (f) gold-quartz vein occurrences – north, vector lengths <140 km.
Fig. 6. Results of Fry analysis for ore fields with >0.1 t of contained gold in the Hodgkinson Province. Rose diagrams for: (a) gold-antimony ore fields; (b) gold-quartz vein ore fields – all vector lengths; (c) gold-quartz vein ore fields – vector lengths <150 km.

3.1.4. Regional variation of kernel-smoothed spatial density of mineral occurrences and ore fields

Spatial density was modelled in ArcGIS™ 10.2, using its isotropic quadratic kernel function (Eq. 6), with the smoothing bandwidth selected guided by the ‘rules of thumb’ described in Section 2.4.2. For example, the Silverman’s rule of thumb (Eq. 8), modified for the two-dimensional space (Eq. 7), suggests an optimal bandwidth for the isotropic Gaussian kernel of 15 km and 17 km for the Au-Sb and Au-Qtz datasets, respectively. This corresponds to a rescaled bandwidth of 43 km and 48 km for the isotropic quadratic kernel. The automatically selected bandwidths may be slightly over-smoothing, considering the apparently non-Gaussian distribution of occurrences within the study area. An examination of kernel-smoothed density maps with bandwidths varying from 20 km to 60 km suggested that the bandwidth of 30 km and 40 km adequately highlights
regional variations of mineral occurrence density at a scale of tens of kilometres for Au-Sb and Au-Qtz mineralisation styles, respectively (Fig. 7). To examine regional distribution of ore fields (rather than individual occurrences), their kernel-smoothed spatial density was estimated in a similar manner (Fig. 8), with the bandwidth selection initially guided by Scott’s (Eq. 7) Silverman’s (Eq. 8) and rules, followed by an examination of multiple maps produced using different bandwidths.

**Fig. 7.** Kernel-smoothed occurrence density maps (number of occurrences per 1 km²) for the Hodgkinson Province: (a) Au-Sb (30 km bandwidth); (b) Au-Qtz (40 km); (c) both types combined (40 km). Grey colour represents zero density.
Kernel-smoothed ore field density maps: (a) Au-Sb (70 km bandwidth); (b) Au-Qtz (80 km); (c) all ore fields with >1 t of contained gold (80 km).

Kernel-smoothed mineral occurrence and ore field density maps indicate strong regional heterogeneity of the spatial distribution of orogenic gold mineralisation of both Au-Qtz and Au-Sb styles. Regional heterogeneity is particularly prominent for Au-Sb occurrences and ore fields, which are strongly concentrated in a narrow northwest-trending zone in the south-west of the province and practically absent in the north. This zone, and its possible extensions to the north and south-east (jointly delineated as a mineralised belt, Figs 7-8), also includes the majority of Au-Qtz occurrences and ore fields. Within the
belt, Au-Sb and Au-Qtz occurrences concentrate in adjacent smaller domains which only partially overlap (Figs 7-8). The northwest-trending main part of the mineralised belt, clearly defined by high spatial density of Au-Sb mineralisation and all ore fields with >1 t of contained gold, has the same orientation as the dominant trend indicated by analysis of directional anisotropy of orogenic gold mineralisation in the south of the Hodgkinson Province. Thus, in this case, results of the centrographic and Fry analyses apparently also reflect the presence of the single intensely mineralised zone visually highlighted by kernel-smoothed density maps.

3.1.5. Clustering or dispersion of mineral occurrences and ore fields

Strong regional heterogeneity and anisotropy of the spatial distribution of gold occurrences demonstrated in the previous sections clearly violate major assumptions of the classical tests of point interaction (Diggle, 2003), thus making their applications to the entire study area, in a strict sense, invalid and their results – equivocal. The following section illustrates more appropriate tests taking into account regionally variable intensity of metallogenic processes responsible for the formation of gold occurrences and ore fields. Traditional methods were applied to a restricted domain with a relatively homogeneous internal spatial distribution of occurrences and ore fields, defined from kernel-smoothed density maps (to minimise effects of regional heterogeneity on test results). For ore fields, results were further validated by an inhomogeneous $L$ function test (Baddeley et al., 2000) applied to the total study area. Analysis was performed in Spatstat (Baddeley and Turner, 2005).

A quasi-homogeneous domain was manually delineated as a linear belt encompassing zones of high spatial density of mineral occurrences and ore fields in the south-west and west of the province (Figs 7-8). This domain (hereafter referred to as the mineralised belt) is larger than the minimum bounding rectangles or convex hulls for any specific style of occurrences or ore fields. In particular, it is defined substantially beyond the extent of known Au-Sb ore fields and occurrences along the belt to the north and south-east. As such a definition is likely to bias results of traditional homogeneous tests for this mineralisation style (potentially overestimating any clustering tendencies within the broad mineralised belt), validation tests were also performed restricted to a smaller area much more closely corresponding to a zone of quasi-homogeneous density of Au-Sb occurrences and ore fields, as defined by kernel-smoothed density maps (Figs 7a, 8a).
The belt occupies approximately 30% of the total permissive study area and contains all 7 Au-Sb ore fields and 9 out of 10 Au-Qtz ore fields (including all 8 ore fields of both styles with >1 t of contained gold), as well as 85% of all occurrences in the province. Occurrences of both styles are characterised by strong clustering, as indicated by Clark-Evans ratios $R < 1$ (significant at $p = 0.01$, from one-sided Monte Carlo tests based on 99 simulations of random patterns within the mineralised belt) and confirmed by Monte Carlo tests of homogeneous $G$, $F$, $J$ and $L$ summary functions (Figs 9-10). Potential bias of homogeneous summary functions for Au-Sb occurrences (due to their virtual absence in the northern and southern portions of the outlined mineralised belt) does not affect an overall interpretation of their strong local-scale clustering. A validation test restricted to a smaller more homogeneous area indicated that the test results for the broader mineralised belt only slightly over-estimate significance of occurrence clustering at distances over 4 km (Figs 10c-d).

![Fig. 9](image_url)

**Fig. 9.** Neighbour distance summary functions for Au-Qtz occurrences in the mineralised belt (Fig. 7): (a) $G$; (b) $F$; (c) $J$; (d) $L$. Here and on the other summary function graphs, simulation envelopes represent pointwise minimum and maximum values estimated from 99 simulations of corresponding random point patterns, with no edge corrections applied.

While the above analysis clearly indicates local-scale clustering of individual occurrences, it is particularly important to understand spatial distribution of ore fields – discrete clusters of mineral occurrences. Ore fields contain almost all primary gold
endowment in the region and it is such composite metallogenic objects (rather than individual occurrences) that would be targets for any further systematic exploration for undiscovered potentially economic deposits. Distance-based summary statistics describing distribution of individual occurrences are clearly dominated by clustering effects at a scale of less than several kilometres, obscuring larger-scale spatial properties of gold mineralisation in the region. To specifically investigate whether or not ore fields are clustered at a scale of tens of kilometres, analysis of spatial interaction was applied to ore fields, represented as points.

Fig. 10. Neighbour distance summary functions for Au-Sb occurrences in the mineralised belt (Fig. 7): (a) $G$; (b) $F$; (c) $J$; (d) $J$ function, with simulation envelopes estimated for a smaller area more closely corresponding to a domain with quasi-homogeneous Au-Sb occurrence density (Fig. 7a); (e) $L$. 

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In a strong contrast to significant clustering of occurrences, results of Monte Carlo tests of different summary functions and statistics for ore fields are generally inconsistent with their clustering within the mineralised belt. For example, Clark-Evans ratios for ore fields each containing >0.1 t of gold, of Au-Sb, Au-Qtz and both styles combined, are 1.3, 1.6 and 1.5, respectively. For the eight largest ore fields of both styles each containing >1 t of gold, R = 1.4. Such high values apparently suggest significantly dispersed distribution (with \(p < 0.001\) for standard \(z\) tests). However, such possible erroneous interpretation would be due to a severe bias of a standard \(z\) test (which estimates a summary statistic for a totally random pattern assuming a contiguous isotropic area), caused by complex anisotropic geometry of the mineralised belt. The presence of extensive internal areas where gold deposits could not be formed, preserved or discovered would likely result in an apparent dispersed pattern, regardless of a true spatial distribution of the complete population of all gold deposits formed in the region. Monte Carlo tests based on 99 simulations of random patterns within the actual complex geometry of the mineralised belt indicate that the estimates of \(R\) for all four ore field patterns are not significantly different from those for corresponding random distributions within the belt (with \(p\) values for a two-sided test ranging from 0.48 for Au-Sb ore fields to 0.84 for all ore fields each containing >1 t of gold).
Fig. 11. Neighbour distance summary functions for ore fields in the mineralised belt. $J$ function: (a) Au-Sb ore fields; (b) Au-Qtz ore fields; (c) combined ore fields of both types; (d) all ore fields with >1 t of contained gold. $L$ function: (e) Au-Sb ore fields; (f) Au-Qtz ore fields; (g) combined ore fields of both types; (h) all ore fields with >1 t of contained gold. Inhomogeneous $L$ function for the total province (i) Au-Sb ore fields; (j) Au-Qtz ore fields; (k) combined ore fields of both types; (l) all ore fields with >1 t of contained gold.
Multi-distance neighbourhood analysis for ore fields is somewhat complicated by their relatively small number, which almost precludes confident strong inferences. However, Monte Carlo tests of homogeneous $J$ and $L$ functions also tentatively suggest that the spatial distribution of ore fields within the mineralised belt is generally not significantly different from random (Figs 11a-h). $J$ function for all ore fields of both styles with $>0.1$ t of contained gold indicates their possible dispersed distribution at larger distances ($>20$ km, Fig. 11c), but the observed deviation of the observed function beyond the simulation envelope occurs towards the extreme where $J$ function becomes unstable, which may downplay significance of this departure. On the other hand, $J$ function for Au-Sb ore fields indicates their possible clustering at comparable distances (Fig. 11a).

Within the total study area of the Hodgkinson Province, the spatial distribution of Au-Sb ore fields and all ore fields with $>1$ t of contained gold is very close to singular, with the ore fields only present in a very narrow central part of the mineralised belt. This suggests that their distribution within the province is controlled by a singular factor not present elsewhere in the region. In such a situation, applying an inhomogeneous $L$ function (Baddeley et al., 2000), which assumes non-zero intensity of a point process at every location in a study area, may be not strictly appropriate. With this caveat, results of inhomogeneous $L$ function analysis for ore fields (Figs 11i-l) are also consistent with a proposition that apparent concentration of ore fields in the south-west and west of the province is a consequence of extreme regional heterogeneity of their distribution, while within the single zone of their concentration ore field distribution is random.

### 3.1.6. A likely linear regional metallogenic control

The above exploratory spatial data analysis indicated that known gold deposits in the Hodgkinson Province are strongly focused in a single narrow north-east trending zone in the south-west of the province. Notably, the mineralised zone does not correspond to any obvious geological feature, trending at a low angle to most of the surface geological structures. Lisitsin et al. (2014) concluded that the metallogenic zone is controlled by a major deep crustal domain boundary, independently inferred on the basis of coincident changes in the geochronology and geochemistry of Carboniferous to Permian felsic magmatic rocks and regional metamorphic grades, supported by crustal seismic data. The inferred deep crustal domain boundary, represented by the boundary between the Herborton and Tate Igneous subprovinces (Champion and Bultitude, 2013), has the strongest spatial association with known significant gold deposits compared to any other
geological feature recognised in the region (Fig. 12). Possible mechanisms by which this inferred deep crustal boundary controlled the strongly linear distribution of orogenic gold deposits in the region are discussed by Lisitsin and Pitcairn (2015).

In contrast, there is no meaningful overall spatial association between gold deposits and any recognised major faults. While small segments of some of them host significant deposits within the metallogenic zone, they are poorly mineralised or barren elsewhere, sometimes for tens of kilometres along strike. Gold deposits are mostly associated with smaller faults, often >10 km from any major structures, with no evidence of being “second-order” splays of larger faults. Faults can only be considered as more local ore field scale controls within the province, focusing mineralisation at their intersections with the more fundamental deep-seated regional metallogenic control (Lisitsin et al., 2014).

3.2. **Orogenic gold deposits in central Victoria, Australia**

3.2.1. **Geological setting and orogenic gold mineralisation**

The Victorian gold province lies in the southern part of the Palaeozoic accretionary Lachlan Orogen formed along the convergent Pacific margin of Gondwana from the Cambrian to the Early Carboniferous (Vandenberg et al., 2000). Based on regional variations of the geological composition and history, the Lachlan Orogen is divided into the western, central and eastern subprovinces (Champion et al., 2009), which are
further subdivided into structural zones (Fig. 13). The Western Lachlan Orogen includes the Stawell, Bendigo and Melbourne zones (Vandenberg et al., 2000), with the first two comprising by far the most endowed part of the Victorian gold province (Phillips et al., 2003). Interpretation of deep seismic reflection data indicates broad similarities in the crustal architecture and geological history of the Stawell and Bendigo zones, as opposed to the Melbourne Zone (Willman et al. 2010; Cayley et al. 2011).

![Fig. 13. Regional geology and orogenic gold mineralisation of the Bendigo and Stawell zones. Geology is not shown for the Delamerian Orogen in the west and the Melbourne Zone in the east.](image)

Most primary gold deposits in the Western Lachlan Orogen are characterised by free gold in quartz veins, with minor sulphides and ferroan carbonates (Phillips et al., 2003). This is the dominant deposit style in the Stawell and Bendigo zones, commonly classified as mesozonal orogenic (Groves et al., 1998; Lisitsin et al., 2010). More detailed discussions of orogenic gold mineralisation in the Bendigo and Stawell zones can be found in Vandenberg et al. (2000), Phillips et al. (2003), Lisitsin et al. (2010), Willman et al. (2010), Lisitsin and Pitcairn (in press) and references therein.

The following spatial data analysis focuses only on gold-quartz vein mineralisation (Au-Qtz) in the Bendigo and Stawell zones. There are more than 10,000 recorded gold occurrences in the region, mostly clustered in larger ore fields (Olshina and Lisitsin, 2011a, b). As discussed for the Hodgkinson Province, strong local-scale occurrence clustering,
combined with inconsistent definitions of individual occurrences, can complicate analysis of regional metallogenic trends. To avoid this, the following analysis used ore fields as a sampling unit.

### 3.2.2. Definition of the study area

Significant gold-quartz vein deposits in the Bendigo and Stawell zones are hosted almost exclusively by Cambrian to Ordovician meta-turbidites and rare Cambrian metavolcanic rocks (Vandenberg et al., 2000, Phillips et al., 2003). The widespread late Silurian to Late Devonian granites post-date the bulk of Au-Qtz mineralisation and do not host any substantial gold deposits. Few deposits have been discovered completely under post-mineralisation cover. Only the areas of exposed Cambrian to Ordovician volcano-sedimentary rocks and areas of shallow cover adjacent to known significant gold deposits can be considered geologically permissive and well-explored for near-surface gold-quartz vein deposits (Lisitsin et al., 2010). To minimise bias, the study area was therefore limited to the exposed Cambrian to Ordovician rocks.

### 3.2.3. Geographic spread and directional anisotropy

The SDE for the 38 ore fields, each containing >0.5 t of gold (Fig. 14a), indicates relatively weak overall directional anisotropy of their spatial distribution which cannot be easily explained by the distribution of exposed permissive rocks. This apparent anisotropy can be largely due to the paucity of ore fields both in the eastern Bendigo Zone and the central and western Stawell Zone.

Analysis restricted to only the 10 largest ore fields, each containing more than 15 t (~0.5 Moz) of gold, indicates a much more significant heterogeneity and directional anisotropy of their spatial distribution (Fig. 14b). The Stawell ore field in the west is an apparent spatial outlier of this group. Analysis of directional distribution including the Stawell ore field does not clearly show any dominant regional trend but a strong north-northeasterly alignment (to 12°) is clearly highlighted by analysis restricted to the nine remaining ore fields located in the Bendigo Zone (Fig. 14b).

Results of Fry analysis (Fig. 15) confirm the overall anisotropic distribution of all the ore fields, each containing >0.5 t of gold, in a relatively wide south-south-east trending belt. In contrast, results for the 10 largest ore fields with >15 t of gold in each (Fig. 16) indicate the dominant north-easterly trend (between 2° and 35°).
Notably, the spatial outlier of the Stawell ore field has only a marginal effect on the Fry analysis (Fig. 16b), in contrast to simple directional distribution analysis (Fig. 14b).

**Fig. 14.** Standard Deviational Ellipses for gold-quartz vein ore fields in the Bendigo and Stawell zones: (a) >0.5 t of contained gold (SDE for the exposed permissive rocks are shown for comparison); (b) >15 t of contained gold.
3.2.4. Regional variation of the average spatial density of ore fields

Maps of kernel estimates of average spatial density of gold ore fields indicate regional heterogeneity of the spatial distribution of orogenic gold mineralisation within the Bendigo and Stawell zones (Fig. 17). Notably, the regional spatial density pattern does not simply reflect the structural zone geometries. The vast majority of ore fields are located in the western Bendigo Zone and eastern Stawell Zone, within an overall broad Y-shaped area of high spatial density of ore fields which transgresses the structural zone boundary along the Avoca Fault and does not display any obvious change across the boundary.

A broad mineralised area with a relatively homogeneous internal spatial intensity of gold mineralisation can be approximately outlined by kernel-smoothed density of ore fields with >0.5 t of contained gold in each exceeding 1 ore field per 1,000 km² (using the quadratic kernel in ArcGIS, Eq. 6, with bandwidth of 60 km, selected following a general process described in Section 3.1.4). The spatial definition of the outer boundary of this broad mineralised zone is rather arbitrary. It does not correspond to any apparent
features or sharp property gradients in common geological datasets, other than in the spatial density of ore fields. It can be loosely defined as a continuous zone with relatively high average spatial density of orogenic gold ore fields, which, consequently, includes their disproportionately large number. The zone, as defined here, occupies half of the total exposed permissive study area and contains 90% of all ore fields with >0.5 t of contained gold in each, with an average overall spatial density of 3.5 ore fields per 1,000 km² of exposed permissive rocks. If the zone is made progressively smaller compared to the accepted outline, it would exclude a proportionate number of ore fields on the peripheries of the zone, with no clear logic for any alternative smaller outline. Conversely, if the zone is made larger, it would only include a disproportionately small number of additional ore fields compared to an increase of the area.

This reasoning is similar to the concept of fractal dimensions (Mandelbrot, 1982; Cheng et al., 1994; Carranza, 2009) used to characterise self-similarity and scale dependency of a spatial pattern. Fractal analysis for ore fields with >0.5 t of gold in each indicates a bifractal distribution with a cross-over distance of ~40 km (Fig. 18). This distance is close to the average width of the broad mineralised zone (shown on Fig. 17). Notably, both the fractal dimensions and a cross-over distance are similar to those observed by Raines (2008) for totally different mineral systems.
Fig. 18. Results of fractal analysis of the spatial distribution of Au-Qtz ore fields with >0.5 of contained gold in the Bendigo and Stawell zones.

Within that broad mineralised zone, all nine major Au-Qtz ore fields in the Bendigo Zone with >15 t of contained gold in each (as well as the >82 t Fosterville refractory gold ore field, Lisitsin et al., 2014) occur in a significantly smaller single northeast-trending belt, oblique to and mostly distal from the zone-bounding (and major intra-zone) faults (Fig. 19).

Fig. 19. Kernel-smoothed point density map (60 km smoothing bandwidth) for Au-Qtz ore fields with >15 t of contained gold in the Bendigo and Stawell Zones

3.2.5. Clustering or dispersion of ore fields

As discussed for the Hodgkinson Province, analysis of relatively local-scale ore field clustering or dispersion needs to take into account the regional spatial heterogeneity of gold mineralisation, particularly pronounced for the major ore fields. Thus, traditional summary statistics (Clark-Evans ratio, \( G \), \( F \), \( J \) and \( L \) functions) estimated assuming spatial homogeneity could only be adequately applicable to sub-domains with a relatively
constant average ore field density – the broad mineralised zone for all ore fields (Fig. 17) and the smaller linear belt (Fig. 19) for the major ore fields. Additionally, inhomogeneous versions of summary functions (Baddeley et al., 2000; van Lieshout, 2011) could be applied for the total area.

Fig. 20. Neighbour distance summary functions for all ore fields with >0.5 t of contained gold in the broad mineralised zone (a-e) and major ore fields with >15 t of contained gold in a smaller linear belt (f-g): (a) $G$; (b) $F$; (c) $J$; (d) homogeneous $L$ within the mineralised zone; (e) inhomogeneous $L$ within the total permissive exposed area of the Bendigo and Stawell zones; (f) $J$; (g) $L$. 

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Neighbour distance-based tests suggest significantly dispersed (regular) distribution of all ore fields in the broad mineralised zone. Clark-Evans test indicates $R = 1.62$, with $p = 0.01$ for a one-sided alternative based on 999 simulations of a random pattern, with no edge correction applied. Significant regularity (dispersion) at a scale of tens of kilometres is also indicated by $J$ and $L$ homogeneous functions estimated for the mineralised zone and an inhomogeneous $L$ function applied to the total study area, while uncorrected $G$ and $F$ functions could be consistent with a random distribution (Fig. 20).

**Fig. 21.** Spatial association between deep crustal block boundaries, major ore fields and kernel density of ore fields (from Figs 17, 19) with: (a) $>0.5$ t of contained gold; (b) $>15$ t of contained gold.
Spatial distribution of major ore fields (those with >15 t of gold in each) is of a particular interest. Fig. 19 indicates the presence of a single linear belt which contains all nine major Au-Qtz ore fields in the Bendigo Zone. Distance-based tests restricted to this main richly endowed belt indicated that within it the major ore fields display a strong tendency for dispersion. Average distance between central parts of major ore fields is 26 km, with a minimum distance of 19 km. Clark-Evans test for the major ore fields based on 999 simulations, with no edge correction, indicates significant regularity ($R = 2$, $p = 0.01$ for a one-sided test). Multi-distance $J$ and $L$ functions, although hampered by a small number of points for analysis, also provide evidence of regularity (Fig. 21).

To avoid a potentially biased interpretation, results of the above tests indicating a regular distribution of ore fields in the Bendigo and Stawell zones should be appropriately qualified. While ore fields in the spatial analysis were represented by points, some of them have significant spatial dimensions. For example, ore fields with >15 t of contained gold in each are from 5 km to 30 km long (with the mean of 16 km) and from 1.6 km to 7 km wide (with the mean of 4.7 km), elongated in a general north-south direction (Olshina and Lisitsin, 2011a, b). This strongly inhibits possible nearest neighbour distances between central parts of adjacent ore fields of less than several kilometres, precluding them altogether at distances of less than 1.6 km. Such a local-scale spatial inhibition due to the actual physical dimensions of ore fields represented as points is likely to affect results of point pattern tests modelling CSR as a null hypothesis, over-emphasising any dispersion tendencies in the spatial distribution of ore fields. The pronounced anisotropy of ore field geometries and their widely variable dimensions complicate the selection of a theoretical point pattern model of spatial inhibition that would adequately represent the observed spatial distribution of ore fields. To roughly assess possible ‘dispersion bias’ of the above tests of ore field clustering, multiple simplistic validation tests were performed, modelling simulation envelopes of $J$ function for the major ore fields in the Bendigo Zone using a hardcore model of strong spatial inhibition at distances of 10 km to 15 km as a null hypothesis (using $rHardcore$ function in Spatstat). The hardcore model assumes that no points can occur within a set inhibition distance from each other. The validation tests also suggest a dispersion tendency for the major ore fields. However, the observed $J$ function does not significantly depart from simulation envelopes based on hardcore models, thus indicating a better consistency with a random distribution. Therefore, while results of the above tests clearly indicate a lack of ore field clustering, they are insufficient to prove their regularity.
3.2.6. Likely linear regional metallogenic controls

Exploratory spatial data analysis indicates broad regional heterogeneity in the distribution of gold-quartz vein deposits in the Bendigo and Stawell zones. In particular, 90% of all known in the region ore fields with >0.5 t of contained gold in each are located in a broad mineralised zone in the western Bendigo and eastern Stawell zones (Fig. 17). Within that zone, a distinct northeast-trending linear belt contains all nine major Au-Qtz gold ore fields with >15 t of contained gold in each known in the Bendigo Zone, with the refractory gold Fosterville ore field lying immediately next to it (Fig. 19). The geometries of neither the broad mineralised zone nor the richly endowed linear belt correspond to any obvious surface geological features. However, they can be explained by the deep crustal architecture of the region.

Deep crustal seismic has confirmed that older cratonic blocks underlay the Stawell and eastern Bendigo zones in the lower crust (Cayley et al., 2011). The Delamerian Orogen extends under the Stawell Zone from the west, while the Proterozoic to Cambrian Selwyn Block underlies the eastern Bendigo and Melbourne zones. The Y-shaped broad mineralised zone with a high spatial density of ore fields closely corresponds to the geometry of the older cratonic blocks, as modelled by Williams et al. (2008) and Skladzien et al. (2009) (Fig. 21a).

The richly endowed linear mineralised zone, which contains all the major Au-Qtz ore fields in the Bendigo Zone, is oblique to the surface geological structures and does not correspond to any major fault. However, its position closely corresponds to the modelled western boundary of the Selwyn Block in the lower crust (Fig. 21b), which probably acted as a critical regional metallogenic control responsible for the north-easterly trend in the distribution of major gold ore fields in the Bendigo Zone (as suggested by Wilson et al., 2009 and Hronsky et al., 2012). The nature of this cryptic at surface major linear metallogenic control is discussed by Lisitsin and Pitcairn (2015).

4. Discussion and conclusions

Systematic spatial data analysis can help to identify fundamental properties of spatial distribution of mineral deposits within metallogenic provinces. Those properties, in turn, can be used to infer fundamental characteristics of large-scale mineral systems, which generated the deposits and defined their spatial patterns. Such new insights into the spatial aspects of metallogenic processes can have critical implications for regional exploration targeting and quantitative mineral resource assessments.
It is important to adequately define a study area before commencing a spatial pattern analysis. The concept of well-explored permissive tracts (Singer, 1993; Singer and Menzie, 2010) is very useful to limit an analysis only to areas where mineral deposits of a type under consideration are geologically possible and mostly identified. Standard box-shaped study areas would be inappropriate for an overwhelming majority of spatial pattern analyses or mineral prospectivity studies. For example, in the presence of geologically non-permissive rocks (where deposits could not be originally formed or subsequently preserved) or cover sequences (which could effectively mask mineral deposits from past exploration), any apparent clustering or dispersion tendencies inferred on the basis of an analysis assuming an internally contiguous box-shaped study area would often be an artefact due to multiple geological processes not directly related to the formation or preservation of mineral deposits. Additionally, if a study region was affected by significant post-mineralisation structural deformations, their possible effects on the original spatial distribution of mineral deposits should be taken into account.

Results of spatial data analysis discussed in this paper are likely to jointly reflect original spatial properties of orogenic gold mineralisation in both regions, not significantly affected by any post-mineralisation processes (such as effects of cover, magmatism destroying original mineralisation or major structural deformations). In the described examples, the areas where deposits could not be formed, preserved or discovered were specifically masked out and excluded from study areas. Interpretations of observed summary statistics and functions were based on Monte Carlo simulations using only the permissive exposed study areas, thus greatly reducing effects of cover and magmatism. There is also no evidence that the overall observed patterns of orogenic gold mineralisation in either region were significantly affected by any post-mineralisation deformations.

A suite of methods for spatial statistical analysis can be used to characterise individual aspects of spatial distributions of mineral deposits. At a regional scale of analysis, mineral deposits can be adequately represented by points as their spatial dimensions are typically insignificant compared to the size of a study area. This justifies the use of methods for point pattern analysis. However, investigations focusing on spatially extensive metallogenic objects (such as ore fields), need to consider possible effects of their actual physical dimensions on the point pattern analysis results.

No individual simple global statistic used to characterise an overall spatial pattern for the whole study area (such as average spatial density, a standard deviational ellipse or the Clark-Evans nearest neighbour ratio) provides an adequate measure of spatial
distribution of mineral deposits and their isolated use can lead to grossly biased or at least inappropriate interpretations. A suite of complementary methods investigating various aspects of spatial distribution (such as regional intensity, and clustering or dispersion tendencies) is required to reach valid conclusions about metallogenic processes reflected in spatial patterns of mineralisation.

Simple classical global summary statistics and functions based on nearest neighbour distance measures may be often erroneously interpreted to conclude regional-scale dispersed or clustered patterns of mineral deposits. In the presence of richly endowed metallogenic zones, estimating traditional distance based summary statistics and functions (such as $G$, $F$, $J$ and $L$, which assume homogeneous spatial distribution) using entire geological or metallogenic provinces as study areas is statistically invalid. Such outputs of traditional ‘homogeneous’ tests are likely to mostly reflect regionally heterogeneous distribution (discrete mineralised zones), rather than more local-scale clustering or regularity. Such situations can be indicated by a prior analysis of intensity, such as mapping kernel-smoothed spatial density. Local clustering can then be investigated by either applying traditional homogeneous tests only to domains with relatively homogeneous deposit density (with conclusions only applicable to those domains), or by applying inhomogeneous versions of traditional summary functions (Baddeley et al., 2000; van Lieshout, 2011) to an entire study area.

Overall strong clustering of occurrences indicated by global point spatial statistics may be overwhelmingly dominated by clustering of occurrences at a deposit scale of up to several kilometres. The global point statistics are strongly influenced by the choice of the sampling unit. In particular, the use of all recorded historic mines and occurrences accentuates the apparent clustering due to socio-economic factors at the time of mining – multiple small mines, as opposed to much larger operations in the modern period. Mixing up points indicating historic occurrences and recent mining operations would obscure overall regional spatial distribution of mineral deposits (Harris, 1984). On a regional scale of analysis, more meaningful results can be obtained by analysing the distribution of consistently defined ore fields – clusters of adjacent deposits and occurrences.

Spatial data analysis performed in this study indicates that the regional spatial distribution of orogenic gold mineralisation in the Hodgkinson Province of north Queensland and the Western Lachlan Orogen in central Victoria, Australia, is strongly heterogeneous. Most of the largest gold deposits in each region are concentrated in relatively narrow (20 to 40 km wide) linear metallogenic zones, oblique to most recognised
major surface structures. While smaller gold deposits occur outside those zones, the largest ore fields in each province are mostly confined within them. The richly endowed zones in both the Hodgkinson Province and the Bendigo Zone probably correspond to major crustal-scale heterogeneities in the middle to lower crust with only subtle and indirect surface expressions (Lisitsin et al., 2014; Lisitsin and Pitcairn, 2015). In both regions, the metallogenic zones spatially correlate with metamorphic zone boundaries between greenschist and sub-greenschist zones and do not show any relationship with major regional faults.

Analysis of the spatial distribution of orogenic gold ore fields within well explored geologically permissive rocks within richly endowed metallogenic zones in the Hodgkinson Province and the Bendigo and Stawell zones indicates that they are not clustered (as commonly assumed in the economic geology and practical exploration targeting in established ‘brownfield’ metallogenic provinces) but display a random pattern, with a possible tendency for dispersion in the Bendigo Zone. Most endowed parts of larger gold ore fields within each analysed region appear to be more likely at a relatively large distance to any adjacent major ore fields (generally >20 km) than in their close proximity. This can be interpreted as an indication that the locations of ore fields have a certain ‘zone of influence’ – concentrating migration of mineralising fluids from a relatively large surrounding area (and underlying volume).

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References


Chapter 4


Chapter 5

OROGENIC GOLD MINERAL SYSTEMS OF THE WESTERN LACHLAN OROGEN (VICTORIA) AND THE HODGKINSON PROVINCE (QUEENSLAND): CRUSTAL METAL SOURCES AND CRYPTIC ZONES OF REGIONAL FLUID FLOW

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Abstract

Orogenic gold mineral systems in the Western Lachlan Orogen (Victoria) and the Hodgkinson Province (Queensland) produced gold provinces characterised by vastly different scales of gold endowment and strongly uneven distribution of gold mineralisation within each province. The volume of hydrous pyrite-bearing rocks undergoing metamorphic devolatilisation during thermo-tectonic events driving orogenic gold mineral systems represents a fundamental first-order constraint on the total gold endowment and its broad spatial distribution, both between and within the provinces. Most of the largest gold deposits in both regions occur in linear, richly-endowed metallogenic zones, oblique to the dominant regional structures and related to deep crustal domain boundaries. These boundaries, with only subtle surface expressions, were the major regional structural controls which promoted focused near-vertical flow of mineralising metamorphic fluids above the outer margins of cratonic blocks in the lower crust. Recognised major faults represented only more local scale and often indirect controls on the focused fluid flow, particularly effective above the deep cratonic block boundaries overlain by relatively thick crustal source rocks.

Keywords: orogenic gold; mineral system; Western Lachlan Orogen; Hodgkinson Province; metallogenic zone

1. Introduction

Effective regional exploration targeting for major mineral districts in poorly explored regions is one of the most significant challenges for the mineral exploration industry. The mineral system framework, defining the critical factors jointly required
to form a major mineral deposit, has been proposed to assist exploration targeting at different scales (Wyborn et al., 1994; McCuaig et al., 2010). Comprehensive analysis of the regional scale controls on a mineral system can provide critical insights into the distribution of significant mineralisation. It is particularly important considering that the most fundamental regional-scale components of a mineral system (such as sources of metals and fluids and major regional crustal fluid pathways) are often not directly reflected in traditional geological datasets.

Phanerozoic orogenic gold mineral systems are relatively well defined and understood at a broad conceptual level. Significant efforts have been directed at identifying the main geological factors controlling orogenic gold mineralisation at both a local scale (from deposits and ore shoots up to a few tens of kilometres – camps, or ore fields) and a broad regional scale, at which the tectonic setting and geodynamic evolution favourable for formation of major orogenic gold provinces play a critical role. However, the critical controls on orogenic gold mineral systems operating at an intermediate regional scale (tens to hundreds of kilometres – metallogenic zones or mineral districts), are commonly overlooked. As a consequence, explaining why some provinces (or their parts) are richly endowed, whereas others that may appear geologically analogous are only poorly mineralised or barren, still remains problematic.

The Western Lachlan Orogen in central Victoria and the Hodgkinson Province in north Queensland (Australia) show many geological similarities but have dramatically different levels of province-scale orogenic gold endowment and highly irregular internal distribution of gold mineralisation (Lisitsin et al., 2010, 2014). The geodynamic evolution and crustal architecture of these two terranes have been extensively investigated (Goldfarb et al., 1998; Bierlein et al., 2002, 2004; Hough et al., 2007; Vos et al., 2007; Champion et al., 2009; Willman et al., 2010; Cayley et al., 2011; Henderson et al., 2013). Properties of orogenic gold deposits in both regions and their local-scale geological controls have been also well studied (Phillips and Hughes, 1996; Ramsay et al., 1998; Phillips et al., 2003; Bierlein et al., 2004; Vos et al., 2005; Vos and Bierlein, 2006; Willman, 2007; Phillips, 2010; Denaro, 2013; Wilson et al., 2013), often with a strong emphasis of structurally controlled focused flow of mineralising fluids (Cox et al., 1991a, b; Cox, 1995; Sibson and Scott, 1998; Leader et al., 2012, 2013; Zhang et al., 2013). However, factors that control the heterogeneous distribution of mineralisation, both between and within the provinces, remain poorly understood.
This paper attempts to identify and review critical components of orogenic gold mineral systems operating at a scale of tens to hundreds of kilometres (arguably, the most challenging scale for predictive mineral prospectivity modelling, Hronsky and Groves, 2008). An orogenic gold mineral system is considered here (following a general conceptual framework of Wyborn et al., 1994 and McCuaig et al., 2010) as an active interplay between five fundamental critical components: (1) source(s) of fluids and metals; (2) mechanisms of mobilising auriferous fluids from the source(s); (3) focused fluid flow from source regions to deposition sites; (4) metal deposition mechanisms; (5) modification and preservation factors affecting (enrichment, dilution, mineralogical and geochemical changes, changes of the geometry and structure etc.) and potentially destroying originally deposited mineralisation. The paper discusses regional controls on metallogenesis in each region to constrain the factors that have contributed to the uneven distribution of mineralisation both between and within the regions. It addresses two main conceptual questions: (i) what are the regional geological factors that controlled the overall scale of gold endowment in each region? (ii) which geological factors led to the formation of distinct richly endowed metallogenic zones that comprise the bulk of significant orogenic gold mineralisation in both regions?

2. Phanerozoic orogenic gold mineral systems – an overview of the metamorphic conceptual model

2.1. A summary on orogenic gold deposits and alternative genetic models

Orogenic gold deposits commonly occur in metamorphic accretionary or collisional terranes along convergent tectonic margins, in the fore-arc accretionary prism, inverted back-arc or arc settings (Groves et al. 1998, 2003, 2005; Goldfarb et al., 1998, 2005). Deposits are hosted by a wide variety of rock types. In Phanerozoic provinces, deposits are commonly hosted by meta-sedimentary rocks regionally metamorphosed to the greenschist facies, but also occur in higher-grade metamorphic rocks and mafic to felsic igneous bodies (Groves et al., 1998, 2005; Goldfarb et al., 2005; Phillips and Powell, 1993, 2010). The orogenic gold model (Groves et al., 1998; Goldfarb et al., 2005) suggests that orogenic deposits may form over a wide range of crustal conditions – from <6 km depth and 150 – 300°C (mostly corresponding to sub-greenschist conditions of the anchizone) to >12 km and >475°C (hypozonal, extending into the amphibolite and even granulite conditions).
metamorphic zones). The genetic viability of the formation of orogenic gold deposits under thermo-baric conditions of the upper amphibolite and granulite metamorphic zones has recently been disputed (Phillips and Powell, 2009, 2010; Tomkins, 2010).

Orogenic gold deposits are characterised by relatively consistent geochemical signatures, with typical enrichments in Au, Ag, As, Sb and Hg, sometimes accompanied by elevated Se, Te, W and Bi (Groves et al., 1998, 2005; Goldfarb et al., 2005; Phillips and Powell, 2010). Deposits almost universally have gold as the only economic commodity (the ‘gold-only’ type of Phillips and Powell, 1993, 2014), although silver and antimony may be of an additional, and occasionally dominant, economic significance.

A number of different genetic models for the formation of orogenic gold deposits have been proposed, with key variables being the sources of metals and fluids and mechanisms of their mobilisation. Some authors invoke models involving deeply circulating meteoric waters (Nesbitt et al., 1986; Nesbitt, 1991; Hagemann et al., 1994). However, most researchers accept some form of crustal to lithospheric devolatilisation as the most critical metallogenic process, with possible contributions from prograde metamorphism, magmatic or mantle processes (e.g., as discussed by Goldfarb et al., 2005).

Magmatic models link the genesis of orogenic gold deposits to exsolution of auriferous fluids from igneous intrusions (Lindgren, 1933; Burrows and Spooner, 1989; Colvine 1989). While this has been clearly demonstrated for a distinct group of intrusion-related gold deposits (Thompson et al., 1999; Lang and Baker, 2001), invoking major contributions to orogenic gold mineral systems from magmatic processes (as direct sources of fluids, metals or energy) is not generally applicable in many provinces (e.g., Goldfarb et al., 2005, and references therein). For example, although crustal melting is often broadly coeval with regional metamorphism and formation of orogenic gold deposits in many provinces (Phillips and Powell, 1993), there is no consistent relative timing relationships between magmatism and orogenic gold mineralisation (Goldfarb et al., 2005). Notably, in some orogenic gold provinces, including central Victoria (Australia), there are no documented magmatic activities occurring within tens of millions of years from regional metamorphism and province-wide formation of orogenic gold deposits (Goldfarb et al., 2005; Pitcairn et al., 2006; Willman et al., 2010; Phillips et al., 2012). There is also a common lack of geochemical evidence of major magmatic inputs into orogenic gold mineralising fluids. This suggests that both metamorphism and crustal melting may be related to the same crustal or lithospheric heating event – rather than having a cause and effect relationship (Goldfarb et al., 2005).
A major input of auriferous fluids from lithospheric or even convecting mantle has also been suggested (Colvine et al., 1984; Cameron, 1988; Rock and Groves, 1988; Hronskey et al., 2012). For example, Hronskey et al. (2012) proposed that by far the most important source of gold in major orogenic gold mineral systems is ‘fertile’ lithospheric mantle, metasomatised and enriched in gold, H₂O and CO₂ during earlier geological processes involving sublithospheric mantle, mostly in subduction-related settings. This hypothesis invokes remobilisation of gold from the fertile upper mantle either through partial melting (generating gold and fluid-rich magmas, evolving to hydrothermal fluids), or by directly generating CO₂-H₂O auriferous fluids.

In contrast, many researchers advocate derivation of auriferous fluids in most orogenic gold provinces predominantly from prograde crustal metamorphic processes (Henley et al., 1976; Kerrich and Fryer, 1979; Goldfarb et al., 1991, 2005; Phillips and Powell, 1993, 2010; Pitcairn et al., 2006, 2014b; Large et al., 2011). In particular, most previous research indicates that the vast majority of orogenic gold deposits in the Western Lachlan Orogen and the Hodgkinson Province were formed by fluids with regionally uniform chemical compositions, probably generated by regional metamorphism in the underlying crust (Cox et al., 1987, 1991b; Peters et al., 1990; Bierlein and McNaughton, 1998; Phillips et al., 2003; Vos and Bierlein, 2006; Vos et al., 2007; Phillips and Powell, 2010; Willman et al., 2010; Large et al., 2011; Thomas et al., 2011; Fairmaid et al., 2011; Fu et al., 2012; Wilson et al., 2013), with no direct material contributions from either the mantle or crustal magmatic sources. The conceptual model proposed here is thus explicitly based on the hypothesis that orogenic gold deposits in the Western Lachlan Orogen (Victoria) and the Hodgkinson Province (Queensland) were generated, entirely or at least predominantly, by crustal metamorphic processes.

### 2.2. Sources of fluids and metals and mobilisation mechanisms

The most commonly proposed source of orogenic auriferous fluids is hydrous volcano-sedimentary rocks undergoing regional metamorphism in the middle to lower crust (Goldfarb et al., 1991; Phillips, 1993; Phillips and Powell, 1993, 2010, 2014; Tomkins, 2010, 2013). Prograde devolatilisation reactions at the greenschist to amphibolite transition produce large volumes of low-salinity H₂O-CO₂ fluids due to thermal breakdown of hydrous greenschist facies minerals (mostly chlorite) and carbonates (Phillips, 1993; Phillips and Powell, 1993). Sulphur and, most likely, gold are incorporated into this fluid due to metamorphic desulphidation of pyrite to pyrrhotite, leading to the release of the bulk...
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of gold originally contained in pyrite which is thought to be the most significant reservoir of gold in unmetamorphosed volcano-sedimentary rocks (Pitcairn et al., 2006; Large et al., 2009, 2011; Tomkins, 2010, 2013). Large amounts of auriferous H$_2$O–H$_2$S±CO$_2$ fluids, capable of transporting significant concentrations of gold, are thus produced, mostly in the range of temperatures between 500°C and 550°C (Phillips and Powell, 1993, 2010; Tomkins, 2010).

The nature and degree of source rock ‘fertility’ required to produce significant orogenic gold mineralisation is debated. A significant original enrichment of some crustal rock types in gold has been suggested as a major reason for elevated gold endowment in some provinces (Keays and Scott, 1976; Bierlein et al., 1998a) or smaller metallogenic zones (Jowitt et al., 2012). Average gold content of typical unmetamorphosed magmatic and sedimentary rocks mostly varies from 0.5 ppb to 5 ppb (Jones, 1969; Gottfried et al., 1972; Crocket, 1991; Pitcairn, 2011). Potential source rocks with higher gold contents include marine carbonaceous pyritic shales, commonly containing >10 ppb of gold (Large et al., 2009; 2011; Pitcairn, 2011). Mafic magmatic rocks (and associated magmatic or hydrothermal gold-enriched sulphides) have long been considered a more prolific potential source of auriferous metamorphic fluids (Keays and Scott, 1976; Keays, 1987; Phillips and Powell, 1993, 2010; Bierlein et al., 1998a, 2006; Jowitt et al., 2012). In contrast, some recent research suggests pyritic sedimentary rocks as a generally more suitable potential fluid and metal source for metamorphic orogenic gold mineral systems (Pitcairn et al., 2006; 2014a; Large et al., 2009; 2011; Tomkins, 2010). For example, metamorphism of dominantly mafic magmatic rocks is likely to generate fluids with much lower concentrations of H$_2$S (and thus much less capable of transporting significant concentrations of gold) compared to sedimentary rocks enriched in organic carbon (Tomkins, 2010, 2013). Besides gold, source rocks must also release the other elements enriched in orogenic gold deposits, such as arsenic and antimony. Carbonaceous sedimentary rocks are often relatively enriched in gold (>5 ppb) and arsenic (>10-20 ppm), as well as Sb, Hg, and Mo, compared to the average crustal abundances of those elements (Large et al., 2009; 2011). In contrast, mafic magmatic rocks have relatively low original contents of arsenic (0.1 to 1 ppm) and other elements commonly enriched in orogenic gold deposits (Pitcairn et al., 2014). Therefore, invoking mafic volcanic rocks as the sole or even dominant source of both fluids and metals in orogenic gold mineral systems creates a conceptual problem of mass balance for elements such as arsenic and antimony. Resolving this problem would require an assumption of a separate major source of those
elements and a viable mechanism of their extensive mobilisation into mineralising fluids in their transit between a gold source region and deposition sites.

2.3. Regional focused fluid flow controls

Focusing regional outflow of metamorphic fluids from commonly spatially extensive source regions towards relatively small areas is critical for the formation of orogenic gold mineralisation (Groves et al., 2003; Goldfarb et al., 2005). Focused structurally controlled fluid flow can potentially concentrate significant volumes of metamorphic auriferous fluids into relatively small deposition blocks, forming orogenic gold deposits, mostly in the brittle to ductile greenschist and brittle sub-greenschist metamorphic zones (Cox, 1999, 2005). Fluids present in the lower aseismic portion of the crust are generally compressed at the lithostatic pressure, while fluids in the overlying seismogenic crust are characterised by hydrostatic pressures (Connolly, 1997, 2004; Cox, 2005; Sibson, 2007). The base of the upper crustal seismogenic zone generally acts as a permeability barrier for overpressured metamorphic fluids generated in the underlying aseismic zone (Connolly, 2004; Cox, 2005; Sibson, 2007a).

Rocks in the lower parts of the brittle crust are characterised by negligible inherent porosity and permeability and fluid flow can only occur through periodically reactivated inter-connected fractures, which lose their permeability shortly after each pulse of overpressured fluids (Cox, 1999, 2005; Sibson 1992, 2004, 2007a, 2007b). Analysis of fluid flow in orogenic gold mineral systems is most commonly focused on regionally significant deeply penetrating fault zones (e.g., Goldfarb et al., 2005). In many orogenic gold provinces, such major deeply penetrating ‘crustal-scale’ faults, generally inferred as the major or even exclusive conduits of focused fluid flow, are not mineralised (Cox et al., 1991b; Groves et al., 2003; Goldfarb et al., 2005). The gold deposits are often hosted by adjacent minor low-displacement ‘second-order’ faults that are commonly inferred to be linked to nearby major faults at depth. This empirical phenomenon of common structural controls on orogenic gold mineralisation is consistent with modern observations in seismically active regions, indicating that secondary small-displacement structures adjacent to a major fault often maintain episodic permeability long after the main rupture event along the major fault (Sibson, 2004, 2007b, 2009, 2013, Sibson et al., 1988; Cox, 2005, Cox and Ruming, 2004, Micklethwaite and Cox, 2004).

In addition to faults as a universally recognised major type of control on crustal fluid flow, there are also other types of more subtle focused fluid flow pathways of a major
significance for orogenic gold mineral systems. This is indicated by numerous examples of documented major flow of mineralising fluids not directly related to any individual significant faults, but controlled by systems of inter-connected fold-related structures (Cox et al., 2001; Schaub and Wilson, 2002; Cox, 2005; Craw et al., 2006, 2010, 2013) or topography (Craw et al., 2013). During events of broadly synchronous generation of metamorphic fluids and compressional tectonic deformation, overpressured fluids can drive the formation of self-generated fault and fracture meshes – often genetically unrelated to and spatially distinct and distal from any major faults (Sibson, 1996, 2004, 2007a). Self-generated fault and fracture meshes, affecting relatively large volumes and periodically reactivated by over-pressured fluids, can support substantially higher fluid flow through the impermeable rocks than discrete active fault zones (Sibson, 2001).

There is also a growing recognition of a major metallogenic significance of deep-crustal to lithospheric domain boundaries and other pre-existing basement structures with only subtle expressions at the current erosional level (McCuaig and Hronsky, 2014). Such controls have been suggested both for the Western Lachlan Orogen (Wilson et al., 2009; Lisitsin and Rawlings, 2011; Hronsky et al., 2012) and the Hodgkinson Province (Lisitsin et al., 2014).

### 2.4. Deposition factors

Common mechanisms driving precipitation of gold from mineralising fluids at deposition sites are related to episodic catastrophic de-pressurisation of fluids immediately after each breach of overpressured through a fault or fracture segment (Sibson et al., 1988; Cox et al., 1991b; Wilkinson and Johnston, 1996) and chemical interactions between mineralising fluids and host rocks (Phillips and Powell, 1993, 2010; Cox et al., 1991b, 1995; Goldfarb et al., 2005). Rapid de-pressurisation leads to fluid unmixing with a loss of CO₂, with a resultant significant reduction of solubility of gold, quartz and sulphides. This repeated mechanism is pronounced in the formation of typical in orogenic deposits gold-bearing laminated veins or stockworks, hosted by almost any rock type present in a given province (including relatively chemically inert sandstones, cherts, felsic dykes, granites).

Chemical reactions with wall rocks may also locally play a significant role in gold precipitation. Two rock types most commonly cited as causing enhanced precipitation of gold from hydrothermal fluids are carbonaceous black shales and iron-rich rocks such as basalts, dolerites and banded iron formations (BIF). Carbonaceous black shales can
cause reduction of a gold-bearing hydrothermal fluid and decrease the solubility of AuHS-hydrothermal species through the following reaction:

\[
\text{Au(HS\textsubscript{-})}_2 + 0.5\text{H}_2 = \text{Au(s)} + \text{H}_2\text{S} + \text{HS\textsubscript{-}} \tag{1}
\]

where \(\text{Au(HS\textsubscript{-})}_2\) is broken down by the interaction with \(\text{H}_2\), either in the form of solid carbonaceous material or \(\text{CH}_4\) liberated from carbonaceous material during thermal degradation (e.g., Bottrell et al., 1988, Connolly and Cesare, 1993). Iron-rich rocks promote gold precipitation through sulphidation of wall rock which consumes \(\text{H}_2\text{S}\) from the fluid due to reaction with iron in silicate of oxide minerals:

\[
\text{FeO (silicate)} + 2\text{H}_2\text{S} = \text{FeS}_2 + \text{H}_2\text{O} + \text{H}_2 \tag{2}
\]

\[
\text{Fe}_3\text{O}_4 (oxide) + 6\text{H}_2\text{S} = 3\text{FeS}_2 + 4\text{H}_2\text{O} + 2\text{H}_2 \tag{3}
\]

The consumption of \(\text{H}_2\text{S}\) by sulphidation reactions (Equations 2-3) causes precipitation of gold by driving the reaction described by Equation 1 to the right (Phillips and Groves, 1983).

3. Orogenic gold mineral systems in the Western Lachlan Orogen

3.1. Geological setting, crustal architecture and geodynamic evolution of the Western Lachlan Orogen

The Western Lachlan Orogen (WLO) is a major western subprovince of the accretionary Lachlan Orogen, formed along the convergent Pacific margin of Gondwana from the Cambrian to Devonian (Vandenberg et al., 2000; Champion et al., 2009; Cayley et al., 2011). At the current erosional level, the Western Lachlan Orogen, subdivided into the Stawell, Bendigo and Melbourne structural zones, is dominated by regionally deformed Cambrian to Devonian turbidites and associated pelagic shales, with minor locally exposed Cambrian oceanic boninitic and MORB-type tholeiitic basalts and arc-related volcanic rocks (Vandenberg et al., 2000). Regionally deformed dominantly sedimentary sequences were intruded by post-tectonic late Silurian to Late Devonian granites and locally covered by Late Devonian to Quaternary sedimentary and volcanic rocks (Fig. 1). The age of the Palaeozoic sedimentary rocks broadly decreases from west to east, from the Cambrian in the Stawell Zone to Ordovician in the Bendigo Zone and to mostly Silurian and Devonian in the Melbourne Zone (Vandenberg et al., 2000).
Understanding of the overall crustal architecture and geodynamic evolution of the Western Lachlan Orogen has greatly improved over the last decade, particularly following the interpretation of a series of deep crustal seismic surveys transecting the orogen (Cayley et al., 2011). The seismic data indicated that both the Stawell and Bendigo zones are composed of Cambrian oceanic and arc-related metavolcanic and interbedded metasedimentary rocks, overlain by thick Cambrian to Ordovician metaturbidites (Cayley et al., 2011). The structurally thickened Cambrian metavolcanic and associated metasedimentary rocks form a contiguous lower crustal region below a depth of approximately 6 km in the Stawell Zone and approximately 15 km in the...
Bendigo Zone (Fig. 2). The Melbourne Zone has a completely different composition of the middle and lower crust. It is entirely underlain by older Proterozoic to Cambrian continental crust of the Selwyn Block which also underlies the eastern Bendigo Zone (Vandenberg et al., 2000; Cayley et al., 2002, 2011). The Selwyn Block is overlain by up to 15 km of tectonically thickened Palaeozoic turbidites in the Melbourne Zone, thinning out under the eastern Bendigo Zone where its outer margin underlies 35 km of Cambrian and Ordovician volcanic and sedimentary rocks.

![Interpreted composite cross section of the Western Lachlan Orogen](image)

**Fig. 2.** Interpreted composite cross section of the Western Lachlan Orogen, along the seismic lines shown on Fig. 1 (adapted from Willman et al, 2010).

Parts of the WLO experienced three major regional deformational events: the Delamerian (520 to 490 Ma), Benambran (455 to 440 Ma), and Tabberabberan (~390) orogenies (Vandenberg et al. 2000, Champion et al. 2009; Cayley et al., 2011). The Delamerain Orogeny has been documented along the western margin of the Stawell Zone (Miller et al., 2006) but may have affected the entire Stawell Zone (Willman et al., 2010; Cayley et al., 2011). The Benambran Orogeny was the main deformational event in the Bendigo Zone which also affected the Stawell Zone (Cayley et al., 2011). Finally, the Tabberabberan Orogeny was the main deformational event in the Melbourne Zone which also affected the eastern Bendigo Zone and reactivated some pre-existing structures further west. The bulk of the exposed volcano-sedimentary rocks in the WLO are characterised by regional metamorphism of the greenschist facies, with the amphibolite facies present along the western margin of the Stawell Zone and the subgreenschist facies prevalent in the eastern Bendigo and Melbourne zones (Offler et al., 1998, 2003; Wilson et al. 2009).

Geodynamic history of the WLO involves its origin as an oceanic basin in a fore-arc setting in the Cambrian, evolving into a sediment-filled back-arc basin, inverted and
cratonised by the Benambran Orogen. Cayley et al. (2011) proposed a tectonic model of the convergence between the Cambrian Delamerian Orogen in the west and the Selwyn Block in the east in a back-arc setting in the Ordovician, culminating in their collision and deformation of the Stawell and Bendigo zones during the Benambran Orogeny. A major feature of this collisional event was that the Cambrian oceanic crust of the Bendigo Zone was not consumed by subduction but tectonically thickened by shallow thrusting. The Melbourne Zone, deposited on top of the micro-continental Selwyn Block, was not deformed during the Benambran Orogeny, protected by the underlying rigid crustal block. It was inverted and tectonically thickened by the Tabberrabberan Orogeny.

3.2. Orogenic gold mineralisation in the Western Lachlan Orogen

Orogenic gold mineralisation is widely, but unevenly, distributed in the Western Lachlan Orogen (Fig. 1). Orogenic gold deposits mostly formed during two distinct major metallogenic events, at approximately 445 Ma and 370-380 Ma (Arne et al., 1998, 2001; Bierlein et al., 2001; Phillips et al., 2012). The first event was the main phase of gold mineralisation in the region, forming almost all significant gold deposits in the Bendigo and Stawell zones. It coincided with the late stages of the Benambran Orogeny which was not accompanied or closely followed by any documented magmatism (Vandenberg et al., 2000; Cayley et al., 2011). The 375 Ma event formed all the gold deposits in the Melbourne Zone and a few deposits in the rest of the Western Lachlan Orogen – mostly in the eastern Bendigo Zone, including the Fosterville ore field, containing >2.5 Moz of gold (Lisitsin et al., 2014). This gold event post-dated the main phase of the Tabberabberan Orogeny and was broadly synchronous with the emplacement of post-tectonic granites and dykes (Vandenberg et al., 2000; Bierlein et al., 2001; Phillips et al., 2012).

There are two distinct sub-types of orogenic gold mineralisation in the Western Lachlan Orogen, mostly formed during different metallogenic events and occurring in distinct regional domains (Hughes et al., 1997; Ramsay et al., 1998; Bierlein and Maher, 2001; Bierlein et al., 2004; Lisitsin et al., 2010; Willman et al., 2010). Most deposits in the Bendigo and Stawell zones and in the Walhalla–Woods Point belt in the Melbourne Zone are characterised by free gold in quartz veins (tens of centimetres to several metres wide), with minor (up to a few per cent) sulphides, generally dominated by pyrite and arsenopyrite, with subordinate chalcopyrite, sphalerite and galena. Fluid inclusions indicate deposition from low-salinity (<10% NaCl) H₂O–CO₂–H₂S±CH₄ fluids at temperatures of 300°C to 350°C, rising to 450°C at Stawell (Cox et al., 1995; Gao and Kwak, 1995; Changkakoti
et al., 1996; Vandenberg et al., 2000). Deposits of this group (including the Bendigo, Ballarat, Stawell and Walhalla ore fields), classified as mesozonal orogenic (Bierlein et al., 2004; Goldfarb et al., 2005; Lisitsin et al., 2010), formed at approximately 445 Ma in the Bendigo and Stawell zones and at 370-380 Ma in the east of the Melbourne Zone (Phillips et al., 2012).

Another distinct mineralisation sub-type is characterised by the prevalence of refractory, or ultra-fine (usually <10 μm), gold in sulphide grains (arsenopyrite and pyrite in thin veins and stockworks and disseminated in host turbidites), or by free and submicroscopic gold in stibnite–quartz veins. Deposits of this sub-type typically contain stibnite, either as a minor component in quartz–pyrite–arsenopyrite refractory gold deposits or as a major to dominant mineral in stibnite–quartz veins. These deposits, jointly referred to as gold-antimony-arsenic (Ramsay et al., 1998), or epizonal orogenic (Bierlein et al., 2004; Goldfarb et al., 2005; Lisitsin et al., 2010), formed at 370-380 Ma in the eastern Bendigo and western Melbourne zones (Phillips et al., 2012). Deposits of this group include the Fosterville, Nagambie and Bailieston ore fields. Gold was deposited from low-salinity (<10% NaCl) \( H_2O–CO_2±H_2S±CH_4±N_2 \) fluids at temperatures between <200 °C and 280 °C (Gao and Kwak, 1995; Gao et al., 1995; Changkakoti et al., 1996; Mernagh, 2001).

Orogenic gold deposits of both sub-types are characterised by strongly anomalous arsenic (typically >500 ppm), with elevated antimony also common in refractory gold deposits (generally >50 ppm) and particularly pronounced in stibnite-quartz veins (Bierlein et al., 1998, 2000; Arne et al., 2008). Gold deposits commonly occur in clusters, sometimes >10 km along the dominant structural trend, spatially grouped and described as ore fields (Olshina and Lisitsin, 2011a, b, c).

At a regional scale, both between and within individual structural zones, the spatial distribution of ore fields is strongly heterogeneous. The Bendigo Zone is by far the most richly endowed region, with >70 Moz of total gold production (60% of which from alluvial deposits), compared to 7 Moz produced from the Stawell Zone and >4 Moz from the Melbourne Zone (Phillips and Hughes, 1996; Phillips et al., 2003). The mesozonal orogenic gold-quartz vein deposits of the Bendigo and Stawell zones apparently represent products of the same regional Benambran mineral system, spatially and chronologically distinct from the younger Tabberabberan mineral system which produced orogenic gold deposits across the Melbourne Zone and the eastern Bendigo Zone (Willman et al., 2010; Phillips et al., 2012). The bulk of the older deposits form a contiguous densely
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mineralised area in the western Bendigo and eastern Stawell zones (with their overall spatial distribution apparently not affected by the inter-zone Avoca fault), but the Stawell ore field (>5 Moz of gold, Lisitsin et al., 2010) and several relatively small gold deposits are located along the western margin of the Stawell Zone (Figs 1, 3). In the Bendigo Zone, the major mesozonal orogenic gold-quartz vein ore fields, each containing >0.5 Moz (15 t) of gold, form a linear belt oblique to the regional structures (Fig. 3). The younger Fosterville refractory gold ore field lies immediately to the east of the mineralised belt as shown on Fig. 3.

![Fig. 3. Orogenic gold ore fields in the Bendigo and Stawell zones. Devonian Fosterville refractory gold ore field lies immediately next to a linear mineralised belt including all major older mesozonal orogenic gold ore fields in the Bendigo zone.](image)

4. Orogenic gold mineral systems in the Hodgkinson Province

4.1. Geological setting, crustal architecture and geodynamic evolution

The Hodgkinson Province, generally considered to be part of the Mossman Orogen, formed along the convergent Pacific margin of the North Australian Craton in the Silurian to Carboniferous (Henderson et al., 2013; Glen, 2013). In the west and southwest, it is separated from the Palaeo- to Meso-Proterozoic Etheridge Province by the Palmerville
Fault, and in the southeast it is faulted against the Barnard Province of the Neoproterozoic to Ordovician Thomson Orogen (Fig. 4).

Fig. 4. Regional geology and orogenic gold deposits of the Hodgkinson Province. Areas of post-Carboniferous cover are masked out

At the current erosional level, the Hodgkinson Province is dominated by multiply deformed late Silurian to early Carboniferous turbidites of the Hodgkinson Formation, locally with minor basalts and cherts. Shallow-marine early Silurian to Early Devonian limestones, siliciclastic units and basalts of the Chillagoe Formation form a narrow belt in the west of the province (Henderson et al., 2013). Ordovician rocks of the Thomson Orogen are commonly present along the province’s western margin as narrow (<5km)
discontinuous fault-bounded belts between the Chillagoe Formation and the Palmerville Fault and as smaller isolated blocks tectonically emplaced within the Chillagoe Formation.

The volcano-sedimentary sequences were intruded by pre- to syn-tectonic minor Late Devonian granites (in the east of the Province) and widespread Carboniferous to Permian granites with associated felsic volcanic rocks of the Kennedy Igneous Association. The volcano-sedimentary rocks of the Hodgkinson Province have been regionally metamorphosed up to the greenschist facies (Bain and Draper, 1997; Henderson et al., 2013).

The Hodgkinson Province was affected by multiple late Palaeozoic tectonic events (Henderson et al., 2013). The main regional event affecting the whole province (D₂ of Henderson et al., 2013) involved an early Carboniferous major east–west compression, accompanied by regional metamorphism, which generated the bulk of widespread tight to isoclinal folds and penetrative cleavage. Subsequent tectonic events, mostly reactivating existing structures and locally producing complex crenulation foliations, have not been documented in the south-west of the province. Regional faults often acted as sinistral structures during later tectonic events, but an earlier D₂ origin of at least some of them is likely (Henderson et al., 2013).

**Fig. 5.** Crustal architecture of the south-western Hodgkinson Province – line 07GA-A1 (based on Korsch et al., 2012).

A deep seismic profile crossing the south-western part of the Hodgkinson Province (Fig. 5) indicated that the province represents only a relatively thin portion of the upper crust (<12 km thick), completely underlain by several distinct blocks of older continental crust (Korsch et al., 2012). The Palmerville Fault has a general listric geometry, dipping steeply to the east and north-east at the current erosional level and becoming sub-horizontal with depth. It is interpreted to bifurcate into two segments.
Fig. 6. Forward gravity modelling along sections 1-6 (a-f) shown on Fig. 4, based on a regional interpretation of the deep crustal architecture of the Hodgkinson Province (from Lisitsin et al., 2013). Average densities of the crustal blocks are mostly adopted from Korsch et al. (2012).
The top segment forms a nearly horizontal detachment zone separating the Hodgkinson Province from the underlying seismic region interpreted to represent the Thomson Orogen (at the depth of approximately 10 km along the deep seismic line 07GA-A1 and Section 1 on Figs 5-6) and the other separates the Thomson Orogen from the underlying Agwamin Seismic Province. The latter is not exposed anywhere in the region and it is assumed to represent a Neoproterozoic passive continental margin which formed the basement to the Thomson Orogen (Korsch et al., 2012). The deepest crustal block interpreted from the seismic data is the Abingdon Seismic Province, deemed to represent Palaeoproterozoic continental basement to the Etheridge Province (Korsch et al., 2012). Gravity modelling, constrained by the seismic data in the southwest, suggests that the Hodgkinson Province is completely underlain by older cratonic blocks and thins out towards the province margins (Fig. 6).

Details of the geodynamic evolution of the Hodgkinson Province remain uncertain. The main proposed alternative models, reviewed by Henderson et al. (2013) include the Siluro-Devonian development of the Hodgkinson Province as a forearc accretionary prism (Korsch et al., 2012) or as a back-arc basin (Vos and Bierlein, 2006; Vos et al., 2007). The accretionary prism model suggests that the Mossman Orogen originally formed in an oceanic forearc environment, on the oceanic crust which was subsequently consumed by subduction. In this model, the orogen represents an accretionary prism, ‘stripped away’ from its original oceanic substrate and obducted over the older continental crust of the Thomson Orogen and North Australian Craton at ~360 Ma (Korsch et al., 2012). In contrast, the back-arc model suggests that the Mossman Orogen was originally formed on the attenuated Precambrian to Ordovician continental crust of the eastern margin of the North Australian Craton (including a segment of the Neoproterozoic to Ordovician Thomson Orogen) during a Siluro-Devonian extension, terminated by an early Carboniferous inversion.

An important point of agreement between both models, with major implications for understanding the region’s orogenic gold mineral system, is that the current crustal architecture was broadly set up at least by the end of the major contractional tectonic event D2. For example, a post-tectonic character of late Carboniferous I-type granites intruding the Palmerville Fault in the south-west of the province and their isotopic signatures indicating melting of Proterozoic continental crust (Murgulov et al., 2013) suggest a lack of any major subsequent changes of the broad crustal architecture in the
area. The existing architecture can thus be deemed broadly representative of that at the
time of gold mineralisation.

4.2. Orogenic gold mineralisation

Three distinct styles of orogenic gold deposits are present in the Hodgkinson
Province (Lisitsin et al., 2014). Most deposits are characterised by free gold (0.01 mm to
>1 mm) in laminated to massive quartz veins, with minor sulphides (mostly pyrite and
arsenopyrite) and ferroan carbonates (Lisitsin et al., 2014). Gold–bearing quartz veins
are usually associated with brittle–ductile faults and hosted by Devonian turbidites. The
second major deposit style is characterised by refractory, or ultra-fine (usually <10 μm),
gold in sulphide grains (arsenopyrite and pyrite), occurring in thin veins and stockworks
or disseminated in host turbidites in and adjacent to fault zones of various scales
(Lisitsin et al., 2014). Quartz-stibnite±gold veins represent the third distinct style of gold
mineralisation in the region (Lisitsin et al., 2014), relatively widespread in the south-west
of the Hodgkinson Province but only sporadically occurring in other parts of the region.
The veins commonly occur in close proximity to or within some refractory gold deposits,
as well as distinct mineralised areas and isolated veins. The two latter styles have been
jointly described as gold-antimony mineralisation (Denaro, 2013; Lisitsin et al., 2014).

All three mineralisation styles are characterised by strongly anomalous arsenic
(typically >500 ppm). Elevated antimony is common in refractory gold mineralisation
(generally from 10 ppm to 100 ppm) and particularly pronounced in stibnite-quartz
veins (Lisitsin et al., 2014). Limited published fluid inclusion data from three deposits
representing all three gold mineralisation styles suggested their formation from similar
low-salinity (<10% NaCl) aqueous fluids with very low concentrations of CO$_2$ (Peters,
1987; Peters et al., 1990; Vos and Bierlein, 2006), with fluid inclusion homogenisation
temperatures mostly varying from 170°C to 300°C. Latest fluid inclusion studies at several
other gold-quartz and stibnite-quartz vein deposits confirmed low salinities of auriferous
fluids (<5% NaCl), but also identified common CO$_2$-rich fluid inclusions (with minor CH$_4$
and N$_2$), homogenising mostly between 220°C and 300°C, present together with aqueous
inclusions homogenising mostly between 120°C and 200°C (Pitcairn, unpublished). The
fluid inclusion and isotopic data (including δ$_{\text{VSMOW}}^{18}$O (quartz) = 14‰ - 20‰, Golding
et al., 1990; Peters et al., 1990; Pitcairn, unpublished) are generally similar to typical
orogenic gold deposits elsewhere and consistent with the dominantly crustal metamorphic
source of mineralising fluids. Geological observations suggest that stibnite-quartz veins
Orogenic gold mineral systems generally post-date both gold-quartz veins (de Keyser and Lucas, 1968; Peters et al., 1990; Bultitude et al., 1997) and refractory gold mineralisation (Vos et al., 2007).

Ar-Ar geochronology of hydrothermal micas from alteration and mineralisation zones at ten deposits representing all three styles of orogenic gold mineralisation in the Hodgkinson Province, indicates that all significant orogenic gold deposits in the region formed during two or three episodes in the Carboniferous (from 350 Ma to 300 Ma) and suggests that refractory gold deposits are generally older than gold-quartz veins (Phillips, 2013). These conclusions are consistent with earlier results of Morrison (1988) and Morrison and Beams (1995) who reported late Carboniferous ages (300 Ma and 328 Ma) for two samples from gold-quartz veins, while Vos et al. (2007) suggested 340 Ma as a possible age of refractory gold mineralisation at one deposit.

![Fig. 7. Orogenic gold ore fields in the Hodgkinson Province, forming a narrow mineralised belt. The geology legend is the same as at Fig. 4.](image)

Gold occurrences commonly occur in dense clusters (ore fields). The spatial distribution of orogenic gold ore fields and isolated occurrences in the province is strongly heterogeneous (Lisitsin, 2015). All eight significant ore fields with >1 t of contained gold and 9 out of 10 smaller ore fields with >0.1 t of contained gold are located in the west of the province, within a narrow (mostly <25 km wide) mineralised belt (Fig. 7). That belt, oblique to the regional faults, is spatially associated with broadly coincident igneous subprovince and metamorphic zone boundaries, which probably mark the eastern boundary of the Proterozoic Etheridge crustal block extending under the Hodgkinson Province (Lisitsin et al., 2014).
5. Discussion

5.1. Regional metallogenic controls – Western Lachlan Orogen

5.1.1. Likely crustal sources of auriferous fluids

Deep seismic data (Cayley et al., 2011) highlighted the presence of variable volumes of originally hydrous potential source rocks, portions of which in the middle to lower crust underwent amphibolite-grade metamorphism and associated devolatilisation (Willman et al., 2010). Their volume in the Stawell and Bendigo zones mirrors the V-shaped (in the east-west cross-section) geometry created by the fault-bounded outer margins of the Delamerian Orogen in the west and the Selwyn Block in the east, reaching the maximum of the full crustal thickness (~38 km) under the western Bendigo Zone not underlain by older continental crust and progressively thinning to the east and west (Fig. 2). In contrast, in the Melbourne Zone, entirely underlain by thick continental crust of the Selwyn Block, tectonically thickened Ordovician to Devonian sedimentary rocks, which could potentially produce auriferous fluids through metamorphic devolatilisation, extend only to a depth of 10-15 km below the current surface, reaching the maximum in the west, where the Melbourne Zone is overthrust by the Bendigo Zone (Fig. 2).

The total thickness of originally hydrous pyrite-bearing rocks (particularly those below the 500°C isotherm during peak metamorphism, probably driving the orogenic gold mineral system in the region) could give a broad indication of an amount of metamorphic auriferous fluids generated in an underlying volume. Using thermo-baric estimates of peak metamorphic conditions at the current erosional surface across the Western Lachlan Orogen (Offler, 1998; Wilson et al., 2009), the peak metamorphic 500°C isotherm lies at the current depth of ~3 km in the Stawell Zone (outside the amphibolite-facies Moornambool Metamorphic Complex), 5 km in the western Bendigo Zone and up to 10 km in the eastern Bendigo Zone (Willman et al., 2010). The latter estimate could be also approximately applicable to the Melbourne Zone. This indicates that, while in the western Bendigo Zone the thickness of potential source rocks which underwent extensive metamorphic devolatilisation exceeded 30 km (including Cambrian mafic volcanic rocks and overlying turbidites), only <2-4 km thickness could be involved in such processes in the Melbourne Zone.

It has long been assumed that Cambrian volcano-sedimentary rocks with a significant proportion of oceanic basalts could be the dominant ‘fertile’ source of gold in the Bendigo
and Stawell zones (Keays and Scott, 1976; Bierlein et al., 1998a; Willman et al., 2010). Their current crustal position indicated by deep seismic data (Fig. 2) suggests that their total thickness across most of the region was affected by amphibolite-grade metamorphism, thus generating significant amounts of metamorphic fluids. Notably, most of the orogenic gold ore fields with >0.5 t of contained gold are located in a broad area in the western Bendigo and eastern Stawell zones underlain by relatively thick Cambrian mafic volcanic rocks (generally >9 km), reflecting the geometry of the older cratonic blocks underlying the Bendigo and Stawell zones in the lower crust (Fig. 8).

**Fig. 8.** Thickness of Cambrian mafic volcanic rocks, deep crustal boundaries (the Delamerian Orogen in the west and Selwyn Block in the east, from Rawling et al., 2011) and orogenic gold ore fields in the Bendigo and Stawell zones. The ore fields legend is the same as at Fig. 3.

However, halogen and argon isotope geochemistry of fluid inclusions from mineralised samples across the Western Lachlan Orogen indicates a major material contribution from crustal sedimentary sources, particularly strong in the Melbourne Zone (Fairmaid et al., 2011, Fu et al., 2012). This suggests that either sedimentary rocks were a major source of auriferous fluids, or that fluids originally derived from metamorphic devolatilisation of mafic volcanic rocks extensively interacted with overlying sedimentary rocks, acquiring their geochemical signatures (Fairmaid et al., 2011; Fu et al., 2012). Notably, the lower several kilometres of tectonically thickened turbidites throughout the most richly endowed Bendigo Zone were also affected by amphibolite-grade metamorphism – and thus produced a significant amount of metamorphic fluids, enriched not only in gold but also arsenic and antimony and bearing other geochemical tracers of their sedimentary origin.
It is therefore likely that meta-sedimentary rocks were a significant source of mineralising fluids in the region, probably in addition to a massive amount of metamorphic fluids generated from underlying volcano-sedimentary rocks.

5.1.2. Major crustal fluid pathways

Major crustal to lithospheric-scale faults (or linked secondary faults) have been commonly suggested as by far the most dominant regional pathways for focused flow of gold-bearing fluids in orogenic gold mineral systems in general (Groves et al., 2003; Goldfarb et al., 2001, 2005; Bierlein et al., 2006) and in the Western Lachlan Orogen in particular (Cox et al., 1991b; Bierlein et al., 2004; Willman, 2007; Willman et al., 2010). Deep seismic data confirmed the crustal-scale nature of many major regional inter-zone and intra-zone faults in the Bendigo and Stawell zones (Willman et al., 2010; Cayley et al., 2011). Faults active during the main orogenic events driving regional metamorphism and extending into the middle to lower crust, to a depth of more than 15-20 km from the current surface, would directly tap into inferred source regions of auriferous metamorphic fluids and could facilitate their transfer to higher crustal levels.

However, the spatial distribution of major orogenic gold deposits in the Bendigo Zone, which form a distinct northeast-trending linear belt oblique to the regional structures (Fig. 3), suggests that a strongly anisotropic factor other than the geometry of crustal-scale faults acted as a more fundamental regional metallogenic control. This richly endowed belt closely corresponds to the inferred western boundary of the Selwyn Block (Fig. 9), although the precise current position of the latter, as well as its position during gold mineralisation at ~445 Ma, remains uncertain. Wilson et al. (2009) suggested that the boundary position during peak regional metamorphism at the end of the Benambran Orogeny (and thus during the main gold mineralising event) is likely to be marked by the metamorphic zone boundary between the greenschist and subgreenschist facies in the eastern Bendigo Zone (Fig. 9). On the other hand, its current position in the south may be more than 20 km to the west from that estimated by Cayley et al. (2011), along a northeast-trending “Melbourne basement terrane” boundary of Chappell et al. (1988), separating regions with oxidised Early Devonian I-type granites in the west and reduced Late Devonian S- and I-type granites in the east. But the latter may reflect a further displacement of the Selwyn Block to the west after the Benambran Orogeny (Wilson et al., 2009; Cayley, 2011) – so the resultant current position of the Selwyn Block boundary would not be relevant for the Benambran orogenic gold mineral system. Notwithstanding
the spatial and temporal uncertainty, the western margin of the Selwyn Block in the lower crust probably acted as a major regional structural control on the distribution of the largest gold ore fields in the Bendigo Zone, focusing crustal flow of mineralising metamorphic fluids in a steep linear zone within a much broader region underlain by thick crustal source rocks, as discussed in Section 5.3.

At a more local scale, areas proximal to the major faults are generally poorly mineralised (Cox et al., 1991; Willman, 2007), with major ore fields commonly located at least 3-5 km away from the nearest crustal-scale fault, sometimes approximately halfway between the adjacent faults (Willman et al., 2010). In particular, zones within 15 km from the most significant lithospheric-scale Mt William and Moyston faults, defining the overall V-shaped (in cross-section) crustal geometry of the Bendigo and Stawell zones (Cayley et al., 2011), contain only relatively minor gold deposits. There is no overall consistent spatial association between significant orogenic gold deposits and proximity to major crustal-scale faults clearly expressed at the current surface in the Western Lachlan Orogen. This suggests that the major faults were not major fluid pathways focusing auriferous fluids towards ore field-scale depositional sites – either at the currently exposed crustal level or within at least several kilometres below (Willman et al., 2010). While this could be due to focused fluid flow controlled by unexposed major faults terminated below
ore fields (Cox et al., 1991b), or by discrete second-order faults tapping fluids from major faults in the deeper crust (Willman, 2007), near-vertical fold-related fault and fracture meshes are more likely camp- to deposit-scale fluid pathways operating in the meta-sedimentary middle crust (Willman et al., 2010). This dominant mechanism of fluid flow may be indirectly supported by strong sedimentary signatures of the halogen and argon isotope geochemistry of fluid inclusions, interpreted as a result of extensive geochemical exchange between mineralising fluids derived from mafic volcanic rocks and overlying sedimentary rocks (Fairmaid et al., 2011, Fu et al., 2012).

5.2. Regional metallogenic controls – Hodgkinson Province

5.2.1. Likely crustal sources of auriferous fluids

The presence of thick cratonic basement blocks completely underlying the Hodgkinson Province creates a critical constraint on the variety and volume of possible crustal sources of mineralising fluids within the province. The mid-crustal Greenvale seismic block, forming the immediate basement of the Hodgkinson Province, is interpreted to represent the Thomson Orogen (Korsch et al., 2012), exposed to the south and north of the Hodgkinson Province. The Thomson Orogen experienced two major orogenic events in the late Cambrian and late Ordovician (Fergusson and Henderson, 2013) – prior to the development of the Hodgkinson Province. Exposed parts of the older portion of the Thomson Orogen affected by the Cambrian event experienced high-grade regional metamorphism, expressed by the widespread upper greenschist to amphibolite facies at the current erosional level. Younger Ordovician rocks exposed in the regional vicinity of the Hodgkinson Province – in the Barnard, Greenvale, Charters Towers and Iron Range provinces – have also been affected by greenschist to amphibolite grade metamorphism (Fergusson and Henderson, 2013). This suggests that the Greenvale seismic block (as well as the underlying Agwamin seismic block and the Proterozoic Etheridge Province extending under the Hodgkinson Province in the south-west) experienced extensive metamorphic devolatilisation before the thermal event genetically related to the Carboniferous orogenic gold mineral systems in the region – and thus could not be a major source of metamorphic auriferous fluids.

In contrast, volcano-sedimentary rocks of the Hodgkinson Province were first affected by metamorphism in the Carboniferous, shortly after their deposition. Regional metamorphic grades are only locally above the lower greenschist facies at the current erosional level, with the sub-greenschist facies dominant in the south-west of the province.
Orogenic gold mineral systems

(Peters, 1987, 1993; Bain and Draper, 1997). This is confirmed by extensive XRD illite
crystallinity results across the Hodgkinson Province (Lisitsin and Uysal, unpublished).
On the basis of the latter, a maximum pressure during peak metamorphism is tentatively
estimated (following Sassi and Scolari, 1974 and Guidotti and Sassi, 1986) within a range
between ~220 MPa (for the sub-greenschist facies in the south-west) and 300 Mpa (for
greenschist facies turbidites, affected by strong multiple cleavages in the north-west).
Assuming average bulk density of the overlying sedimentary rocks of 2.6, this corresponds
to a maximum burial depth of up to ~12 km in the north-west, suggesting a geothermal
gradient of approximately 32°C / km. At such metamorphic conditions, Siluro-Devonian
volcano-sedimentary rocks would reach the amphibolite-grade metamorphism with a peak
temperature of >500°C at a depth ranging between 3.5 km (in the north-west) and 6 km
(in the south-west) below the current erosional surface. Those rocks, including turbidites,
carbonaceous shales and basalts, could be a potential effective source for auriferous fluids
generated by metamorphic devolatilisation.

There is only a broad regional association between the spatial distribution of
primary orogenic gold deposits and the interpreted total thickness of the Siluro-Devonian
formations of the Hodgkinson Province and, by extension, the volume of rocks affected
by the amphibolite-grade peak metamorphism. All significant gold deposits occur
>20 km from the province margins, in a large area underlain by >6 km of tectonically
thickened Siluro-Devonian rocks, with >1-2 km of the latter lying below the inferred
peak-metamorphic 500°C isotherm. However, within that large area, deposits are strongly
concentrated in a single linear belt (Fig. 7; Lisitsin et al., 2014; Lisitsin, 2015), which
suggests the presence of a strong metallogenic zone-scale structural geological control
superimposed on a more regional-scale control of the availability and volume of a crustal
metal and fluid source.

5.2.2. Major crustal fluid pathways

Similar to the Western Lachlan Orogen, there is no direct spatial association between
the major crustal-scale faults and orogenic gold mineralisation in the Hodgkinson
Province. While many known deposits are hosted by regionally significant faults, only
small segments (up to a few km) are locally mineralised in the south-west of the province
and their extensions to the north are essentially barren, sometimes over more than 100 km
(Fig. 7). Proximity to major faults thus has only a very limited (if any) overall predictive
power for the spatial distribution of orogenic gold mineralisation in the region. Notably,
there is no significant orogenic gold mineralisation known within 20 km from the most regionally significant Palmerville Fault, forming the basis of the Hodgkinson Province in the middle crust (Korsch et al., 2012) and thus certainly physically connected with the crustal regions undergoing metamorphic devolatilisation in the Carboniferous. There is no evidence that the fault played any role in focusing fluid flow of orogenic gold mineralising fluids.

**Fig. 10.** The Hodgkinson Province: thickness of Siluro-Devonian rocks, the boundary between the Daintree and Herberton igneous subprovinces (from Champion and Bultitude, 2013), the metamorphic zone boundary between the greenschist facies in the east and the sub-greenschist facies in the west (from Bain and Draper, 1997), Carboniferous to Permian igneous rocks and orogenic gold ore fields.

Extremely strong concentration of orogenic gold deposits within a single linear zone (Fig. 7) cannot be explained by either the distribution of inferred source rocks or the presence and properties of major faults. Its spatial coincidence with the inferred deep crustal domain boundary, related to a margin of the Mesoproterozoic Etheridge continental crust extending under the south-western Hodgkinson Province (Lisitsin et al., 2014), suggests a major metallogenic significance of that cryptic at surface geological feature, probably controlling focused crustal-scale flow of mineralising fluids at a broader scale than any recognised individual fault. The position of the crustal domain boundary is probably marked by the coincident boundary between the Daintree and Herberton igneous subprovinces (Champion and Bultitude, 2013) and the metamorphic zone boundary between the greenschist and sub-greenschist facies (Bain and Draper, 1997). It has by far the strongest spatial association with the distribution of orogenic gold mineralisation in
the Hodgkinson Province than any other geological feature identified in the region (Fig. 10). It probably represents the most significant regional control on the focused crustal-scale flow of mineralising metamorphic fluids – resulting in the creation of a discrete metallogenic zone within a much broader mostly barren area, underlain by a comparable volume of a probable crustal source of auriferous fluids and cut by the same regional faults.

Fault segments hosting orogenic gold deposits within the metallogenic zone provided only secondary and more local-scale fluid flow pathways, intercepting the crustal-scale fluid flow focused above the deep crustal boundary. A lack of substantial mineralisation associated with locally mineralised regional-scale faults outside the linear metallogenic zone suggests that they did not provide an independently effective fluid focusing mechanism in the region. At a local scale, there is a significant spatial association between orogenic gold occurrences and proximity to northwest-trending fault segments, particularly strong for refractory gold and stibnite-gold mineralisation (consistent with conclusions of Zhang et al. (2011), based on regional deformation and fluid flow modelling). However, the apparent strength of the spatial association is probably exaggerated by the fact that north-westerly structural trend is particularly common in the south-west of the province, in the vicinity of the inferred deep crustal domain boundary.

5.3. Similarities and contrasts of regional metallogenic controls in the Western Lachlan Orogen and the Hodgkinson Province

A comparative analysis of the crustal architecture of the Western Lachlan Orogen (Victoria) and the Hodgkinson Province (Queensland) indicates significant differences between the regions, which may account for the differences in their overall orogenic gold endowments and the broad spatial distribution patterns of gold endowment within each province. Both provinces were formed along a convergent cratonic margin and experienced significant tectonic crustal thickening and heating at the onset of their orogenic gold mineral systems. Geodynamic evolution of each region and their tectonic settings during periods preceding and then culminating in the generation of orogenic gold mineral systems set up the general configuration of the factors controlling the mineral systems. In particular, the geodynamics determined the composition and volume of potential source rocks (hydrrous reduced sulphur- and gold-bearing volcanic and sedimentary rocks) accumulated in each province – as well as the mechanisms and extent of their subsequent tectonic thickening, deformation, metamorphism and regional focusing of mineralising fluids. The Bendigo and Stawell zones originated on the oceanic crust which was structurally thickened and
mostly preserved in the Bendigo Zone, but mostly consumed by subduction in the Stawell Zone (Cayley et al., 2011). In contrast, the Melbourne Zone of the Western Lachlan Orogen and, most likely, the Hodgkinson Province were originally formed on thick older continental crust and thus could not attain a larger thickness of hydrous source rocks to drive more substantial metamorphic devolatilisation and thus sustain more productive orogenic gold mineral systems in those regions. Thus, the volume of generated gold-bearing fluids (determined by the volume and composition of potential source rocks, but also the intensity of a regional thermal event driving metamorphic devolatilisation and its temporal relationships with regional tectonic events) is a fundamental first-order constraint on the maximum possible total gold endowment of a metamorphic orogenic gold province – and its broad spatial distribution within the province (Phillips and Powell, 1993; Goldfarb et al., 1998; Bierlein et al., 2004).

However, broad regional variations of the volume of inferred crustal source rocks in both regions cannot account for the existence of the strongly linear richly endowed metallogenic zones. Major metallogenic controls operating at that scale are likely to be related to deep crustal domain boundaries, with only subtle surface expressions. Thus, the western boundary of the Selwyn Block was apparently a critical regional metallogenic control responsible for the observed north-easterly trend in the distribution of major gold ore fields in the Bendigo Zone (Fig. 9), as suggested by Wilson et al. (2009) and Hronsky et al. (2012). A deep crustal domain boundary identified in the Hodgkinson Province (Lisitsin et al., 2014; Lisitsin, 2015) may represent a comparable geological feature – the eastern boundary of the Etheridge Province underlying the south-western Hodgkinson Province in the middle crust. In both regions, the deep crustal domain boundaries are oblique to the regional structures and do not have any discernable relationships with the recognised crustal-scale faults. Such cryptic at surface structures represent more fundamental regional controls on orogenic gold mineral systems, spatially concentrating significant gold deposits in narrow linear zones within much larger metallogenic provinces, than the recognised major faults.

The mechanism by which deep crustal domain boundaries controlled orogenic gold mineral systems – and resultant spatial distribution of significant gold mineralisation in both regions – remains unclear. A regional zone of structural weakness may have formed, and repeatedly reactivated, above the leading edge of a deep crustal block during regional tectonic events. The zone could persistently localise stress heterogeneity (caused by localised buckling or torsion above the block’s margin) and be expressed
by a near-vertical system of individually insignificant interconnected fractures with only minor (if any) displacements along them (McCuaig and Hronsky, 2014). Alternatively (or additionally), the presence of a distinct block of relatively cold continental crust could disturb the regional heatflow during a metamorphic crustal heating event, creating along the edge of the block a linear zone of anomalously strong horizontal geothermal gradient. This zone could then be expressed as a regionally significant steep ‘step’ in the vertical position of the metamorphic zone boundaries – including the boundary between the seismic and aseismic crustal zones. An associated significant localised disturbance of heatflow within the aseismic zone could create a persistent steep zone of total effective stress heterogeneity, localising periodic ruptures of overpressured metamorphic fluids towards the overlying brittle seismic crust. Such locally enhanced steep upward fluid flow could also involve overpressured fluids moving laterally from the adjacent hotter domain not underlain by relatively cold continental crust – and representing the region with a larger volume of generated metamorphic fluids.

A close spatial correspondence between the inferred positions of the deep crustal block boundaries and the distinct linear patterns in the distribution of significant gold deposits in each region suggests an overall sub-vertical orientation of such inferred crustal zones of enhanced permeability, without a major lateral displacement of the dominant fluid flow across its strike. This is a common inferred characteristic of such fundamental deep-seated mineralisation-controlling structures (referred to as vertically accretive structures, McCuaig and Hronsky, 2014). Therefore, long-range (tens to hundreds of kilometres) lateral fluid flow along crustal-scale faults, updip and along their strike, while possible (Willman et al., 2010), is not necessary or justified to explain the formation of even the giant Bendigo ore field (Phillips and Powell, 2010). Assuming such major fault-controlled lateral fluid migration would also create significant conceptual difficulties in explaining the existence of distinct linear metallogenic zones oblique to the regional structures.

A lack of a consistent overall spatial association between major faults and significant gold deposits in the Western Lachlan Orogen and the Hodgkinson Province cannot be readily explained by a hypothesis of focused fluid flow mostly controlled by either crustal-scale faults or by discrete ‘second-order’ faults, linked with adjacent ‘first-order’ faults at depth. At a regional scale (tens to hundreds of kilometres), the dominant linear structural controls are likely to be associated with deep crustal boundaries, underlying regions with relatively thick originally hydrous volcano-sedimentary potential fluid and metal source rocks, rather than crustal-scale faults. On a more local scale, in the Bendigo
Zone, focused fluid flow to deposition sites hosting major gold ore fields was probably controlled by near-vertical fold-related self-generated fault and fracture meshes, rather than discrete individual ‘second-order’ faults (Willman et al., 2010). In the Hodgkinson Province, significant gold deposits are generally located proximal to some significant faults – but this only occurs within the prominent linear metallogenic zone, close to their intersections with the inferred surface projection of the Etheridge crustal domain boundary. Major faults in the reviewed regions may thus represent significant (although often indirect) metallogenic controls at a camp scale (up to several kilometres), but not at more regional scales.

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Chapter 6

MOSSMAN OROGENIC GOLD PROVINCE IN NORTH QUEENSLAND, AUSTRALIA: REGIONAL METALLOGENIC CONTROLS AND UNDISCOVERED GOLD ENDOWMENT

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Abstract

The Hodgkinson and Broken River provinces of the Mossman Orogen in north Queensland host numerous orogenic gold deposits and still remain under-explored. This paper discusses regional metallogenic controls and results of a probabilistic quantitative assessment of undiscovered gold potential in the region. Significant orogenic gold deposits in the region only occur within relatively small well endowed metallogenic zones, likely to be controlled by the eastern margin of the Palaeo-Proterozoic continental crust underlying the western Mossman Orogen. Three distinct styles of primary orogenic gold deposits are present in the area: gold-quartz veins, refractory gold associated with quartz–pyrite–arsenopyrite veins and stockworks and quartz–stibnite±gold veins. Refractory gold deposits are estimated to have the highest potential for significant undiscovered resources in the region. The Hodgkinson Province is estimated to host between 1 and 10 significant undiscovered refractory gold ore fields, containing approximately 20 t of gold (the median estimate), with a 90% probability of at least 1 t. The Broken River Province is estimated to host up to 5 significant undiscovered refractory gold ore fields, with the median estimate of total contained gold of approximately 12 t and an 80% probability of at least 1 t.

Keywords: Quantitative mineral resource assessment, gold endowment, north Queensland

1. Introduction

The Palaeozoic Hodgkinson and Broken River provinces in north Queensland (Fig. 1) have produced over 60 t of gold, mostly in the 19th – early 20th century. There has been a revival of exploration and mining activities since the early 1990’s, with the discovery of several refractory gold deposits in the region. Those deposits have produced
almost 7 t of gold and contain more than 19 t of gold in the remaining identified resources (Republic Gold Ltd, 2011), 65% of which were classified under the measured and indicated categories of JORC (2012). However, only small-scale gold mining is currently taking place in the region and most exploration activities are restricted to the areas in the close vicinity of previously identified mineral deposits. It is likely that significant gold deposits still remain to be discovered in this area of more than 40,000 km², many parts of which having been covered by only cursory modern exploration.

This paper presents results of a province-scale mineral resource assessment which aimed to quantify likely undiscovered gold endowment and gain new insights into regional-scale controls on the orogenic gold mineralisation in the region. Zipf’s law rank statistical analyses have been recently applied to estimate residual endowments of relatively mature metallogenic provinces and countries (Guj et al., 2011; Mamuse and Guj, 2011; Yigit, 2012). In contrast, this study was based on the three-part form of quantitative mineral resource assessment (Singer and Menzie, 2010). The assessment results can be used to support more informed regional planning and policy development by government and to facilitate exploration tenement area selection decisions in this under-explored part of north Queensland.

2. Geological setting and gold mineralization

2.1. Regional geology

The Hodgkinson and Broken River provinces are commonly considered parts of the originally contiguous Palaeozoic Mossman Orogen, formed along the convergent Pacific margin of the Australian Craton in the Silurian to Carboniferous (Champion et al., 2009; Henderson et al., 2013). The provinces are currently separated by Permo-Carboniferous magmatic complexes of the Kennedy Igneous Province. At the current erosional level, the Mossman Orogen is dominated by regionally deformed Siluro-Devonian turbidites, with minor basalts, cherts and limestones, intruded by late to post-tectonic Carboniferous to Permian granites and locally covered by Carboniferous to Quaternary sedimentary and volcanic rocks. The cover sequences attain significant thickness (many hundreds to thousands of metres) in areas of Carboniferous to Mesozoic basins, particularly the Lakefield and Laura basins in the north of the region.

Interpretation of the recent deep seismic data for north Queensland indicated that the Mossman Orogen represents only a relatively thin portion in the upper crust (<12
km thick in the Hodgkinson Province and generally <6km thick in the Broken River Province), completely underlain by blocks of older continental crust (Korsch et al., 2012). The tectonic setting of the Mossman Orogen in the Silurian and Devonian remains controversial. Suggested models include a forearc accretionary prism and a back-arc basin (Vos and Bierlein, 2006; Vos et al., 2007; Korsch et al., 2012; Henderson et al., 2013 and references therein).

The back-arc model suggests that the Mossman Orogen was originally formed on the attenuated Precambrian to Ordovician continental crust of the Australian Craton (including a segment of the Thomson Orogen) during Siluro-Devonian extension, prior to the Late Devonian inversion at ~360 Ma. In contrast, the accretionary prism model suggests that the Mossman Orogen originally formed in an oceanic forearc environment, on the oceanic crust which was subsequently consumed by subduction. In this model, the orogen represents an accretionary prism ‘stripped away’ from its original oceanic crust substrate and obducted over the older continental crust of the Thompson Orogen and Australian Craton during the 360 Ma orogeny (Korsch et al., 2012).

The regional metamorphic grades in the region remain poorly constrained but are generally low, ranging from prehnite–pumpellyite facies in the Broken River and south-western and western Hodgkinson Province up to lower greenschist facies in some other parts of the Mossman Orogen (Shaw et al., 1987; Garrad and Bultitude, 1999; Brime et al., 2003; Henderson et al., 2013). Widespread intrusive and extrusive magmatism (mostly of a felsic to intermediate composition) affected the region in the Carboniferous and Permian.
Primary and associated alluvial gold mineralisation is relatively common throughout the Hodgkinson and Broken River provinces (Fig. 3). Many areas of known mineralisation were extensively mined in 1870’s – early 1900’s, with only relatively minor intermittent production in more recent times. General characteristics of primary gold deposits and the mining history in the region have been extensively discussed by Bultitude et al. (1997), Garrad and Bultitude (1999) and Denaro (2013). Primary gold mineralisation in the
Undiscovered gold in Mossman orogen region belongs to several different genetic groups, including: various types of intrusion-related (in a broad sense) mineralisation genetically related to Permo-Carboniferous felsic intrusions (auriferous porphyry deposits, polymetallic veins, greisens and skarns), minor auriferous volcanic-hosted massive sulfide (VHMS) deposits and the most abundant group of structurally controlled gold and gold-antimony deposits. Mineralisation of the latter group is hosted mostly by regionally metamorphosed sedimentary rocks and does not display any direct genetic or spatial association with magmatic rocks. This group appears to be geologically identical to the metamorphic gold deposits widely described as ‘orogenic’ in the past 15 years (Phillips and Powell, 1993, 2010; Groves et al., 1998; Goldfarb et al., 2005; Hronsky et al., 2012), as previously suggested by Vos et al. (2005, 2007) and Vos and Bierlein (2006).

Review of the available data on fluid inclusions, mineralogy and lithogeochemistry of orogenic gold mineralisation in the region indicates the presence of at least three distinct styles of orogenic gold deposits, possibly formed during different phases of the geological evolution of the region. Deposits from different groups typically have significantly different mineralogical and geochemical characteristics and generally occur in distinct spatial domains, although mineralisation of different mineralogical types are jointly present in some areas.

Most primary gold deposits in the Hodgkinson Province and several small deposits in the Broken River Province are characterised by free gold (0.01 mm to >1 mm) in quartz veins, with minor sulfides (mostly pyrite and arsenopyrite) and ferroan carbonates. These gold–bearing quartz vein deposits are described in many published reviews (Jack, 1884, 1899; Jensen, 1939, 1940; Peters, 1987; Peters et al., 1990; Garrad and Bultitude, 1999). Gold–bearing quartz veins are usually associated with brittle–ductile faults and hosted by Silurian to Devonian turbidites.

Typical average gold grades recovered at the time of historic mining ranged between 30 g/t and 60 g/t. Historical records suggest that the recovery of at least 30 g/t was required at some mines for profitable mining in 1870’s – 1910’s because of the remoteness of the mining areas (Denaro, 2013), so only the rich ore shoots were extensively mined, with an effective cut-off grade likely to be approximately 15 g/t. Exploration and small-scale mining at known goldfields, which intermittently occurred since 1930’s, identified only small-tonnage (up to a few tens of thousands of tonnes) unmined portions of historically worked auriferous quartz veins, with typical gold grades between less than 5 g/t and
15 g/t. Deposits of this style jointly account for more than 90% of the primary gold production before 1990 (totalling approximately 11 t gold bullion).

The gold-quartz vein deposits are probably geologically identical to the low-sulfide gold–quartz veins of Berger (1986) and Drew (2003) and the mesothermal lode-gold of Hodgson (1993).

The second major style of gold deposits in the region is characterised by the prevalence of refractory, or ultra-fine (usually <10 μm), gold in sulfide grains (arsenopyrite and pyrite), which occur in thin veins and stockworks or disseminated in host turbidites adjacent to faults (mostly minor). Due to the refractory nature of gold, not amenable to metallurgically simple gravity extraction, this deposit style had been largely unknown in the region until 1980’s. Extensive exploration in parts of the region has identified a number of deposits of this style, most significant of which are at Northcote, Tregoora, Atric and Reedy in the Hodgkinson Province and Camel Creek, Golden Cup and Big Rush in the Broken River Province. Oxidised ores from several deposits were mined by shallow open cuts and processed by heap leaching in 1990’s, producing almost 7 t of gold. However, most of the identified mineralisation occurs in primary sulphidic ores which have not been mined. Total remaining identified resources exceed 19 t of gold (Republic Gold, 2011). Additional resources are almost certain to exist within or adjacent to the known ore fields as in many of them unoxidised primary mineralisation has been identified by drilling but not sufficiently explored below the base of oxidation.

Typical gold grades of the refractory gold deposits range between 1.5 g/t and 10 g/t, averaging less than 5 g/t. Analysis of extensive borehole data acquired over the identified deposits strongly suggests that the relatively low gold grades (much lower compared to the gold-quartz veins historically mined in the region) are the actual geological feature of this deposit style, rather than an artefact of modern bulk mining techniques. The refractory gold ores are characterised by strongly anomalous arsenic (typically >1,000 ppm As) and moderately anomalous antimony (typically in the range of 20 – 500 ppm Sb, exceeding 1% Sb in the presence of stibnite–quartz veins which probably represent a distinct phase of gold-antimony mineralisation).

Stibnite–quartz±gold veins are relatively widespread in the south-west of the Hodgkinson Province (within the historic Hodgkinson Goldfield area) and also occur in other parts of the region. These veins were a major historic source of antimony production in north Queensland, with stibnite concentrate being the main or, in some cases, the only mine product. Total antimony production from the region was approximately 5,000 t of
stibnite concentrate (Wallis, 1993; Garrad and Bultitude, 1998). The stibnite–quartz veins were of a limited significance in terms of historic gold production and their geological characteristics and genesis remain relatively poorly understood.

Stibnite–quartz veins occur in spatially distinct domains in the vicinity of gold-quartz vein deposits (e.g. at Kingsborough-Thornborough and Munbarra), in a close proximity to some refractory gold deposits (at Northcote, Tregoora and in the vicinity of Atric) and as distinct mineralised areas and isolated veins. Very little data is available on gold grades in stibnite–quartz veins. Limited historic production records indicate average recovered grades of free-milling gold of between 10g/t and 45 g/t (Jack, 1884; Jensen 1940; Republic Gold 2004), which is generally consistent with stibnite–quartz±gold vein deposits elsewhere (Berger, 1993; Lisitsin et al., 2010; Olshina and Lisitsin, 2011).

Refractory gold deposits and stibnite–quartz veins were often jointly described in North Queensland and in other regions as gold-arsenic-antimony and gold-antimony deposits (Berger, 1993; Denaro, 2013), or epizonal orogenic gold deposits (Groves et al., 1998; Vos et al., 2007; Lisitsin et al., 2010). The refractory gold deposits have been also described as disseminated gold (arsenic)-sulfide deposits (Levitan 2008). The refractory gold mineralisation in the Mossman Orogen in North Queensland has similar characteristics to deposits at Fosterville (>80 t Au) and Wiluna (>150 t Au) in Australia, Bakyrchik (>300 t Au) in Kazakhstan and the Olimpiada (>1,500 t Au) and Maiskoye (>200 t Au) ore fields in Russia.

The geochronology of gold mineralisation in the region remains relatively poorly understood. In relative timing of different mineralisation styles, it is generally accepted that stibnite–quartz veins post-date the main phase of gold-quartz vein mineralisation (Jensen, 1939, 1940; de Keyser and Lucas, 1968; Peters et al., 1990; Bultitude et al., 1996). Vos et al. (2005, 2007) indicated that stibnite–quartz veins also post-date the refractory gold mineralisation. The relative timing of the gold-quartz vein and refractory gold mineralisation remains uncertain.

All significant gold deposits in the Mossman Orogen are hosted by tightly folded marine Siluro-Devonian rocks, regionally metamorphosed to sub-greenschist and greenschist facies. In the Hodgkinson Province, these are Devonian turbidites of the Hodgkinson Formation, whereas in the Broken River Province they are turbidites of the Kangaroo Hills Formation in the Camel Creek Subprovince and the upper marine shelf clastic rocks and limestones of the Graveyard Creek and Broken River groups in the Graveyard Creek Subprovince. Minor occurrences are also known in the Ordovician
and older rocks of the Thomson Orogen locally exposed between the Camel Creek and Graveyard Creek subprovinces of the Broken River Province and in the western margin of the Hodgkinson Province. The youngest host rocks are the lowermost Carboniferous (Tournaisian) alluvial to shallow marine Venetian Formation at the base of the Clarke River Basin overlying rocks of the Camel Creek Subprovince, which host two minor gold-antimony occurrences.

Radiometric age dating provides some constraints on the age of the gold mineralisation. Morrison (1988) proposed a late Carboniferous (~300 Ma) age for a gold-quartz vein in the historic Hodgkinson Goldfield, on the basis of K-Ar dating of muscovite from an alteration selvage of an auriferous quartz vein. On the basis of an interpretation of the timing of deformational events in the region, Davis et al. (2002) suggested that, while quartz veins may be of different ages, there was only one major phase of gold mineralisation in the Permian (~270 Ma). Vos et al. (2007) analysed one sample from the Minnie Moxham deposit in the Hodgkinson Province and another sample from the Airport Gold deposit in the Broken River Province. Both samples appear to be associated with the gold-antimony mineralisation. On the basis of discordant Ar-Ar age spectra obtained from analysed micas, Vos et al. (2007) concluded that ~340 Ma may be a reasonable estimate of the the age of the regional metamorphism at both locations and a permissive maximum constraint on the timing of gold mineralisation. Vos et al. (2007) proposed several periods of gold mineralisation in the region: Early Carboniferous (~340 Ma), Late Carboniferous (~300 Ma) and Permian (~270 Ma), with a possible earlier Devonian event (~390 Ma) in the Broken River Province.

3. Method of quantitative mineral resource assessment

3.1. Three-part form of assessment

The quantitative assessment of undiscovered gold endowment in the region was based on the 3-part form of assessment developed by the United States Geological Survey and discussed in detail by Singer (1993) and Singer and Menzie (2010). The specific application of the 3-part assessment approach was similar to that described by Lisitsin (2010) and Lisitsin et al. (2010). It involved the following stages:

- definition of the areas (permissive tracts) that may contain orogenic gold deposits;
- estimation of likely grade and tonnage characteristics of undiscovered deposits by an appropriate grade and tonnage model based on geologically similar known deposits;
○ estimation of the number of undiscovered deposits (as percentiles of a probability distribution) consistent with the selected grade and tonnage model.

The total amount of undiscovered metal endowment was estimated through a Monte Carlo computer simulation using the EMINERS software (Duval, 2012), the workings of which are discussed in detail by Root et al. (1992) and Bawiec and Spanski (2012).

3.2. Regression estimates of number of deposits and contained ore tonnage

The most common approach used to constrain, guide, or substitute subjective expert estimates of the number of undiscovered deposits is based on spatial deposit densities per unit permissive area in well explored control areas (Singer, 1993; Bliss and Menzie, 1993; Singer et al., 2001). For example, Lisitsin et al. (2010) used local deposit densities in well explored exposed parts of metallogenic belts as major guides in the estimation of the numbers of undiscovered deposits in poorly explored parts of the belts under cover. However, direct extrapolation of the deposit density from a control area would require an assumption of a strong similarity of the spatial intensity of mineralisation in the control and assessment areas. Such an assumption is often difficult to validate. Also, for several deposit types, permissive area and deposit density are inversely related (Singer, 2008), which may bias estimates based on direct extrapolation when permissive tracts in control and assessment areas significantly differ in size.

In the previous studies by Lisitsin et al. (2010), the assessment areas represented covered under-explored along-strike continuations of control areas, with evidence of continuation of orogenic gold mineral systems under cover. This justified the tentative assumption of broad metallogenic similarities between the assessment and control areas. In contrast, the current study focused on a mostly exposed metallogenic province, making local statistical extrapolations questionable and increasing the risk of inappropriate analogies with other orogenic gold provinces.

To independently validate quantitative assessment results, addressing possible concerns of bias due to insufficiently constrained subjective expert estimates of the number of undiscovered deposits, we used general statistical models of Singer and Kouda (2011). The total number of deposits (both known and undiscovered) likely to be present within a geologically permissive area can be estimated using a regression model which evaluates deposit density for any deposit type, given the type’s median ore
tonnage and the permissive area size (Singer, 2008; Singer and Menzie, 2010; Singer and Kouda, 2011):

\[
\log_{10}(D_{50}) = 4.2096 - 0.4987 \times \log_{10}(A) - 0.2252 \times \log_{10}(T),
\]

\[
\log_{10}(D_{90}, D_{10}) \approx \log_{10}(D_{50}) \pm 0.449 \times \frac{\sqrt{1.009 + 0.003 \times (3.173 - \log_{10}(A))^2 \times (-0.329 - \log_{10}(T))^2}}{\sqrt{1.009 + 0.003 \times (3.173 - \log_{10}(A))^2 \times (-0.329 - \log_{10}(T))^2}}.
\]

where \(A\) is the permissive area in km\(^2\), \(T\) is the mean of the log-transformed (base 10) tonnage distribution of the deposit model in question, in million tonnes, and \(D_{50}, D_{90}\) and \(D_{10}\) are deposit densities (per 100,000 km\(^2\)) at the 50%, 90% and 10% certainty levels, respectively. The total number of deposits at those certainty levels can then be estimated as:

\[
N_{10(50,90)} = A / 100,000 \times 10^{\log_{10}(D_{50})}.
\]

Total ore tonnage (including tonnages of known deposits) likely to be present in all deposits of a particular deposit type within a permissive tract of size \(A\) (in km\(^2\)) can also be estimated using a general regression model (Singer and Kouda, 2011, updated from Singer, 2008 and Singer and Menzie, 2010):

\[
\log_{10}(T_{50}) = -1.096 + 0.7039 \times \log_{10}(A) + 0.6202 \times \log_{10}(T),
\]

\[
\log_{10}(T_{90}, T_{10}) \approx \log_{10}(T_{50}) \pm 0.664 \times \frac{\sqrt{1.009 + 0.003 \times (3.175 - \log_{10}(A))^2 \times (-0.329 - \log_{10}(T))^2}}{\sqrt{1.009 + 0.003 \times (3.175 - \log_{10}(A))^2 \times (-0.329 - \log_{10}(T))^2}}.
\]

where \(T_{50}, T_{90}\) and \(T_{10}\) are the estimates (at the confidence levels of 50%, 90% and 10%, respectively) of total ore tonnage in all deposits that belong to a selected deposit model with the mean of the log-transformed (base 10) tonnage distribution of \(T\), within an assessment tract.

### 4. Regional metallogenic analysis

#### 4.1. Genetic and descriptive mineral deposit models

As discussed in Section 2.2, three distinct styles of primary orogenic gold mineralisation can be defined in the region on the basis of their mineralogical, geochemical, structural and metallurgical characteristics: free gold in quartz veins, refractory gold in quartz-pyrite-arsenopyrite stockworks and gold in stibnite–quartz veins. There is a broad consensus that all those deposits belong to the orogenic, or metamorphic, group as defined by Phillips and Powell (1993, 2010), Groves et al. (1998), Goldfarb et al. (2005). However, there are still significant uncertainties regarding specific genetic and
chronological relationships between the different deposit styles in the Mossman Orogen. While their high-level regional controls on spatial distribution appear to be broadly similar and mineralisation of two or even all three styles may be present in the same mineralised area, orebodies of different styles typically form distinct spatial clusters. Importantly, deposits of the different styles are likely to be of a significantly different economic importance in the region in the future, both in terms of the remaining number of undiscovered deposits, their grades and tonnages and metallurgical characteristics.

The orogenic, or metamorphic, gold deposits occur in metamorphic accretionary terranes, hosted by a wide variety of rock types, typically regionally metamorphosed to the greenschist facies. The orogenic gold model of Groves et al. (1998) and Goldfarb et al. (2005) suggested that orogenic deposits may form over a wide range of crustal conditions – from <6 km depth and 150°C to 300°C (mostly corresponding to sub-greenschist conditions of the anchizone) to >12 km and >475°C (hypozonal, extending into the amphibolite zone). The viability of formation of orogenic gold deposits in the upper amphibolite metamorphic zone has recently been disputed (Phillips and Powell, 2009, 2010; Tomkins, 2010).

Some aspects of the genesis of orogenic gold deposits, in particular the source(s) of gold, remain open to debate (McCuaig et al., 2010). Some researchers argue that a material contribution from gold-enriched upper mantle is critical for the formation of major gold deposits (Hronsky et al., 2012). On the other hand, a widely accepted metamorphic genetic model links orogenic gold mineral systems with metamorphic devolatilisation of hydrous volcano-sedimentary rocks in the middle crust (Phillips and Powell, 1993, 2010; Goldfarb et al., 2005). The transition of hydrous sulphide and carbonate-bearing rocks into the amphibolite metamorphic zone leads to a series of metamorphic reactions of breakdown of the hydrous greenschist facies minerals, carbonates and pyrite. In particular, metamorphic desulphidation of pyrite to pyrrhotite leads to the release of the bulk of gold originally contained in pyrite (Pitcairn et al., 2006; Large et al., 2009). Large amounts of auriferous H₂O–CO₂–H₂S fluids, capable of transporting significant concentrations of gold, are thus produced. The auriferous fluids then migrate into lower-pressure crustal regions, probably under conditions of ongoing deformation necessary to maintain permeability in the middle crust (Cox, 2005) and facilitate rapid thermal breakdown of pyrite (Tomkins, 2010). Focused structurally controlled fluid flow concentrates large volumes of metamorphic auriferous fluids into relatively small deposition blocks, forming orogenic gold deposits, mostly in the brittle-ductile greenschist metamorphic zone.
The lower temperature boundary permissive for the formation of orogenic gold deposits is not strictly defined. In particular, sub-greenschist zone conditions have been suggested at least for some ‘epizonal’ gold±antimony deposits (Gao et al., 1995; Changkakoti et al., 1996; Groves et al., 1998; Mernagh, 2001; Bierlein and Maher, 2001; Goldfarb et al., 2005). Thermodynamic modeling also indicates that substantial gold mobility is possible at temperatures between 200°C and 300°C (Mernagh and Bierlein, 2008).

Only limited fluid inclusion data are available for gold deposits in the Mossman Orogen. Peters (1987) and Peters et al. (1990) indicated that gold–quartz veins in the Kingsborough ore field formed by low-salinity (<10% NaCl) aqueous fluids with very low concentrations of CO₂. Measured fluid inclusion homogenesiation temperatures mostly varied between 170°C to 250°C, sometimes reaching 320°C to 370°C, with no reliable estimates of the deposition pressure. The data were mostly from the Flying Pig deposit, hosted by a fault cross-cutting earlier gold-quartz vein mineralisation (Jack 1884; Jensen 1940), so it is not clear if the results are truly representative of the bulk of gold-quartz vein mineralisation in the region. Fluid inclusions from quartz veins associated with refractory gold mineralisation indicated ore deposition from low-salinity (<10% NaCl) aqueous fluids (with very minor CO₂ and CH₄), with typical homogenesation temperatures of 150°C to 260°C (Vos et al., 2005; Vos and Bierlein, 2006).

In this study, the orogenic gold deposits were sub-divided into two widely accepted descriptive deposit models: ‘mesozonal’ low-sulphide gold-quartz veins (Berger, 1986; Hodgson, 1993; Groves et al., 1998; Drew, 2003) and ‘epizonal’ gold±antimony deposits (Berger, 1993; Groves et al., 1998; Bierlein and Maher, 2001). This subdivision does not imply any assumptions on the differences in the formation depths or temperatures for the two deposit groups in the region. The ‘epizonal’ group is further subdivided into the refractory gold deposits (equivalent to the arsenian sub-type of Berger, 1993 and gold (arsenic)-sulphide deposits of Levitan, 2008) and stibnite–quartz±gold deposits (antimony sub-type of Berger, 1993; clastic-sediment-hosted Sb-Au of Nokleberg, 2010), which significantly differ in grade and tonnage properties and likely exploration potential in the region.

4.2. Regional spatial distribution of orogenic gold deposits

Orogenic and associated alluvial gold deposits are widely distributed throughout the Mossman Orogen. However, the spatial distribution of orogenic gold mineralisation is highly heterogeneous. In the Hodgkinson Province, the bulk of primary deposits of all three mineralisation styles, containing >98% of the total primary gold endowment discovered
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in the province and including all eight known significant primary ore fields with >1 t (>32,000 oz) of contained gold, occur in a relatively narrow belt in the south-west and west of the province (Fig. 2). Its particularly well mineralised central zone (~130 km long and <20 km wide), characterised by a particularly high spatial density of documented primary gold occurrences, hosts six significant ore fields and contains ~95% of the total endowment of the refractory gold and stibnite–quartz±gold deposits identified to date in the 20,000 km² of exposed Siluro-Devonian volcano-sedimentary rocks of the Hodgkinson Province. Only a few minor gold-antimony occurrences have been discovered at distances of more than 20 km away from the central zone. This metallogenic zone, which closely corresponds to the historic Hodgkinson Goldfield, trends at a low angle to most of the surface geological structures. Its likely geological controls are discussed in the next section.

Fig. 2. Distribution of orogenic gold mineralisation in the Hodgkinson Province. All the significant (>1 t Au) ore fields and most gold occurrences lie within a loosely defined auriferous mineralised belt, with its central zone characterised by a particularly high density of gold mineralisation.
In the Broken River Province, all the known significant refractory gold mineralisation occurs in two distinct mineralised areas: the Amanda Bel Goldfield (Vos et al., 2005; Denaro, 2013) in the Camel Creek Subprovince in the north-east and the Big Rush and Yellow Jack ore fields in the Graveyard Creek Subprovince in the south-west (Fig. 3). The mineralised areas are separated by more than 60 km of exposed Siluro-Devonian rocks which hosts only minor gold deposits and occurrences. All the occurrences currently recorded as gold-quartz veins are very minor. They have not been studied in detail and at least some probably represent gold-antimony deposits.

Fig. 3. Geology and orogenic gold mineralisation of the Broken River Province.

The spatial distribution of orogenic gold mineralisation in the Broken River Province indicates a prominent north-easterly trend along the central axis of the province. This trend is consistent with the overall geometry of the province and the orientation of the Late Devonian (~370 Ma) $D_2$ structures in the Camel Creek Subprovince and middle to late Carboniferous (?) $D_2$ structures in the Graveyard Creek Subprovince (Withnall and Lang, 1993; Henderson et al., 2013). Vos and Bierlein (2005) postulated that gold mineralisation in the Amanda Bel Goldfield is controlled by unrecognised north-east-
trending faults. In the Camel Creek Subprovince, substantial gold mineralisation is only known within ~15 km from the inferred axis of the D\textsubscript{2} Clarke River Orocline (Fig. 3). It is a major province-scale structure bending S\textsubscript{0} and S\textsubscript{1} trends in Siluro-Devonian rocks and apparently focusing high-strain regional D\textsubscript{2} folding (Withnall and Lang, 1993; Henderson et al., 2013) in a wide (~20 km) northeast-trending belt. Its exact position in the north-east is not defined but is likely to pass between the Golden Cup and Camel Creek ore fields (Ian Withnall, pers. comm.), continuing its better defined north-eastern trend in the south-west (Henderson et al. 2013) and consistent with the orientation of D\textsubscript{2} structures. Notably, relatively large gold deposits are only known in the north-east, mostly in an apparent discontinuous group of parallel linear mineralised zones (corresponding to the main part of the Amanda Bel Goldfield) which extends ~10 km along the north-easterly structural trend and ~16 km across the trend (Fig. 3).

Although most known gold deposits are hosted in fault zones (often fold-related), there is no statistically significant regional spatial association between gold deposits and proximity to, or geometry of, mapped faults and fold axes. Areas proximal to (<20 km) province-bounding faults and many major intra-province faults do not host significant gold deposits. While segments of some major faults host significant mineralisation within the Hodgkinson metallogenic zone, they remain barren or only poorly mineralised outside the zone, sometimes for >100 km along strike. No significant gold mineralisation is spatially associated with recognised major faults in the Broken River Province.

**4.3. Deep crustal heterogeneity in the south-western Hodgkinson Province**

A major deep crustal discontinuity can be inferred in the south-western Hodgkinson Province on the basis of the geochronology and geochemistry of Carboniferous to Permian felsic magmatic rocks, supported by a coincident change in regional metamorphic grades. Granite geochemistry and geochronology has long been used to infer the composition of the deep crust and regional geological evolution. In particular, boundaries between domains characterised by dominant I-type or S-type magmatism have been interpreted to represent major geological boundaries in the deep crust (Chappell et al., 1988), which generally do not correspond to any distinct geological structures at the surface.

The south-western part of the Hodgkinson Province experienced intrusive I-type magmatism in the late Carboniferous (~320-300 Ma), followed by extensive shallow intrusive and extrusive I- and A-type magmatism in the early to middle Permian
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(~290-275 Ma) – similar to the adjacent Etheridge Province (the Herberton and Tate Igneous subprovinces; Champion and Bultitude, 2013a). In contrast, the rest of the Hodgkinson Province (the Daintree Igneous Subprovince) was only affected by the middle to late Permian (~280-260 Ma) predominantly S-type intrusive magmatism, which strongly distinguishes that area from the rest of the Kennedy Igneous Association of north Queensland (Champion and Bultitude, 2013a). The earlier onset of magmatism in the south-western Hodgkinson Province suggests its structural distinction from the rest of the province, probably related to its distinct tectonic position and crustal composition.

Geochemical evidence indicates that crustal source rocks of the granites of the Daintree Subprovince were markedly different from those of the Herberton and Tate subprovinces (Champion and Chappell, 1992; Champion and Bultitude, 2013b). In particular, the Daintree Subprovince is characterised by more isotopically ‘juvenile’ basement in the deep crust (\(\varepsilon_{\text{Nd}}(t) = -2.3 – -6.7\), depleted mantle model age \(T_{2DM} = 1.0 – 1.5\) Ga) compared to a more isotopically ‘evolved’ signature of Carboniferous I-type granites in the south-western Hodgkinson Province (\(\varepsilon_{\text{Nd}}(t) = -7 – -9.7\), \(T_{2DM} = 1.6 – 1.8\) Ga) and the Etheridge Province, with \(\varepsilon_{\text{Nd}}(t) = -8.8 – -12.5\), \(T_{2DM} = 1.6 – 2.0\) Ga (Champion and Bultitude, 2013a, b), as illustrated on Fig. 4.

![Fig. 4. Regional metamorphic grades, igneous geochemistry and significant orogenic gold ore fields in the Hodgkinson Province](image_url)
The boundary between the Daintree and Herberton igneous subprovinces, as defined by Champion and Bultitude (2013a), is almost identical to the regional metamorphic zone boundary between the sub-greenschist facies in the western and south-western Hodgkinson Province and the greenschist facies in the rest of the province as defined by Bain and Draper (1997) (Fig. 4). This close spatial association suggests that both boundaries may be related to the same regional geological phenomenon. However, they do not apparently correspond to any recognised surface geological feature.

Champion and Bultitude (2013a) concluded that the observed geochemical differences between the Daintree and Herberton igneous subprovinces could be explained by older continental crust of the Etheridge Province extending under the Herberton igneous subprovince in the western Hodgkinson Province. Murgulov et al. (2013) came to a similar conclusion on the basis of comparative isotopic analyses of zircons from different igneous subprovinces. The spatial patterns of the granite geochemistry and regional metamorphism are consistent with the deep seismic interpretation indicating that the Proterozoic Etheridge Province underlies the south-western Hodgkinson Province in the middle crust (Fig. 6b in Korsch et al., 2012; Henderson et al., 2013). The coincident igneous subprovince and metamorphic zone boundaries probably represent a surface expression of the eastern boundary of this older subsurface crustal block.

### 4.4. Likely regional metallogenic controls

The total gold endowment of the Mossman orogenic gold province is probably controlled by its nature as part of an orogen completely underlain by thick older continental crust. This broad crustal architecture limited the volume of hydrous Siluro-Devonian (and, possibly, underlying low-grade Ordovician?) volcano-sedimentary rocks undergoing metamorphic devolatilisation in the middle crust – the most likely source of auriferous fluids for the orogenic gold mineral systems in the province, thus limiting its ultimate gold endowment. A lack of any deep crustal-scale faults (Korsch et al., 2012) also limited a possibility of a direct focused material or energy input from the mantle or lower crust. The broad spatial heterogeneity of the volume of the inferred source rocks within the province, probably thinning to <5 km towards the province margins as indicated by deep seismic data and gravity modelling, is likely to be a reason for the absence of any significant gold mineralisation within ~20 km from the margins of the orogen. However, the province-scale considerations fail to adequately account for the prominent clustering of orogenic gold mineralisation in the south-west of the Hodgkinson Province.
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The Hodgkinson metallogenic zone in the south-west displays a close spatial association with the surface expression of the inferred deep crustal boundary of the Etheridge Province. More than 85% of all primary gold occurrences recorded in the province, including all 8 ore fields with >1 t of contained gold and all identified refractory gold deposits, lie within 16 km from the approximate position of the boundary (Fig. 4), indicating the strongest recognised metallogenic zone-scale control on orogenic gold mineralisation in the Mossman Orogen. Similar deep crustal heterogeneities probably acted as major regional metallogenic controls in other orogenic gold provinces. One likely analogue is the inferred western edge of the Selwyn Block in central Victoria (Australia), a fragment of Proterozoic (?) continental crust which underlies the eastern half of the Western Lachlan Orogen (Cayley et al., 2011). Its inferred western margin, oblique to the surface regional geological structures, is marked by a transition from greenschist facies rocks intruded by Early Devonian I-type granites to its west to sub-greenschist facies rocks intruded by Late Devonian S- and I-type granites to the east. The surface expression of this deep crustal margin closely corresponds to a mineralised trend defined by several of the largest ore fields in the region (Wilson et al., 2009; Lisitsin and Rawling 2011; Hronsky et al., 2012).

Likely regional metallogenic controls in the Broken River Province are less pronounced and their significance and geological nature remain equivocal. Deep seismic and Sm-Nd isotope data indicate that the Paleoproterozoic(?) basement to the Etheridge Province (the Abingdon Seismic Province) underlies most of the Broken River Province in the lower crust (Chopping and Henson, 2009; Korsch et al., 2012), extending as far east as the Camel Creek ore field (Fig. 3). The exact position of the eastern margin of that deep crustal block is insufficiently constrained and may continue trending south-east towards Charters Towers. The Camel Creek and Golden Cup ore fields and several smaller deposits nearby, which jointly contain almost all known gold endowment in the Camel Creek Subprovince, are located within ~15 km from the intersection between the inferred positions of the eastern edge of the Abingdon Seismic Province and the deformation zone along the axis of the Clarke River Orocline. The intersection may have created the main regional metallogenic control for significant orogenic gold mineralisation in the subprovince by generating a zone of focused deformation and fluid flow.

Major faults and rarely recognised regional-scale folds appear to be relatively weak mineralisation controls in this region on the metallogenic zone scale. They can only be considered as more local ore field-scale controls within the Mossman orogenic gold
province, focusing mineralisation at their intersections with more fundamental inferred crustal-scale controls.

5. Quantitative assessment of undiscovered orogenic gold endowment in the Mossman Orogen

5.1. Grade and tonnage models

5.1.1. Grades and tonnages of known gold ore fields in the Mossman Orogen

To ensure unbiased assessment results, the first stage of this study involved the compilation of the grade and tonnage data for consistently defined orogenic gold ore fields in the Mossman Orogen. As extensively discussed by Harris (1984), Singer (1993), Singer and Menzie (2010) and Lisitsin et al. (2010), individual mines, often used as proxies for mineral deposits in prospectivity analyses, do not usually represent specific geological objects. They only reflect the process of mineral extraction, which was affected by the social, economic, technological and legal conditions at the time of mining. Such external factors often determined whether a particular mineral deposit was developed as a single mine or a group of mines.

In this assessment, grade and tonnage data were consistently compiled for spatially defined ore fields. An ore field was defined as a group of adjacent orebodies that belong to the same deposit model and are horizontally separated by less than 1.6 km (1 mile). Thus, orebodies less than 1.6 km apart were considered to be parts of the same mineralised system and their grades and tonnages were combined. This largely arbitrary spatial aggregation rule was accepted to ensure that the aggregated grade and tonnage data from the region could then be directly compared to the grade and tonnage models of Bliss and Jones (1988) and Lisitsin et al. (2010) developed using the same formal spatial proximity rule. The spatially defined ore fields generally outlined distinct clusters of recorded mineral occurrences separated from any adjacent clusters by hundreds to thousands of meters of essentially barren rocks.

Original pre-mining tonnages (t) and grades (g) for historically mined deposits were assessed using production records and estimates of ore dilution and gold recovery, following the approach of Lisitsin et al. (2010):
\[ t = \frac{t_{\text{extr}}}{1 + d} \]  \hspace{2cm} (6)

where \( t_{\text{extr}} \) is an extracted tonnage and \( d \) is ore dilution expressed as a proportion (typically 0.1 - 0.3), and

\[ g = g_{\text{rec}} \times \frac{1 + d}{r} \]  \hspace{2cm} (7)

where \( g_{\text{rec}} \) is a recovered grade and \( r \) is gold recovery (typically 0.7 – 0.9).

For historically mined gold-quartz vein ore fields, gold grades estimated on the basis of gold bullion production were appropriately reduced to account for the gold bullion impurities (mostly silver, with minor base metals). The available information from geochemical analyses of gold in ores and historic gold bullion sale prices for individual mines suggests that the impurities typically composed between 5% and 25% of the recorded historical gold bullion production (Jack, 1884; Peters, 1987; Peters et al., 1990; Denaro, 2013).

Identified current ore reserves and mineral resources were included in the estimated pre-mining ore field endowments. However, the tonnage estimates for the low-confidence inferred resources, as defined by JORC (2012), were reduced by 20% – 25% (rounding to the second significant figure). This conservative adjustment was done due to significant uncertainties associated with the physical amounts and grades of mineralised rocks estimated at the inferred resource level. For comparison, in the previous studies discussed by Lisitsin et al. (2010), the inferred resources for gold-quartz vein deposits were excluded altogether. The decision to include the bulk of the inferred resources in this study was because all the current inferred resources in the study area were for ore fields dominated by refractory gold deposits, characterised by much less erratic internal distribution of gold mineralisation compared to many gold-quartz vein deposits. The relatively high level of confidence of the inferred resources identified in the reviewed ore fields is also indicated by a high conversion rate to the indicated and measured resource categories following more detailed resource definition drilling (e.g., Republic Gold, 2004, 2006, 2011).

The original ore field grades and tonnages were inferred on the basis of historic gold production and resource estimates. Because of the incomplete historic production records and intrinsic uncertainties of resource estimation, the ore field endowment estimates have significant uncertainty, but they are deemed adequate for the purposes of this study. Possible future discoveries of any major extensions of the identified ore fields would make some of the current ore tonnage estimates conservative.
Undiscovered mineral endowment of an area could be adequately estimated based only on data from relatively large ore fields, which also typically have more reliable information on grades, tonnages and types of mineralisation (Lisitsin, 2010). Therefore, the quantitative mineral resource assessment of the Mossman Orogen was based only on significant ore fields, defined by an arbitrary lower cut-off of 1 t of estimated original contained gold, similar to the definition used by Lisitsin et al. (2010). This approach also represents a simplistic economic filter excluding the effects of small, probably uneconomic, ore fields from assessment results. Estimated pre-mining grades and tonnages of primary gold ore fields with more than 1 t Au identified in the Hodgkinson and Broken River provinces are shown in Tables 1 and 2 and Fig. 5.

Differences between grades and tonnages of the refractory gold deposits in the Hodgkinson Province and those in the Broken River Province (Table 1) are not statistically significant ($p(t) \geq 0.1$ for the $t$-test for log-transformed data). The grade and tonnage distributions for the significant refractory gold and gold-quartz vein ore fields in the region are not statistically different from corresponding log-normal distributions with the same means and standard deviations, as indicated by results of the Lilliefors’ application of the Kolmogorov-Smirnov goodness-of-fit test (Lilliefors, 1967; Abdi and Molin, 2007) and there are no statistical outliers. The log-transformed grades and tonnages for both refractory gold and gold-quartz vein ore fields are inversely related (with Pearson’s product-moment correlation coefficients $R = -0.44$ and $R = -0.70$, respectively), but the correlations are not statistically significant for the sample sizes.

**Table 1.** Estimated pre-mining grades and tonnages of significant (>1 t Au) primary gold ore fields in the Hodgkinson and Broken River provinces – refractory gold deposits.

<table>
<thead>
<tr>
<th>Name</th>
<th>Province</th>
<th>Contained gold, t</th>
<th>Average gold grade, g/t</th>
<th>Total ore tonnage, '000 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northcote</td>
<td>Hodgkinson</td>
<td>9.0</td>
<td>1.9</td>
<td>4,800</td>
</tr>
<tr>
<td>Tregoora</td>
<td>Hodgkinson</td>
<td>6.2</td>
<td>1.6</td>
<td>4,000</td>
</tr>
<tr>
<td>Camel Creek</td>
<td>Broken River</td>
<td>2.8</td>
<td>2.6</td>
<td>1,100</td>
</tr>
<tr>
<td>Atric</td>
<td>Hodgkinson</td>
<td>1.9</td>
<td>1.9</td>
<td>1,000</td>
</tr>
<tr>
<td>Big Rush</td>
<td>Broken River</td>
<td>1.9</td>
<td>2.1</td>
<td>900</td>
</tr>
<tr>
<td>Reedy</td>
<td>Hodgkinson</td>
<td>1.1</td>
<td>1.3</td>
<td>850</td>
</tr>
<tr>
<td>Yellow Jack</td>
<td>Broken River</td>
<td>1.1</td>
<td>1.5</td>
<td>725</td>
</tr>
<tr>
<td>Golden Cup</td>
<td>Broken River</td>
<td>1.1</td>
<td>3.6</td>
<td>300</td>
</tr>
</tbody>
</table>
Table 2. Estimated pre-mining grades and tonnages of significant (>1 t Au) primary gold ore fields in the Hodgkinson Provinces – gold-quartz vein deposits.

<table>
<thead>
<tr>
<th>Name</th>
<th>Contained gold, t</th>
<th>Average gold grade, g/t</th>
<th>Total ore tonnage, '000 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingsborough - Thornborough</td>
<td>5.0</td>
<td>31.4</td>
<td>159</td>
</tr>
<tr>
<td>Maytown</td>
<td>2.3</td>
<td>60.5</td>
<td>38</td>
</tr>
<tr>
<td>Woodville- Victory</td>
<td>1</td>
<td>33.5</td>
<td>30</td>
</tr>
<tr>
<td>Groganville</td>
<td>1.14</td>
<td>57.0</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 5. Grades and tonnages of significant (>1 t Au) orogenic gold ore fields in the Hodgkinson and Broken River provinces. The refractory gold deposits are characterised by much lower gold grades compared to the gold-quartz vein deposits.

5.1.2. Selecting an appropriate grade and tonnage models – refractory gold deposits

The purpose of a grade and tonnage model in quantitative mineral resource assessments is to provide an unbiased representation of the grades and tonnages of the undiscovered mineral deposits in an assessment area. The known deposits in the Mossman Orogen can be used to characterise properties of the undiscovered deposits. However, using only the known local deposits may lead to under-estimation of likely variability of grades and tonnages of the undiscovered deposits, so the use of appropriate global grade and tonnage models is generally recommended – unless the local deposits are demonstrated to be significantly different from the global model (Singer and Menzie, 2010).

Local refractory gold and stibnite–quartz±gold deposits are geologically similar to the ‘epizonal’ gold-antimony deposits characterised by the global grade and tonnage model of Berger (1993) and the local model for central Victoria (Australia) of Lisitsin et al. (2010). Student’s t-test applied to log-transformed data indicated that the tonnage distribution for significant refractory gold deposits in the Mossman Orogen (Table 1) is
similar to the tonnage distributions for the deposits with at least 1 t of contained gold from Berger (1993) and Lisitsin et al. (2010) ($p(t)= 0.81$ and $p(t)= 0.28$, respectively). In contrast, the local grade distribution differs substantially from the grades of significant deposits in both Berger (1993) and Lisitsin et al. (2010), with $p(t)= 0.001$ and $p(t)= 0.02$, respectively. The differences in the grade distributions are due to the different proportion of high-grade stibnite–quartz±gold vein deposits included in the grade and tonnage models. All eight significant gold-antimony ore fields known in the Mossman Orogen are of the refractory gold deposit style (the arsenian sub-type of Berger 1993), with average gold grades ranging between 1.3 g/t and 3.6 g/t. In contrast, 60% of the significant gold-antimony deposits in Lisitsin et al. (2010) and almost 50% in Berger (1993) are of the stibnite–quartz±gold vein style, with gold grades reaching as high as 47 g/t to 60 g/t. When comparative analyses are limited to the refractory gold deposits, gold grade distributions for the ore fields in the Mossman Orogen and central Victoria become very similar, with $p(t)= 0.79$.

The global model of Berger (1993) is based on the deposit information available in 1970’s – 1980’s. Berger (1993) acknowledged that for most deposits included in the model, reliable grade and tonnage information was not available at the time of compilation, so the author often had to make his own approximate estimates on the basis of personal experience and general deposit-scale geological information. It should be emphasised that in most regions, refractory gold deposits have only become a significant target for exploration and mining companies in the past 10-15 years. This relatively recent focus has resulted in many new discoveries and a massive increase of the available grade and tonnage information. Only one out of the 12 refractory gold deposits in north Queensland and central Victoria has been included in Berger (1993). Many deposits in Berger (1993) have been significantly re-evaluated since the model’s compilation. For example, the Olimpiada ore field was estimated to contain approximately 40 t of gold (Berger, 1993) but is now demonstrated to be likely of the order of 1,500 t of gold (Polyus Gold International Ltd, 2012). Similarly, the Wiluna ore field in Western Australia was estimated to contain approximately 6 t of gold (Berger, 1993), but by 2012 it has actually produced over 100 t of gold and still contains >80 t of gold in identified resources (Apex, 2012). The model of Berger (1993) thus significantly underestimates tonnages of many large gold-antimony deposits and it may not be adequately representative of the global population of the refractory gold deposits. To avoid potential biases, the global
model would need to be significantly extended and updated, which was beyond the scope of the current study.

The grade and tonnage model selected to represent grades and tonnages of the undiscovered significant (>1 t Au) refractory gold ore fields in the Mossman Orogen includes eight known ore fields in the Mossman Orogen (Table 1) and four ore fields in central Victoria (Table 3). The combined model is described by summary statistics in Table 4 and graphs on Fig. 6.

**Table 3.** Estimated pre-mining grades and tonnages of significant (>1 t Au) primary refractory gold ore fields in central Victoria. Fosterville – a new estimate, based on Lisitsin et al. (2010), AuRico Gold (2011, 2012), Crocodile Gold Corporation (2012); the others – from Lisitsin et al. (2010) and Olshina and Lisitsin (2011).

<table>
<thead>
<tr>
<th>Name</th>
<th>Contained gold, t</th>
<th>Average gold grade, g/t</th>
<th>Total ore tonnage, ‘000 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fosterville</td>
<td>82</td>
<td>3.3</td>
<td>25,000</td>
</tr>
<tr>
<td>Nagambie</td>
<td>6</td>
<td>1.0</td>
<td>6,000</td>
</tr>
<tr>
<td>Heathcote</td>
<td>1.4</td>
<td>1.2</td>
<td>1,165</td>
</tr>
<tr>
<td>Bailieston</td>
<td>1.2</td>
<td>2.6</td>
<td>471</td>
</tr>
</tbody>
</table>

**Table 4.** Summary statistics for log-transformed (base 10) grade and tonnage distributions of significant (>1 t Au) refractory gold ore fields in north Queensland and central Victoria.

<table>
<thead>
<tr>
<th></th>
<th>Ore tonnage, Mt</th>
<th>Gold grade, g/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ore fields</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Median</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>90th percentile</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>10th percentile</td>
<td>5.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>25</td>
<td>3.6</td>
</tr>
<tr>
<td>Pearson correlation coefficient (significance)</td>
<td>-0.1 (0.76)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6. Grade and tonnage model of significant (>1 t Au) orogenic gold ore fields in north Queensland and central Victoria: a a bivariate grade and tonnage plot; b cumulative frequency distribution of ore tonnages; c cumulative frequency distribution of gold grades.

The gold grade distribution of the combined model is consistent with a log-normal distribution with the same mean and standard deviation, as indicated by results of the Kolmogorov-Smirnov test (Lilliefors, 1967; Abdi and Molin, 2007) and of the Shapiro-Wilk test (R Core Team, 2012). The hypothesis of lognormality of the ore tonnage distribution also cannot be rejected at the 1% confidence level. Neither distribution has any statistical outliers. The log-transformed grades and tonnages are not significantly correlated (with Pearson’s product-moment correlation coefficient $R = -0.1$, $p(t) = 0.75$).
5.2. Permissive tracts

Globally, most orogenic gold deposits are apparently hosted by metamorphic rocks of the greenschist facies (Goldfarb et al., 2005; Phillips and Powell, 2009, 2010). However, the lower boundary of thermo-baric conditions permissive for the formation of orogenic gold deposits is not strictly defined, as mentioned previously. At least some orogenic gold deposits may be hosted by sub-greenschist facies rocks (Bierlein and Maher, 2001; Goldfarb et al., 2005; Peters et al. 1990; Vandenberg et al. 2006; Wilson et al., 2009). Rocks of the sub-greenschist facies are only documented in the south-west and west of the Hodgkinson Province but apparently dominate the Broken River Province (Bain and Draper, 1997; Brime et al., 2003; Henderson et al., 2013) and probably host many orogenic gold deposits in the Mossman Orogen (Fig. 4). Therefore, the sub-greenschist facies cannot be excluded from permissive tracts, either on a theoretical or empirical basis.

No substantial orogenic gold mineralisation has been identified in the Carboniferous and younger magmatic or sedimentary rocks extensively exposed throughout the region. They are likely to post-date the bulk of orogenic gold mineralisation in the region (Golding et al., 1990; Vos and Bierlein, 2006; Vos et al., 2007).

Based on the metamorphic genetic mineral system model (Section 3.1) and the spatial distribution of known orogenic gold mineralisation in the region, permissive tracts for all three styles of gold deposits are defined in this study as the areas of outcropping Silurian to Devonian sedimentary and associated volcanic rocks, metamorphosed to sub-greenschist and greenschist facies, and their sub-surface extensions under shallow cover (up to a few hundred metres). The excluded areas of deep cover over permissive lithologies include most of the Laura Basin in the north and the areas covered by Permo-Triassic sediments in the south-west of the Hodgkinson Province and the bulk of Carboniferous volcano-sedimentary rocks in the Broken River Province.

The mostly exposed parts of the provinces can be considered well explored for near-surface gold-quartz vein and stibnite–quartz±gold vein deposits and moderately to well explored for refractory gold deposits. In contrast, areas of extensive post-mineralisation cover have not undergone any substantial gold exploration. The well explored parts of the permissive tract were defined in this study as the areas within 200 m of exposed Ordovician to Devonian volcano-sedimentary rocks and the areas of cover within the outlines of known ore fields. Well explored permissive areas were delineated on the basis of recent 1:100,000 geological maps for the most of the Broken River and Hodgkinson...
Undiscovered gold in Mossman orogen provinces and on the basis of the 1:250,000 geological maps for the north-eastern part of the Hodgkinson Province.

Based on the above considerations, the mostly exposed part of the permissive tract covers approximately 20,000 km² in the Hodgkinson Province and approximately 6,000 km² in the Broken River Province. A permissive tract under reasonably shallow cover of the Laura Basin (less than several hundred metres), in the north of the Hodgkinson Province, could not be adequately delineated due to a paucity of information on the depth of cover, which is likely to exceed 500 m for most of the basin.

5.3. Number of undiscovered ore fields

Estimation of the number of undiscovered significant (>1 t Au) orogenic gold ore fields in the Hodgkinson and Broken River provinces was performed by an expert panel composed of five Geological Survey of Queensland (GSQ) staff (C. Dhnaram, P. Donchak, M. Greenwood, V. Lisitsin, I. Withnall) and four external experts (M. Barr (Curtain Brothers), T. Delahunty (Tech-Sol Resources), T. Jackson (Territory Minerals), G.N. Phillips (Phillips Gold)). The group reviewed relevant geological information for the region, including its geological history, the genesis and spatial distribution of orogenic gold deposits and the extent and likely effectiveness of past gold exploration. V. Lisitsin and I. Withnall (GSQ) participated in the discussions but did not estimate the number of undiscovered ore fields. Seven other workshop participants made individual estimates of likely numbers of undiscovered ore fields at three levels of certainty, described as the following: (1) median number (‘best estimate,’ equal chances of a higher or a lower number, 50% certainty – \( N_{50} \)); (2) lowest number (this number or higher is considered almost certain, 90% certainty – \( N_{90} \)); and (3) highest number (this number or higher is considered very unlikely, 10% certainty \( N_{10} \)). The verbal descriptions and associated numeric probability values are consistent with the widely used Sherman Kent rating scale (e.g. Meyer and Booker 2001, p. 115). These levels of certainty and associated estimates are consistent with the three-part form of assessment (Singer 1993; Singer and Menzie 2010). If experts estimated \( N_{90} = N_{50} = 0 \), then they were requested to estimate the numbers at even lower certainty levels (\( N_i \) and \( N_{i(5)} \) for 5% and 1% certainty, respectively), to express their opinions on the highest number they consider only remotely possible.

The initial individual estimates and their implications with regards to the consistency with the grade and tonnage model of significant ore fields and the exploration history in the region were discussed by the group. Following the discussion, the assessors could
modify their original estimates. No attempts were made to reach a consensus during the workshop. Behavioural aggregation of individual estimates could substantially complicate the estimation process, introduce significant psychological biases, and underestimate uncertainty (Meyer and Booker 2001; O’Hagan et al. 2006). Instead, individual estimates (Figs 7–8) were analysed and mathematically aggregated using equal weight linear pooling (Gedest and Zidek 1986; O’Hagan et al. 2006; Lisitsin 2010):

\[ f(x) = \sum_{i=1}^{n} w_i f_i(x) \]

where \( n \) is the number of experts, \( w_i = 1/n \) (equal weights given to all experts), and \( f(x) \) is the probability of a particular value of the number of undiscovered ore fields \( x \).

This aggregation approach required a definition of a probability distribution consistent with the expert percentile estimates. The choice of distributions may significantly affect the aggregation results. However, in this study, the use of the uniform and beta standard distributions (Olea 2011) and the MARK3 empirical distribution (the latter discussed in Singer and Menzie 2005, 2010 and Lisitsin 2010) fitted to the individual percentile estimates produced almost identical results.

![Fig. 7](image1.png)  ![Fig. 7](image2.png)

**Fig. 7.** Individual and aggregated expert estimates of the number of undiscovered refractory gold ore fields: a Hodgkinson Province, and b Broken River Province. The aggregated estimates are represented by the red lines with diamond-shaped markers.

As indicated by Fig. 8, the region is generally considered well explored for large gold-quartz vein deposits, with an aggregated median estimate of only one significant ore field with >1 t of contained gold, although many smaller deposits are likely to be present. The higher estimates of Expert 6 were for the ore fields which would not be expressed at surface as auriferous quartz veins and so would be quite challenging to explore. The known ore fields are characterised by small tonnages of tens of thousands of tonnes (which, however, may be partially an artefact of high historic cut-off grades).
Due to the estimated limited potential for major new discoveries of this deposit type in the area, it is not further discussed in this paper.

**Fig. 8.** Individual and aggregated expert estimates of the number of undiscovered gold-quartz vein ore fields in the Hodgkinson Province. The aggregated estimates are represented by the red line with diamond-shaped markers. The square markers represent individual estimates of $N_{90}$, $N_{50}$ and $N_{10}$ and the cross-shaped markers – $N_{5}$ and $N_{1}$.

The general regression model (Equations 1-3) can provide alternative estimates of the number of undiscovered ore fields, totally independent of the expert judgement used in this study. Using the entire exposed permissive area of the Hodgkinson Province (20,000 km$^2$) and the mean of the log-transformed ore tonnage distribution of the accepted model for significant refractory gold deposits (1.6 Mt), the regression estimates, adjusted for the number of known ore fields (4) are 6, 16 and 46 undiscovered significant ore fields at the 90%, 50% and 10% confidence levels, respectively. The regression estimates for the Broken River Province, given the permissive area of 6,000 km$^2$ and 4 known ore fields, are 3, 7 and 21 ore fields. The regression estimates for both provinces (but particularly for Hodgkinson) are significantly higher compared to all of the expert estimates (Table 5). This may be interpreted as either (i) the provinces, as a whole, are characterised by much lower overall spatial deposit densities compared to most other well-studied metallogenic provinces of the world, (ii) the expert estimates are very conservative and significantly under-estimate the number of undiscovered ore fields in the region, or (iii) the defined permissive tracts include a relatively high proportion of non-permissive or very poorly endowed areas. The third interpretation appears to be most consistent with the available geological information, in particular for the Hodgkinson Province, as discussed in Section 3.

When the assessment area was restricted to only the central zone of the inferred Hodgkinson mineralised belt (Fig. 2), the regression estimates, adjusted for the number of ore fields known within that part of the belt (3), become almost identical to the aggregated
expert estimates (1, 4 and 11 undiscovered ore fields, Table 3). The experts generally agreed that the undiscovered refractory gold ore fields were more likely to occur within the inferred metallogenic belt. They did not know the regression estimates at the time of the assessment workshop.

For a permissive area of the same size as the rest of the exposed permissive tract in the Hodgkinson Province outside of the central part of the metallogenic belt (18,000 km²), the regression estimates are 7, 19 and 53 significant ore fields. However, only one ore field (Reedy) has been found in that extensive exposed area – and it lies within the broader inferred mineralised belt as defined in this study, only 15 km from its central zone. These results provide an indirect support for the concept of the Hodgkinson metallogenic zone as by far the most endowed part of the Hodgkinson Province.

Table 5. Estimated number of undiscovered significant (>1 t Au) refractory gold ore fields.

<table>
<thead>
<tr>
<th>Probability</th>
<th>Number of undiscovered ore fields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expert estimates</td>
</tr>
<tr>
<td>Hodgkinson Province</td>
<td>Broken River Province</td>
</tr>
<tr>
<td>90%</td>
<td>1</td>
</tr>
<tr>
<td>50%</td>
<td>3</td>
</tr>
<tr>
<td>10%</td>
<td>10</td>
</tr>
</tbody>
</table>

Accepting the aggregated expert estimates, the Hodgkinson Province is likely to host between 1 and 10 undiscovered refractory orogenic gold ore fields, with a 50% probability of three or more ore fields, and the Broken River Province is estimated to host up to five undiscovered refractory orogenic gold ore fields, with a 50% probability of three or more ore fields. These estimates are limited to significant ore fields, defined by minimum contained gold of more than 1 t.

5.4. Estimated undiscovered ore tonnage and contained gold

Total endowment contained in the undiscovered significant ore fields was estimated using Monte Carlo simulations in EMINERS (Duval, 2012), based on the grade and tonnage model of significant (>1 t Au) refractory gold ore fields in North Queensland and central Victoria (Tables 1 and 3) and aggregated expert estimates of the numbers of undiscovered ore fields (Table 5). Results obtained using the ‘Lognormal’ and ‘Empirical’
modelling options of EMINERS were closely comparable. The modelling results are summarised in Table 6 and Fig. 9. The mean undiscovered refractory gold endowment in the Hodgkinson Province is estimated to be approximately 40 t of gold, with a 90% probability of at least 1 t and a 50% probability of at least 20 t. For the Broken River Province, the mean undiscovered gold endowment is estimated as approximately 25 t, with a 50% probability of at least 12 t.

Table 6. Estimated undiscovered gold endowment in the Hodgkinson province – significant refractory gold deposits.

<table>
<thead>
<tr>
<th></th>
<th>Cumulative probability</th>
<th>Mean</th>
<th>Probability of mean or more</th>
<th>Probability of none</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
<td>50%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td><strong>Hodgkinson Province</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold, t</td>
<td>1</td>
<td>20</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Ore, Mt</td>
<td>0.5</td>
<td>10</td>
<td>45</td>
<td>20</td>
</tr>
<tr>
<td>Number of ore fields</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Broken River Province</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold, t</td>
<td>0</td>
<td>12</td>
<td>55</td>
<td>24</td>
</tr>
<tr>
<td>Ore, Mt</td>
<td>0</td>
<td>7</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Number of ore fields</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Fig. 9. Estimated undiscovered primary orogenic gold endowment in: a the Hodgkinson Province, and b the Broken River Province

The general regression model of Singer and Kouda (2011) (Equations 4-5) can provide alternative estimates of the total amounts of ore-grade material within the assessed permissive tracts (Table 7). The regression estimates for the total permissive areas in both provinces are much higher compared to the results of Monte Carlo simulations of
undiscovered endowment (Table 6) and tonnages of known deposits (Table 1). However, when limited only to the inferred central metallogenic zone in the Hodgkinson Province, the regression estimates (5 Mt, 22.5 Mt and 105 Mt at the 90%, 50% and 10% confidence levels, respectively) are very close to the Monte Carlo estimates (0.5 Mt, 10 Mt and 45 Mt), plus the ore tonnage of the known deposits within the zone (10 Mt).

**Table 7.** Estimates of total undiscovered ore tonnages in the Hodgkinson and Broken River provinces, using the regression model of Singer and Kouda (2011).

<table>
<thead>
<tr>
<th>Probability</th>
<th>Total ore tonnage, Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regression model</td>
</tr>
<tr>
<td>Hodgkinson Province – total exposed</td>
<td>Hodgkinson Province – central</td>
</tr>
<tr>
<td>permissive area</td>
<td>metallogenic zone</td>
</tr>
<tr>
<td>90%</td>
<td>24</td>
</tr>
<tr>
<td>50%</td>
<td>114</td>
</tr>
<tr>
<td>10%</td>
<td>535</td>
</tr>
</tbody>
</table>

### 6. Discussion

The spatial distribution of orogenic gold deposits in the Mossman Orogen indicates the presence of cryptic regional metallogenic controls which strongly enhance prospectivity of relatively small zones. The most fundamental geological control operating at the metallogenic zone scale in the Hodgkinson Province is likely to be related to the edge of Paleoproterozoic continental crust underlying the south-western and western parts of the province. A similar deep crustal metallogenic control is also possible (although less pronounced) in the east of the Broken River Province. Information on such major metallogenic controls, often related to deep crustal or even lithospheric heterogeneities with only subtle expressions in the surface geology, is critical for exploration targeting and mineral resource assessments.

The Mossman Orogen is likely to host several significant (> 1 t Au or >32,000 oz Au) undiscovered orogenic gold ore fields with a substantial total gold endowment, possibly in excess of 1 Moz (31 t). The study quantified the likely undiscovered endowment in a probabilistic form to clearly convey uncertainty of the estimates. The assessment results depend on some critical assumptions and qualifications, which are briefly reviewed below. Importantly, there is no evidence of an upward bias, as indicated by alternative estimates based on independent statistical models.
The terms ‘ore field’, ‘orebody’ and ‘gold endowment’ are used here in a broad sense to denote metallogenic objects and their physical properties, without a specific consideration of current mineral economics. While average gold grades of known and estimated undiscovered gold ore fields in the region are comparable to those at some operating gold mines, we are not making any statements regarding probability of profitable exploitation of orogenic gold endowment in the region in the near future.

Estimates of undiscovered endowment are expressed here in terms of probability. However, they are only interpreted from frequencies of simulated predictions made following the outlined process and accepting the ‘base model’ assumptions and measures of uncertainty. Varying assessment assumptions of the model and modifying its parameters, or using a different statistical model, would result in different numerical estimates of probability. This is an intrinsic property of any probabilistic forecast model for a complex system.

Expert estimates of the numbers of undiscovered ore fields are likely to be strongly influenced by the properties and spatial distribution of known orogenic gold deposits in the Mossman Orogen, the current level of understanding of orogenic gold mineral system(s) in the region and perceptions of the effectiveness of past exploration. Accuracy of the aggregated expert estimates thus depends on accuracy of the assumptions accepted by the majority of the workshop participants. In particular, this concerns the assumptions of (i) high effectiveness of past exploration for major high-grade deposits with free gold throughout the exposed parts of the region, and (ii) the spatial distribution of known orogenic gold deposits and occurrences being indicative of the underlying spatial patterns of large-scale metallogenic processes.

The assessment results also strongly depend on the choice of a grade and tonnage model. As modelling is based on the principle of analogy, using the selected refractory gold model based on the known ore fields in the Mossman Orogen and central Victoria implies that the undiscovered deposits will have grades and tonnages statistically similar to that group of known deposits. Ore fields in the Broken River Province have not been completely explored below the level of oxidation, so there is a substantial probability of under-estimation of their ore tonnages, which would result in downward bias in the estimates of total undiscovered endowment.

The inclusion of the Victorian deposits, notably the Fosterville ore field (80 t Au), arguably, ensured a more adequate expression of uncertainty for ore tonnages of the undiscovered ore fields compared to a local model only based on the ore fields know
in the study region. However, the use of such a small-sample (12) model may still have under-estimated variances of grades and tonnages of undiscovered ore fields. In particular, there may be a further upside ore tonnage potential – due to a theoretical possibility of the presence of one or more undiscovered ore fields significantly larger than the ore fields included in the accepted model. Such low probabilities are inherently difficult to evaluate using methods based on analogy and supported by a reasonably small number of observations. Global statistical models may assist in the evaluation of potential effects of high-magnitude low-probability events.

The global regression models of Singer and Kouda (2011), totally independent of any existing information on the assessment area (other than the size of the permissive tract and tonnages of known ore fields), provided an indication of the scale of the theoretical upside potential for the region (Tables 5, 7). The regression estimates further indirectly supported the proposed model that only a relatively small part of the Hodgkinson Province (the central Hodgkinson metallogenic zone) is likely to be favourable for significant refractory gold ore fields.

Overall, we believe that the quantitative assessment results presented in this paper are a balanced representation of the undiscovered orogenic gold endowment in the region and its uncertainty (including the downside risks) – consistent with the current level of understanding of orogenic gold mineral system(s) in the region and its exploration maturity.

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Undiscovered gold in Mossman orogen


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Chapter 7

RANK-SIZE STATISTICAL ASSESSMENTS OF UNDISCOVERED GOLD ENDOWMENT IN THE BENDIGO AND STAWEll ZONES (VICTORIA) AND THE MOSSMAN OROGEN (QUEENSLAND, AUSTRALIA): COMPARISON WITH THREE-PART ASSESSMENT RESULTS

Vladimir A. Lisitsin
Natural Resources Research (under revision)

Abstract

The Bendigo and Stawell zones in Victoria and the Mossman Orogen in north Queensland host numerous orogenic gold deposits and are still likely to contain significant undiscovered gold resources. This paper discusses applications of Zipf’s Law to estimate the scale of residual gold endowment in each of the regions. Testing various plausible scenarios on whether or not the largest deposit in each region has been discovered and its endowment adequately evaluated provided a measure of uncertainty of assessment results. The total residual orogenic gold endowment of the Mossman Orogen is estimated to be between 3 t and 30 t of gold, contained in both extensions of known deposits and up to six significant undiscovered gold ore fields, each containing more than 1 t of gold. The Bendigo and Stawell zones are estimated to host 12 undiscovered ore fields with >31 t (1 Moz) of contained gold and another 35 undiscovered ore fields with >10 t (0.32 Moz) of gold, containing in total 1,600 t (51 Moz) of gold. These estimates are comparable to results of recent three-part quantitative assessments for both regions.

1. Introduction

A quantitative estimate of undiscovered mineral endowment of a geological province can be a critical factor for province-scale exploration targeting decision-making, as well as for a wide range of land-use planning considerations. Several methods have been used previously to provide such quantitative assessment results (Allais, 1957; Griffiths, 1978; Harris, 1984; McCammon and Kork, 1992; Drew, 1997). Many recent assessments have been based on the three-part approach (Singer, 1993; Singer and Menzie, 2010; Lisitsin et al., 2010, 2014). An easy to implement assessment approach is based on the common
observation that many natural phenomena are apparently characterised by an inversed power relationship between absolute quantitative measures of objects (‘size’) and their relative rank (Newman, 2005). One formulation of such a statistical relationship is known as ‘Zipf’s law’ (Zipf, 1949). It has been applied to characterise total ‘natural’ and residual mineral endowments of geological terranes and countries (Rawlands and Sampey, 1977; Merriam et al., 2004; Guj et al. 2011; Mamuse and Guj, 2011; Yigit, 2012).

This paper applies the size-rank statistical analysis based on Zipf’s law to two regions in central Victoria and north Queensland (Australia) for which quantitative mineral resource assessments of undiscovered endowment have been recently performed using other methods (Lisitsin et al., 2010, 2014). The paper reviews some implicit assumptions of Zipf’s law applied to mineral resource assessments and discusses their implications for assessment results and their uncertainties.

2. Basic principles of rank-size statistical analysis applied to quantitative assessment of mineral endowment

Zipf’s law is essentially a discrete version of the continuous Pareto distribution – a power law distribution with the cumulative distribution function represented as a rank-frequency or rank-size plot (Newman, 2005). In a general form, Zipf’s law can be mathematically expressed as:

$$A_r = A_1 r^k \quad | k < 0$$

(1)

where $r$ is a rank of an object in a sequence of objects arranged in the order of descending sizes, $A_1$ is the size of the largest object in the sequence, $A_r$ is the size of the $r^{th}$ object and $k$ is a constant. When applied to estimating amounts of contained metal (endowment) of mineral deposits, Zipf’s law thus implies that endowments of all the deposits present in a province – and thus its total endowment – can be adequately estimated on the basis of only two parameters – endowment of the largest deposit present in the province and the value of $k$. Total metal endowment of the province $M$ can then be estimated as:

$$M = \sum_{r=1}^{n} M_r \times r^k$$

(2)

where $M_r$ is metal endowment of the $r^{th}$ deposit in a decreasing rank-ordered sequence and $n$ is the number of largest deposits considered in the analysis, which can be defined by setting the minimum individual deposit endowment considered in an analysis. Previous studies applying Zipf’s law to analyse endowments of mineral deposits found that in
relatively mature mineral provinces $k$ was very close to -1 (Guj et al., 2011; Mamuse et al., 2011). This special case of Zipf’s law is referred to in this paper as a standard Zipf endowment model. If the condition of $k = -1$ is accepted by default, or indicated as a likely option consistent with properties of known deposits in a region under consideration, then endowments of all the deposits present in the region can be modelled given knowledge of a single parameter – endowment of the largest deposit in the region. If that is known, then, in accordance with a standard Zipf endowment model, the second largest deposit in the province should contain one half the amount of metal contained in the largest deposit, the third largest – one third of the largest, and so on.

While assuming knowledge of total endowment of the largest existing deposit can be problematic in a province which has not been exhaustively explored, it has often been suggested that the largest deposits within a province tend to be discovered at relatively early stages of the exploration history (Hronsdy and Groves, 2008). In relatively mature provinces, this observation provides tentative empirical support to the use of Zipf’s law to characterise the province’s endowment on the basis of endowment of the largest deposit known at the time of analysis. It can also be argued that, even if the largest deposit in a province may have not been found or fully evaluated, Zipf’s model could be used to estimate minimum residual endowment or to infer possible existence of the largest deposit (Guj et al., 2011).

3. Rank-size statistical analysis of orogenic gold endowment in the Mossman Orogen, north Queensland

Mineral deposits data and geology of the area have been reviewed in detail by Denaro (2013) and Lisitsin et al. (2013, 2014). The Silurian to Devonian Mossman Orogen includes two individual geological provinces (Hodgkinson and Broken River), currently separated by spatially extensive Carboniferous to Permian igneous rocks of the Kennedy Igneous Association (Jell, 2013). Both provinces contain significant orogenic gold deposits of two distinct deposit styles – gold-quartz veins and ‘gold-antimony’ (including dominant refractory gold deposits). Chronological and genetic relationships between those styles remain unclear. Current estimates of original contained gold (including production and identified resources) for spatially defined ore fields with at least 0.3 t of gold (Lisitsin et al., 2013), their deposit styles and relative ranks are summarised in Table 1.
Table 1. Estimates of contained gold in orogenic gold ore fields in the Mossman Orogen (north Queensland).

<table>
<thead>
<tr>
<th>Name</th>
<th>Contained gold, t</th>
<th>Province</th>
<th>Deposit style</th>
<th>Deposit rank – overall</th>
<th>Deposit rank by province</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northcote</td>
<td>9</td>
<td>Hodgkinson</td>
<td>Au-Sb</td>
<td>1</td>
<td>Hodgkinson</td>
</tr>
<tr>
<td>Tregoora</td>
<td>6.2</td>
<td>Hodgkinson</td>
<td>Au-Sb</td>
<td>2</td>
<td>Broken River</td>
</tr>
<tr>
<td>Kingsborough-Thornborough</td>
<td>5</td>
<td>ason</td>
<td>Au-Qtz vein</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Camel Creek</td>
<td>2.8</td>
<td>Broken River</td>
<td>Au-Sb</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Maytown</td>
<td>2.3</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Atric</td>
<td>1.9</td>
<td>Hodgkinson</td>
<td>Au-Sb</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Big Rush</td>
<td>1.9</td>
<td>Broken River</td>
<td>Au-Sb</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Woodville - Victory</td>
<td>1.3</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Groganville</td>
<td>1.1</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Reedy</td>
<td>1.1</td>
<td>Hodgkinson</td>
<td>Au-Sb</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Yellow Jack</td>
<td>1.1</td>
<td>Broken River</td>
<td>Au-Sb</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Golden Cup</td>
<td>1.1</td>
<td>Broken River</td>
<td>Au-Sb</td>
<td>12</td>
<td>4</td>
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<tr>
<td>Minnie Moxham</td>
<td>0.8</td>
<td>Hodgkinson</td>
<td>Au-Sb</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Great Australian</td>
<td>0.64</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Mount Peter</td>
<td>0.37</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Red Gold</td>
<td>0.36</td>
<td>Broken River</td>
<td>Au-Sb</td>
<td>16</td>
<td>5</td>
</tr>
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<td>Dina</td>
<td>0.33</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Monarch</td>
<td>0.32</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Munburra</td>
<td>0.3</td>
<td>Hodgkinson</td>
<td>Au-Qtz vein</td>
<td>19</td>
<td>14</td>
</tr>
</tbody>
</table>

The distribution of contained gold between all the known ore fields in the Mossman Orogen (Table 1) can be characterised by a best-fit negative power function of the relative ore field ranks shown on Fig. 1. The power coefficient of -1.225 is substantially different from the coefficient of -1 typically used to characterise deposit endowments by Zipf’s law in most previous studies (Guj et al., 2011; Mamuse and Guj, 2011).
Assess undiscovered endowment by Zipf law

Fig. 1. Distribution of estimated gold endowments for orogenic gold ore fields in the Mossman Orogen as a function of their relative ranks.

One possible explanation of this deviation from the standard Zipf’s law ($k = -1$) is that it may be due to the presence in the region of undiscovered ore fields (most likely of intermediate and small sizes) and errors in current estimates of individual ore field endowments (often due to the presence of additional yet unidentified resources). This explanation is commonly accepted in recent applications of Zipf’s law to characterise mineral deposit endowment (Guj et al., 2011; Mamuse and Guj, 2011; Yigit, 2012). Accordingly, let us assume that the total population of orogenic gold ore fields in the Mossman Orogen (including any undiscovered ore fields) conforms to Zipf’s law with the power coefficient $k$ of -1. Then, total undiscovered (residual) gold endowment of the Mossman Orogen $M_u$ could be characterised by the difference between the total ‘natural’ endowment of ore fields above a certain minimum cut-off as predicted by Zipf’s law and the total identified endowment contained in known ore fields:

$$M_u = \sum_{r=1}^{n} Z_r(M_1) - \sum_{r=1}^{m} M_r \quad | \quad Z_n = M_m = \min(Z_r)$$

(3)

where $m$ is the total number of known ore fields larger than or equal to the accepted low cut-off. Zipf endowment model can be applied assuming that (a) the total natural endowment of the Mossman Orogen can be adequately characterised by Zipf’s law with $k = -1$; (b) the largest ore field existing in the province has been found (Northcote), and (b) endowment of the largest ore field has been adequately estimated in Table 1 (Scenario 1), as shown on Fig. 2.
Chapter 7

This scenario suggests that the largest undiscovered ore field apparently missing from the distribution would rank No. 15 and contain no more than 0.6 t of gold. Attempting to estimate total residual gold endowment of ore fields with at least 1 t (0.032 Moz) of contained gold for Scenario 1 leads to a physically impossible solution of -9 t of gold. This is because accepting the assumptions of Scenario 1 leads to the conclusion that all the top ore fields from the second to 14th largest currently known in the Mossman Orogen have gold endowments exceeding the estimates of the standard Zipf’s function with $M_i = 9$ t and $k = -1$ by up to 70% (for $M_j$). This discrepancy cannot be explained by systematic over-estimation of gold endowment for all the largest ore fields with ranks between 2 and 14, as for most of them the estimates are largely based on documented past production. Moreover, at least some of them are almost certain to have additional currently unquantified ore-grade gold mineralisation not mined or properly delineated due to its metallurgical properties which were unfavourable at the time of mining.

![Known gold ore fields and Zipf estimates](image)

**Fig. 2.** Gold endowment – rank plot showing estimated endowments of known ore fields in the Mossman Orogen with their ranks fitted to the standard Zipf’s law function assuming that the Northcote ore field is the largest deposit in the region and that its total gold endowment current estimate.

Thus, it is apparent that at least some assumptions of Scenario 1 do not hold true. Accepting the general applicability of the standard Zipf’s endowment model in the Mossman Orogen leads to a conclusion that either the largest ore field in the region has not been adequately delineated or it may not have been discovered yet (cf. Guj et al., 2011). Notably, best-fit power trend lines fitted to both the ranked distribution of the known ore fields (Fig. 1) and the Zipf’s endowment model of Scenario 1 (Fig. 2) suggest
that the largest ore field should have gold endowment significantly higher than the 9 t estimate for the Northcote ore field – respectively, 15 t and 13 t. The Northcote ore field has experienced only relatively minor mining activities, with the bulk of its endowment represented by current gold resources. It is reasonable to assume that total estimated endowment of the ore fields is likely to significantly increase over time, similar to the historic observations for many significant mineral deposits around the world (e.g., Guj et al., 2011). Assuming that the total ‘natural’ endowment of the Northcote ore field is 13 t, the corresponding endowment model (Scenario 2 - Fig. 3) shows almost a perfect correspondence between the standard Zipf model and the best-fit power trend line for the known ore fields with their ranks adjusted for maximum consistency with Zipf estimates. Total residual gold endowment of ore fields with at least 1 t (0.032 Moz) of contained gold in each for Scenario 2 is estimated as 6.6 t (including 4 t of additional endowment for the Northcote ore field). An important implication of Scenario 2 is a likely presence of two significant undiscovered ore fields with more than 1 t of contained gold in each.

Fig. 3. Gold endowment – rank plot showing estimated endowments of known ore fields in the Mossman Orogen with their ranks fitted to the standard Zipf’s law function assuming the total gold endowment of 13 t for the Northcote ore field (Scenario 2), for: (a) all the ore fields with >0.3 t of contained gold; (b) significant ore fields with >1 t of contained gold.

In addition to a likely possibility that the endowment of the largest known ore field has been significantly under-estimated (Scenario 2), it is also possible that the largest ore field present in the Mossman Orogen has not yet been found, or that the actual total endowment of one of the known ore fields is currently under-estimated by a factor of 2 or more. The latter case would essentially constitute a new discovery. Although the largest deposits tend to be found early in the exploration process (Hronsky and Groves, 2008),
their total endowments, typically not known until late stages of their mining history, commonly exceed initial resource estimates by a significant factor (e.g., Guj et al., 2011). A possibility of a major new discovery cannot be completely discarded in the Mossman Orogen, particularly for the refractory gold deposits. The latter have only become an attractive exploration target in the region in the last 30 years and most exploration efforts since the middle 1990-s have focused on previously discovered deposits.

Using only the available information on the known ore fields in the Mossman Orogen and assuming that the distribution of the ‘natural’ gold endowment between ore fields of different sizes conforms to the standard Zipf distribution, it is difficult to estimate likely total gold endowment of the largest ore field which may be present but not yet discovered (or sufficiently evaluated) in the region. A reasonably conservative approach is to assume that the second largest ore field in the region is the Northcote ore field (or an ore field with gold endowment equivalent to the current estimate for the Northcote ore field). The Zipf endowment model for this Scenario 3 (Fig. 4) suggests possible presence of six significant undiscovered ore fields each containing more than 1 t (0.032 Moz) of gold. Based on this scenario, total residual endowment of all significant ore fields (including any additional resources within both known and undiscovered ore fields) can be estimated as almost 30 t (~1 Moz) of gold.

**Fig. 4.** Gold endowment – rank plot showing estimated endowments of known significant (>1 t of gold) ore fields in the Mossman Orogen with their ranks fitted to the standard Zipf’s law function assuming that the largest ore field, containing 18 t of gold, is yet to be discovered (Scenario 3).

A notable property of Scenarios 1 to 3 is that they include both gold-quartz-vein and ‘gold-antimony’ ore fields. In addition to uncertainties about genetic relationships between those two groups of gold deposits, they were also characterised by different ‘discoverability’ in the past. The vast majority of the former were effectively discovered
more than 100 years ago by direct detection of free visible gold both in alluvial and eluvial sediments and primary gold-quartz veins. In contrast, endowment of the refractory gold deposits, which comprise all the significant ore fields in the ‘gold-antimony’ group, has been only recognised in the past 20 years. Those deposits commonly do not have an obvious surface expression and their complex metallurgy and relatively low grades would not make them prominent targets for historic prospecting and exploration before the 1980-s. It is therefore most likely that the significant undiscovered ore fields implied by the Zipf endowment model of Scenarios 2 and 3 would be of the refractory gold style.

If we assume that a standard Zipf’s function (with $k = -1$) is adequately applicable to characterise the ‘natural’ total gold endowment in the Mossman Orogen, then Scenario 1 (Fig. 2), which implies that that all the significant ore fields in the region (including the largest one) have been discovered and sufficiently evaluated, cannot be accepted. On the other hand, Scenarios 2 and 3 may provide a measure of uncertainty for estimated total residual gold endowment in the Mossman Orogen. Then it follows that, on the basis of the alternative Zipf endowment models, the region is likely to contain between two and six significant (containing $>1$ t of gold) undiscovered orogenic gold ore fields and the total residual gold endowment contained in all significant ore fields is likely to be between approximately 6 t and 30 t of gold.

It would be challenging to assign specific confidence levels to the above estimates. It can be argued, though, that both higher and lower estimates consistent with reasonable assumptions for alternative Zipf endowment models are possible. For example, the total ‘natural’ endowment of the Northcote ore field may be below 13 t assumed in Scenario 2. Thus, assuming it to be 12 t would lead to a Zipf endowment model (Scenario 4) consistent with no more than one possible significant undiscovered ore field (Fig. 5a) and probably none – considering that some of the smaller ore fields are likely to contain additional currently unidentified endowments (Fig 5b). This model indicates the total residual gold endowment of approximately 3.5 t (including 3 t of additional endowment in the Northcote ore field). Scenario 4 probably represents a likely minimum end member of possible standard Zipf endowment models as it implies that individual endowments of almost all known significant ore fields (except the largest one) have been completely evaluated (with no possibility for additional resources) or even over-estimated. This is highly unlikely at least for several known ore fields which were only drilled out to shallow depths of less than 50 m.
Fig. 5. Gold endowment – rank plots showing estimated endowments of known ore fields in the Mossman Orogen consistent with the standard Zipf’s law function assuming the total gold endowment of 12 t for the Northcote ore field (Scenario 4): (a) ranks of deposits 9-13 increased by 1, implying the presence of an undiscovered ore field with endowment corresponding to rank 8; (b) assuming that deposits 8-10 (hatched) contain up to 20% of additional gold endowments – thus implying no significant undiscovered ore fields in the region.

On the other hand, the total maximum endowment of the largest ore field in the Mossman Orogen may significantly exceed 18 t assumed for Scenario 3. Various assumptions are at least theoretically possible and a Zipf endowment model defining the maximum limit of endowment cannot be strictly defined only on the basis of properties of known orogenic gold ore fields in this region.

It is useful to compare the above results of testing multiple alternative scenarios of the Zipf endowment model with results of the recent quantitative mineral resource assessment for the region completed using a different approach and discussed in detail in Lisitsin et al. (2013, 2014). The previous assessment was performed separately for each major deposit style (gold-quartz veins and refractory gold deposits) within the Hodgkinson and Broken River provinces. It was based on the three-part form of assessment (Singer, 1993; Singer and Menzie, 2010). The results are summarised in Tables 3 and 4.
Table 3. Probabilistic assessment of undiscovered orogenic refractory gold endowment in the Hodgkinson and Broken River provinces of the Mossman Orogen (north Queensland) using the three-part form of assessment (from Lisitsin et al., 2014).

<table>
<thead>
<tr>
<th>Cumulative probability</th>
<th>Hodgkinson Province</th>
<th>Broken River Province</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>50%</td>
<td>10%</td>
</tr>
<tr>
<td>Number of significant undiscovered ore fields</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Number of significant undiscovered ore fields</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4. Assessment of undiscovered orogenic gold endowment in the Mossman Orogen, north Queensland, based on multiple scenarios of the Zipf endowment model.

<table>
<thead>
<tr>
<th>Relative confidence level</th>
<th>Minimum</th>
<th>Low</th>
<th>High</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold, t</td>
<td>3.5</td>
<td>6</td>
<td>30</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Number of significant undiscovered ore fields</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>&gt;6</td>
</tr>
</tbody>
</table>

Results presented in Tables 3 and 4 are not directly comparable. For example, Zipf endowment models estimate total residual endowment which may include additional endowments of known ore fields (Table 4), whereas the three-part form of assessment focuses entirely on the undiscovered ore fields. Also, the reviewed Zipf models included both the gold-quartz vein and refractory gold ore fields while the results in Table 3 are limited to the latter. However, the comparison indicates a broad similarity between the two sets of results. For example, both sets indicate a small but not negligible probability that there are no significant (with >1 t of gold) undiscovered ore fields left in the Mossman Orogen. Also, ‘High’ estimates based on the Zipf endowment model of Scenario 3 (the probability of which is not defined – and hence the term ‘High’ may be misleading) are comparable to the combined median cases for both the Hodgkinson and Broken River provinces in Table 3. Finally, a significant positive skewness of the probabilistic endowment model described by Table 3 is consistent with the currently unbound maximum Zipf endowment model.
4. Rank-size statistical analysis of orogenic gold endowment in the Western Lachlan Orogen, central Victoria

Orogenic gold deposits in the Western Lachlan Orogen and their estimated total pre-mining endowments have been extensively analysed by Lisitsin et al. (2010) and Olshina and Lisitsin (2011a, b, c). Current estimates of original contained gold (including production and identified resources) for spatially defined ore fields with at least 0.8 t of gold and their relative ranks are summarised in Table 5.

A broad metallogenic overview of the Western Lachlan Orogen indicated significant similarities in the deep crustal architecture, tectonic history and associated metallogeny between the Bendigo and Stawell zones, as opposed to the Melbourne Zone (Willman et al. 2010). Also, gold deposits in the Melbourne Zone formed significantly later (~375 Ma) than the bulk of deposits in the Bendigo and Stawell zones (~445 Ma). Therefore, the two regions represent two distinct mineral systems, both geographically and chronologically. The following analysis has thus excluded orogenic gold deposits in the Melbourne Zone.

Table 5. Estimates of contained gold in orogenic gold ore fields in the Bendigo and Stawell zones, central Victoria (from Lisitsin et al., 2010).

<table>
<thead>
<tr>
<th>Name</th>
<th>Contained gold</th>
<th>Structural zone</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t</td>
<td>Moz</td>
<td></td>
</tr>
<tr>
<td>Bendigo</td>
<td>590</td>
<td>19</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Stawell</td>
<td>143</td>
<td>4.6</td>
<td>Stawell</td>
</tr>
<tr>
<td>Ballarat</td>
<td>103</td>
<td>3.3</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Fosterville</td>
<td>82</td>
<td>2.6</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Maldon-Muckleford</td>
<td>64</td>
<td>2.1</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Clunes</td>
<td>41</td>
<td>1.3</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Castlemaine</td>
<td>32</td>
<td>1</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Daylesford</td>
<td>25</td>
<td>0.8</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Tarnagulla</td>
<td>19.5</td>
<td>0.6</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Egerton-Gordon</td>
<td>17.5</td>
<td>0.6</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Berringa- Smythesdale</td>
<td>17.5</td>
<td>0.6</td>
<td>Bendigo</td>
</tr>
<tr>
<td>St Arnaud</td>
<td>12.5</td>
<td>0.4</td>
<td>Stawell</td>
</tr>
<tr>
<td>Steiglitz</td>
<td>8.2</td>
<td>0.3</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Taradale-Lauriston</td>
<td>7.5</td>
<td>0.2</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Dunolly- Moliagul</td>
<td>6.3</td>
<td>0.2</td>
<td>Bendigo</td>
</tr>
<tr>
<td>Name</td>
<td>Contained gold</td>
<td>Structural zone</td>
<td>Rank</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>t</td>
<td>Moz</td>
<td></td>
</tr>
<tr>
<td>Inglewood</td>
<td>6.2</td>
<td>0.2</td>
<td>16</td>
</tr>
<tr>
<td>Sebastian</td>
<td>6.2</td>
<td>0.2</td>
<td>17</td>
</tr>
<tr>
<td>Maryborough</td>
<td>6</td>
<td>0.2</td>
<td>18</td>
</tr>
<tr>
<td>Blackwood-Trentham</td>
<td>5.9</td>
<td>0.2</td>
<td>19</td>
</tr>
<tr>
<td>Moyston</td>
<td>2.6</td>
<td>0.1</td>
<td>20</td>
</tr>
<tr>
<td>Heathcote</td>
<td>2.2</td>
<td>0.1</td>
<td>21</td>
</tr>
<tr>
<td>Burke’s Flat</td>
<td>2.1</td>
<td>0.1</td>
<td>22</td>
</tr>
<tr>
<td>Wehla</td>
<td>2</td>
<td>0.1</td>
<td>23</td>
</tr>
<tr>
<td>Raywood</td>
<td>1.7</td>
<td>0.1</td>
<td>24</td>
</tr>
<tr>
<td>Amherst</td>
<td>1.6</td>
<td>0.1</td>
<td>25</td>
</tr>
<tr>
<td>Pitfield</td>
<td>1.4</td>
<td>0.05</td>
<td>26</td>
</tr>
<tr>
<td>Elaine - Mount Doran</td>
<td>1.4</td>
<td>0.05</td>
<td>27</td>
</tr>
<tr>
<td>Wilsons Reef</td>
<td>1.1</td>
<td>0.04</td>
<td>28</td>
</tr>
<tr>
<td>Linton</td>
<td>1</td>
<td>0.03</td>
<td>29</td>
</tr>
<tr>
<td>Stuart Mill</td>
<td>0.9</td>
<td>0.03</td>
<td>30</td>
</tr>
<tr>
<td>Crusoe</td>
<td>0.8</td>
<td>0.03</td>
<td>31</td>
</tr>
<tr>
<td>Redbank - Moonambel</td>
<td>0.8</td>
<td>0.03</td>
<td>32</td>
</tr>
<tr>
<td>Bamganie</td>
<td>0.8</td>
<td>0.03</td>
<td>33</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,214</strong></td>
<td><strong>39</strong></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 6. Location, structure and gold mineralisation in the Western Lachlan Orogen (WLO). Geology is not shown for the Delamerian Orogen (west of the Moyston Fault) and the Central Lachlan Orogen and Eastern Lachlan Orogen (east of the Governor Fault, CLO and ELO).

Similar to the Mossman Orogen, the distribution of contained gold for the ore fields in the Bendigo and Stawell zones can be characterised by a best-fit negative power function of the relative ore field ranks as shown on Fig. 7. Notably, the observed power coefficient of -1.991 is significantly lower than the standard coefficient of -1 typically used to characterise deposit endowments by Zipf’s law. A systematic bias of the estimation of $k$ by least squares regression used to generate a best-fit power trend line indicated by Goldstein et al. (2004) cannot adequately explain this difference. Possible explanations
include the following: (1) the ‘natural’ total endowment model for the region conforms to the standard Zipf function and the observed deviation is due to the presence of a large number of undiscovered major ore fields; (2) the ‘natural’ total endowment model for the region does not conform to the standard Zipf function and is characterised by a significantly steeper power function suggested by the properties of known ore fields – either for the whole population or for particular size categories; (3) the presence of mixed populations represented by the known ore fields; and (4) a combination of two or more of the above.

![Distribution of estimated gold endowments for orogenic gold ore fields](image)

**Fig. 7.** Distribution of estimated gold endowments for orogenic gold ore fields (with >0.8 t of gold) in the Bendigo and Stawell zones as a function of their relative ranks. Zipf estimates refer to a standard Zipf function with \( k = -1 \).

The possibility that a large number of significant gold ore fields in the region still remain undiscovered is quite likely. More than half of geologically permissive rocks of the Bendigo and Stawell zones are under the post-mineralisation volcanic and sedimentary cover. Previous quantitative mineral resource assessments of undiscovered gold endowment under cover in northern Victoria indicated that the northern covered parts of the Bendigo and Stawell Zones may host, respectively, more than 25 and more than 33 ore fields with >0.8 t of contained gold (Lisitsin et al., 2010). Additional undiscovered ore fields are also likely to be present under cover in the central and southern parts of the region. Therefore, the known ore fields probably represent less than half of the total number of significant gold deposits actually present in the region.

However, unlike the earlier example for the Mossman Orogen, a standard Zipf function could not adequately characterise the total gold endowment of the Bendigo and Stawell zones for the whole range of ore field sizes by a simple adjustment of ore field ranks. For example, given the estimated total gold endowment of the largest known ore
field in the region – Bendigo – of approximately 590 t, the standard Zipf function would suggest the presence of almost 600 individual ore fields with more than 1 t of contained gold. This dramatically contrasts with only 29 known ore fields of such a size and an estimate (based on the model and data in Lisitsin et al., 2010) that the total number of such ore fields which remain undiscovered in the northern Bendigo and Stawell zones is likely to be less than 100. Assuming that all the currently ‘missing’ smaller ore fields predicted by Zipf’s law still remain undiscovered appears to be highly unlikely. This may suggest that, if a standard Zipf function is indeed applicable to characterise sizes and frequencies of ore fields in the Bendigo and Stawell zones, it may only be appropriate for ore field sizes significantly larger than 1 t. In that case, the observed situation would be consistent with the conclusion of Quirk and Ruthrauff (2006) in relation to petroleum deposits that Zipf’s law tends to overestimate the number of small deposits. Similar observations have also been made in other physical and social sciences, indicating that a power law distribution (including Zipf’s law) is often only applicable to characterise statistical properties of relatively large (and thus rare) objects (Newman, 2005).

The presence of mixed populations of gold deposits of different types is not likely to be a significant factor in the observed ‘misfit’ between the contained gold distribution for the known ore fields and the standard Zipf model assuming the Bendigo ore field to be the largest and adequately evaluated gold deposit in the region. Out of the total 33 ore fields listed in Table 5, gold endowments of 30 are entirely – or at least dominantly – composed of gold-quartz veins classified as mesozonal orogenic and formed at ~445 Ma (Lisitsin et al., 2010). The Fosterville ore field (rank 4) is the only major ore field in the region representing the epizonal orogenic (‘gold-antimony’) refractory gold mineralisation style, formed at ~375 Ma. The Steiglitz and Heathcote ore fields (ranks 13 and 21) probably represent a mixture of both styles. The Steiglitz ore field was probably dominated by mesozonal orogenic gold-quartz veins, while the Heathcote ore field contained about 1.3 t of gold of the refractory gold mineralisation style. A complete exclusion of those three ore fields from the model would only result in additional deposits and associated gold endowment of ~83 t (2.7 Moz) ‘missing’ from the Zipf endowment model on Fig. 8, without affecting the total endowment model or its fit to the known endowment.

Fitting the ranks of known ore fields to a standard Zipf function leads to a Zipf endowment model shown on Fig. 8. The model suggests that the majority of significant ore fields existing in the region (including 12 with >31 t, or 1 Moz, of contained gold and another 35 with >10 t, or 0.32 Moz, of gold) remain undiscovered. Accepting this
endowment model results in an estimate of the total residual gold endowment of 2,900 t (93 Moz) contained in ore fields with >1 t of gold in each, including 1,600 t (>51 Moz) in ore fields with >10 t of gold. Two largest undiscovered ore fields predicted by the model would contain approximately 295 t and 196 t (9.5 Moz and 6.3 Moz, respectively).

Fig. 8. (a) showing all the ore fields with >1 t of gold; (b) showing only the ore fields with >10 t of gold.

While the standard Zipf model apparently grossly overestimates the likely number of relatively small significant (>1 t of gold) ore fields, particularly in the range of 1 t to 10 t, it leads to an estimate of total undiscovered endowment comparable to the estimates of the previous assessments (Lisitsin et al., 2010) obtained using a totally different approach and assumptions (Table 6).

Table 6. Probabilistic assessment of undiscovered orogenic gold endowment under cover in the northern parts of the Bendigo and Stawell zones, central Victoria, using the three-part form of assessment (from Lisitsin et al., 2010).
An interesting conceptual experiment can be designed to test one of the apparent critical limitations of the rank-size statistical analysis. The estimates of Lisitsin et al. (2010) specifically refer to the significant undiscovered ore fields likely to be present in the northern parts of the Bendigo and Stawell zones under contiguous extensive post-mineralisation cover of the Murray Basin, while the above Zipf endowment model characterises the total ‘natural’ endowment of the region. The spatial extent of the Cainozoic Murray Basin sediments is likely to be unrelated to the geological factors which determined the total gold endowment of the region formed in the Palaeozoic. Theoretically, the sedimentary cover could extend further south, covering some of the known ore fields, in which case they would still likely remain undiscovered at present. If the cover had extended ~30 km further south in the Bendigo Zone only, it would have covered the Bendigo ore field – the largest known ore field in the region – as well as nine other significant ore fields. A standard Zipf function fitted to the remaining ore fields is shown on Fig. 9.

![Fig. 9](image)

**Fig. 9.** Gold endowment – rank plots showing a hypothetical Zipf endowment model excluding five ore fields in the northern Bendigo Zone (including the Bendigo ore field) and assuming that the Stawell ore field was the largest ore field present in the province: (a) showing all the ore fields with >1 t of gold; (b) showing only the ore fields with >10 t of gold.

As the main assumption of a Zipf endowment model is that the largest ore field has been found and sufficiently evaluated, the above model would fail to predict the presence of the actual largest ore field in the province. The total residual gold endowment would be estimated as ~300 t (9.6 Moz), contained almost entirely in the predicted more than 100 ‘undiscovered’ ore fields each containing between 1 t and 10 t of gold. Arguably, the Zipf model on Fig. 9 does not show a good fit to the actual ore field endowment
data, with the ore fields ranking from 2 to 6 all containing more gold than predicted by the model. This could be interpreted as evidence that the largest ore field in the region still remained undiscovered. A conservative approach would be to assume that the largest ‘undiscovered’ ore field should contain twice the amount of gold endowment of the largest ore field included in the model on Fig. 9. The corresponding standard Zipf endowment model, assuming that the largest undiscovered ore field contains 300 t (9.6 Moz) of gold, can provide almost a perfect fit to the deposit data included in the previous hypothetical model (Fig. 10). This new model would estimate the total residual gold endowment contained in ore fields with >1 t of gold as approximately 1,070 t (34 Moz), including 443 t (14 Moz) contained in the ore fields with >10 t of gold.

**Fig. 10.** Gold endowment – rank plot showing a hypothetical Zipf endowment model excluding five ore fields in the northern Bendigo Zone and assuming that the largest undiscovered ore field (hatched) contained 300 t (9.6 Moz) of gold.

Given an apparent perfect fit of the Zipf model on Fig. 10 to the actual ore field endowment data, an analyst would have to find very strong additional reasons to correctly ‘guess’ that the actual largest ore field in the region is actually four times (or more) the size of the largest ore field shown in Fig. 9 and at least twice the size of the assumed largest undiscovered ore field shown on Fig. 10.

5. **Conclusions and discussion**

Zipf’s law can be used as an easy to implement tool to provide a quick quantitative assessment of the total mineral endowment of a geological province or district and its distribution between deposits of different sizes. A comparison of such a theoretical endowment model with the inventory of known deposits may provide indications
of a degree of the relative exploration maturity of the region and maximum expected endowments of undiscovered deposits. However, robustness of a Zipf endowment model strongly depends on the validity of several basic assumptions which need to be critically examined and validated.

In particular, Zipf models are extremely sensitive to a single major assumption – that the largest deposit existing in the province has been discovered and is adequately characterised in terms of its endowment. A conceptual experiment ‘masking’ the largest known ore field in central Victoria illustrated a major limitation of the Zipf’s law in adequately characterising endowment of a province where extraneous geological factors (such as the presence of extensive post-mineralisation cover) may result in a situation when the largest deposit in the region may be still undiscovered. This possibility needs to be appropriately evaluated and taken into account.

The other significant model parameter is a value of the power coefficient $k$. While it has been frequently stated – and demonstrated for several provinces – that assuming $k = -1$ is an appropriate default option, this conclusion may be not universally applicable. Also, it is likely that the standard Zipf’s law can adequately characterise the distribution of deposit sizes only for relatively large deposits – but not over the entire range of deposit sizes. For example, analysis results for orogenic gold deposits in central Victoria indicate that the standard Zipf’s model apparently grossly over-estimates the number of relatively small ore fields.

Varying assumptions of the Zipf endowment model – particularly whether or not the largest deposit in a region has been discovered and adequately evaluated – can provide a measure of uncertainty of an estimate of total residual endowment. However, it would be difficult to assign specific confidence levels to outputs of such multiple alternative scenarios. Estimates of residual gold endowment in parts of central Victoria and north Queensland (Australia) based on the standard Zipf model, as described in this paper, closely correspond to results of the earlier quantitative mineral resource assessments which used an entirely different approach (Lisitsin et al. 2010, 2014). This similarity suggests that the estimates of undiscovered gold endowment in both regions are robust.

References

Assess undiscovered endowment by Zipf law


Chapter 8

PROBABILISTIC FUZZY LOGIC MODELING – QUANTIFYING UNCERTAINTY OF MINERAL PROSPECTIVITY MODELS USING MONTE CARLO SIMULATIONS

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Abstract

Significant uncertainties are associated with the definition of both the exploration targeting criteria and computational algorithms used to generate mineral prospectivity maps. In prospectivity modeling, the input and computational uncertainties are generally made implicit, by making a series of best-guess or best-fit decisions, on the basis of incomplete and imprecise information. The individual uncertainties are then compounded and propagated into the final prospectivity map as an implicit combined uncertainty which is impossible to directly analyze and use for decision making. This paper proposes a new approach to explicitly define uncertainties of individual targeting criteria and propagate them through a computational algorithm to evaluate the combined uncertainty of a prospectivity map. Applied to fuzzy logic prospectivity models, this approach involves replacing point estimates of fuzzy membership values by statistical distributions deemed representative of likely variability of the corresponding fuzzy membership values. Uncertainty is then propagated through a fuzzy logic inference system by applying Monte Carlo simulations. A final prospectivity map is represented by a grid of statistical distributions of fuzzy prospectivity. Such modeling of uncertainty in prospectivity analyses allows better definition of exploration target quality, as understanding of uncertainty is consistently captured, propagated and visualized in a transparent manner. The explicit uncertainty information of prospectivity maps can support further risk analysis and decision making. The proposed probabilistic fuzzy logic approach can be used in any area of geosciences to model uncertainty of complex fuzzy systems.
1. Introduction

Effective identification and ranking of exploration targets is one of the most significant challenges of mineral exploration (Hronsky and Groves, 2008). Methods of GIS-based mineral prospectivity analysis and predictive modeling have been developed in the last 30 years in an attempt to complement expertise of exploration geologists with objective tools more suitable for efficient and repeatable processing and integration of vast amounts of data from numerous information sources (Bonham-Carter, 1994; Carranza, 2009). Mineral prospectivity maps are typically produced through a combination of evidential maps representing individual mineralization targeting criteria. The targeting criteria are defined and combined based on measured (data-driven) or subjectively estimated (knowledge-driven) spatial or genetic associations with mineralization and each other.

The datasets and mathematical tools used to create geological models and make predictions (such as identifying areas which may contain undiscovered mineral deposits) have significant uncertainties which need to be appropriately assessed to facilitate more informed decision making (Caers, 2011). The diverse sources of uncertainty can be broadly subdivided into those due to limitations of the data (stochastic) and due to a lack of knowledge (systemic, Porwal et al., 2003a; McCuaig et al., 2007, 2009). Sources of stochastic uncertainty (e.g., measurement inaccuracy and imprecision, inconsistent data coverage and resolution, etc.) are relatively well recognized. In contrast, many sources of systemic uncertainties remain poorly understood. For example, many geological concepts and their spatial representations used in prospectivity modeling are not precisely and uniquely defined, leading to uncertainty due to vagueness and ambiguity of definition (Klir and Yuan, 1995). Numerous uncertainties (both stochastic and systemic) are likely to be compounded and propagated through prospectivity model operations into the final outputs of any prospectivity analysis. Furthermore, a prospectivity model itself, defining a process of integrating multiple evidential datasets, is also not unique and has intrinsic uncertainties.

Unless the individual uncertainties are explicitly modeled and their propagation is evaluated, it is not practical to quantify uncertainty of final model outputs. However, most applications of prospectivity modeling do not adequately model uncertainty. This precludes or at least severely limits any further risk analysis, particularly for the data-poor areas with the inherently highest level of uncertainty, so decision making cannot be effectively assisted by objective information on uncertainty.
This paper introduces an approach to implement a probabilistic fuzzy logic model to quantify uncertainty of predictive mineral prospectivity maps (Lisitsin and Porwal, 2012). The paper first briefly summarizes general principles of mineral prospectivity modeling (Sect. 2) and reviews main sources and types of uncertainty of mineral prospectivity maps (Sect. 3). It then outlines the fuzzy logic method and discusses general approaches which could be used to assess uncertainty of a fuzzy prospectivity map (Sect. 4). Section 5 describes the proposed probabilistic fuzzy logic method and illustrates its application, followed by a general discussion and conclusions (Sect. 6).

2. General principles of GIS-based mineral prospectivity modeling

Mineral prospectivity modeling of an area typically aims to delineate relatively small potentially mineralized zones, based on the presence and spatial distribution of geological objects and properties which are demonstrated or deemed to be associated with target mineralization. The presence of these objects and properties, referred to as targeting criteria, often can only be inferred from their indirect partial expressions in various geoscientific datasets. The individual spatial datasets, appropriately processed to provide spatial representations (proxies) of targeting criteria, are commonly called evidential or predictor maps. An evidential map displays two or more evidential classes of a particular type of geoscience information (e.g., rock types, distance to the nearest fault, etc.) which indicate the presence or absence of one or more targeting criteria. A solid geology map reclassified into two evidential classes corresponding to rock types considered as either favorable or unfavorable for a certain mineralization type is an example of a simple binary evidential map. A collection of such maps is analyzed and integrated in a geographic information system (GIS) environment to delineate potentially mineralized zones in areas of overlapping GIS proxies for targeting criteria (favorable evidential classes) from different evidential maps.

A typical application of mineral prospectivity modeling for a particular target deposit type, or model, involves the following steps: (i) compiling relevant datasets and processing them into evidential maps representing various targeting criteria; (ii) quantifying relationships between the classes of the evidential maps and the target mineralization, on the one hand, and between the evidential maps, on the other; (iii) combining information from the individual evidential maps using a particular mathematical aggregation model. The main output represents a map showing the spatial distribution of the relative
probabilistic fuzzy logic method

probabilistic prospectivity, which can be loosely interpreted as a measure of probability of occurrence of a target mineralization type. It can be expressed as a rank, a category (e.g., highly prospective) or a numerical score. The latter is often expressed in probabilistic terms (such as posterior probability), or in terms of the fuzzy set theory (fuzzy prospectivity).

A generalized spatial mathematical model of mineral prospectivity for a particular mineral deposit type $P_D$ at a location within a study area, given a particular combination of evidential classes from $n$ evidential maps, can be expressed as

$$P_D = F(x_{1k}, x_{2m}, \ldots, x_{nj})$$ (1)

where $x_{1k}$, $x_{2m}$ and $x_{nj}$ are, respectively, the $k^{th}$, $m^{th}$ and $j^{th}$ evidential classes of the first, second and $n^{th}$ evidential maps and $F$ represents one or more mathematical aggregation operations, designed to model the spatial association of a joint presence of the evidential classes with target objects (mineral deposits or occurrences of a type under consideration).

Various methods of mineral prospectivity modeling can be broadly subdivided into data-driven and knowledge-driven types (Bonham-Carter, 1994), depending on relative roles of statistical relationships derived from data, on the one hand, and theoretical and subjective considerations, on the other, in the formulation of a data aggregation function $F$ (Eq. (1)). Data-driven methods (such as weights of evidence, logistic regression and neural networks) are typically used in data-rich areas with a relatively large number of known target objects, sufficient to reliably estimate statistical measures of spatial association. They include methods based on powerful non-linear machine learning models (Brown et al., 2000; Porwal et al., 2003b, 2006). Knowledge-driven methods (such as fuzzy logic), on the other hand, are commonly used for prospectivity modeling in areas with few known target objects. Hybrid methods, using a combination of expert knowledge and measures of statistical association, have also been applied (Porwal et al., 2003a, 2004; Carranza, 2009).

3. Accuracy and uncertainty of mineral prospectivity maps

A major challenge for prospectivity modeling is to ensure unbiased identification and ranking of exploration targets. Modeling results can be strongly biased by arbitrary selection of input datasets and inadequate conceptual and mathematical models. Biased datasets may omit essential input information (resulting in a failure to recognize critical targeting criteria indicative of the presence of a mineral deposit), or capture irrelevant data and include multiple representations of the same phenomena (leading to information
redundancy and potentially over-emphasizing naturally weak or even fortuitous spatial associations). An example of such spurious associations could be a statement of high prospectivity of a specific rare host rock type on the basis of its presence at several known hydrothermal deposits. Inadequate conceptual and mathematical models significantly differ in context (boundaries) and internal structure (Walker et al., 2003) from natural geological systems they attempt to characterize, so modeling results would not be applicable to those systems.

To address the risk of bias, some recent applications of mineral prospectivity modeling use principles of mineral systems (Wyborn et al., 1994; McCuaig et al., 2010). This approach imposes an explicit systematic framework guiding consistent definition of a conceptual model and data collection and analysis. It is particularly important in cases of few or no known examples of target mineral deposits, so statistical relationships with evidential classes cannot be effectively used as a basis for data integration. In this approach, a conceptual model is constructed to define the critical processes (or components) of a natural system, all of which would be required to produce target mineral deposits.

The critical processes (for example, metal and fluid source, active pathways, physical and chemical deposition drivers and preservation factors, McCuaig et al., 2010) are almost invariably represented by non-unique constituent components. For example, there may be multiple geological environments favorable for the presence of metal source(s) and multiple types of pathways for mineralizing fluids. Therefore, while a critical process is required to form a mineral deposit, the absence of any specific constituent component of that process does not preclude the formation of a deposit (McCuaig et al., 2010).

The critical and constituent processes of a mineral system are represented in spatial datasets as targeting elements – geological expressions of the constituent processes, such as coeval felsic volcanic and sulfidic sedimentary rocks can be used as targeting elements to identify rifts. Finally, specific mappable targeting criteria represent targeting elements in geological datasets which, after appropriate processing, can be used in prospectivity mapping as evidential maps (McCuaig et al., 2010).

Although the mineral system framework may reduce the risk of bias, any prospectivity model is inevitably characterized by significant uncertainty due to numerous uncertainties of the input datasets and a data aggregation model, which propagate into the prospectivity map. Theoretical understanding of the mineral systems is still evolving and there are significant uncertainties on their critical processes, relative importance of the constituent components and targeting criteria and their possible relationships. There are also major
uncertainties involved in the translation of the inferred critical components of the mineral system into mappable targeting criteria (McCuaig et al., 2010), as well as the representation of the targeting criteria by evidential maps. For example, likely critical processes of a mineral system are rarely accurately and precisely reflected in existing geological datasets. Even in the best-case scenario, when there is a direct correspondence between a critical process and a mappable criterion (e.g., a particular rock type), the spatial distribution of that criterion is mostly interpretative. For example, it may be based on interpolation between, or extrapolation beyond, the observation points, or non-unique interpretations of geophysical datasets. When critical processes can only be recognized indirectly by proxy, there is an additional uncertainty of the representativeness of the proxies expressed by evidential maps.

Typically, these numerous uncertainties of the original input data and derivative evidential maps are not explicitly expressed and their impacts on uncertainty of final modeling results are not estimated. Instead, a modeling process involves a series of non-transparent best-guess decisions, made on the basis of information available to prospectivity modeling analysts at the time of analysis. Information on uncertainty of the individual decisions is usually ignored, leading to final prospectivity models and maps which may indicate an inappropriately high level of confidence. In effect, standard applications of most prospectivity modeling methods (including those using statistical concepts and tools) thus represent essentially deterministic models of mineral prospectivity. Such models are based only a single set of geological interpretations and a single mathematical representation of one specific conceptual model. Prospectivity maps derived on the basis of such deterministic models may be useful in highlighting and ranking exploration targets. However, they do not clearly indicate uncertainty of the predictive models, while such information may be critical in exploration targeting decision making.

Adequate assessment of uncertainty of a mineral prospectivity map requires a relatively comprehensive internally consistent uncertainty model – equivalent to a mineral prospectivity model itself used to generate the prospectivity map and preferably integrated with it. Ideally, a comprehensive uncertainty model needs to: (i) identify the significant sources of uncertainty; (ii) quantify uncertainties of the input evidential parameters (iii) define conceptual and mathematical models characterizing interactions between the input uncertainties and their propagation to the prospectivity map; (iv) assess uncertainty of the conceptual and mathematical models. The task is complicated by the presence of fundamentally different types of uncertainty which may require different methods for
their modeling. A subdivision of uncertainty sources of a prospectivity model into the stochastic (related to data) and systemic (related to knowledge) groups (Porwal et al., 2003a; McCuaig et al., 2007, 2009) is an important step towards a complete definition of an uncertainty model characterizing total uncertainty of a predictive prospectivity map. Distinct types of uncertainty need to be further analyzed to define most appropriate methods for their assessment.

Different sources of uncertainty are commonly subdivided into two fundamental types (Bardossy and Fodor, 2001; Walker et al., 2003; Kiureghian and Ditlevsen, 2009; Caers, 2011): uncertainty due the intrinsic randomness of natural phenomena (aleatory, or stochastic, in a strict sense) and due to a lack of knowledge of those phenomena (epistemic, or systemic). In a strict definition, aleatory uncertainty (or variability) cannot be reduced by additional data but could only be better defined. In contrast, epistemic uncertainty can be reduced and, in principle, even eliminated by additional data and research. Using such strict definitions, total uncertainty in geoscience models is likely to be strongly dominated by epistemic uncertainty (Caers, 2011). However, in practical applications of predictive modeling the distinction between the aleatory and epistemic types may be unclear and uncertainties of both types can be often assessed using the same statistical methods.

For such practical applications, sources of uncertainty can be classified into three types on the basis of methods that could be used for their modeling: error (e.g., imprecision, errors of attribute and spatial measurement, data processing, interpolation, classification, etc.), fuzziness (fuzziness or vagueness of definition of concepts and objects due to their gradational boundaries) and ambiguity (non-specificity of interpretation or contradictory interpretations) (Klir and Yuan, 1995; Fisher, 1999). Uncertainty due to error and imprecision is dominant in the systems of strictly defined concepts and objects. It is the only uncertainty type recognized by the classical probability theory, well developed methods of which can be effectively used to model uncertainty of this type (hereafter referred to as stochastic, in a broad sense). Uncertainty due to fuzziness of definitions and ambiguity (collectively referred to as systemic uncertainty) is prevalent in the models of highly complex and poorly understood systems, including the definition of alternative scientific hypotheses and resolving their contradictions. Fuzziness can be treated with the fuzzy set theory (Zimmermann, 1991) which forms the basis of fuzzy logic prospectivity modeling. Treatment of ambiguity has not been adequately addressed for the spatial systems (Fisher, 1999).
Mineral prospectivity models and maps obviously involve significant uncertainties of all three types. However, previous attempts to explicitly address uncertainties of the input targeting criteria in prospectivity modeling and to assess uncertainty of resultant prospectivity maps have at best focused at partial measures of uncertainty of a single type. For example, the standard weights of evidence method only quantifies partial uncertainty due to variance of model parameters and missing data (Bonham-Carter et al., 1989; Bonham-Carter, 1994), which reflects stochastic uncertainty assuming no fuzziness and perfect accuracy and precision of the input data. In some cases, several data integration models and several model assumptions are implemented to visually compare results (Joly et al., 2012). This qualitatively highlights systemic uncertainty of ambiguity – discord between outputs of different models. However, such a manual process can only test a relatively small number of possible scenarios consistent with the available data and current limited knowledge. Therefore, similarities between individual predictive mineral prospectivity maps can only be considered as weak qualitative evidence of a relative precision of the compared models, with little information on their accuracy. Typical applications of knowledge-driven prospectivity modeling do not explicitly estimate uncertainty of output prospectivity maps at all.

In the mineral system framework, derivative mappable targeting criteria are commonly not truly representative of corresponding components of a natural mineral system as defined by a mineral system model. Moreover, the mineral system model itself may be not an adequately accurate and precise reflection of the natural mineral system. Therefore, it is practically impossible to strictly define a mappable targeting criterion that would cover all the space where a particular mineral system component was certainly present during a metallogenic event but exclude the rest of the space where that component was certainly absent. Simple geological examples of inherently fuzzy targeting criteria include a definition of a geochemical anomaly by setting a specific threshold value (particularly where there is a gradual spatial transition from anomalous to background values), or translating a criterion of proximity into a specific distance threshold: define exactly how far from an object a proximal zone extends. This is a common problem of precise definition of gradational boundaries. A more complex example is mapping relative fertility of a particular (assumed) source of gold in orogenic gold systems: define a quantitative relationship between the source’s properties and its metallogenic fertility and set a precise boundary between a source and non-source (both conceptually and spatially). Such a prevalence of fuzziness in mineral system models suggests that that the fuzzy set theory
(Zadeh, 1965; Zimmermann, 1991; Klir and Yuan, 1995) may be a more appropriate conceptual framework for modeling mineral systems (and assessing total uncertainty of such models) than the classical theory of probability which cannot account for fuzziness. The fuzzy logic method of prospectivity modeling (An et al., 1991; Porwal et al., 2003; Carranza, 2009), with its strengths of flexibility and general applicability (including areas with few known target objects), is therefore used in this paper to illustrate the proposed approach to quantifying total uncertainty of prospectivity maps.

4. Fuzzy logic prospectivity modeling – addressing fuzziness of targeting criteria

4.1. Method overview

A generalized fuzzy logic model for GIS-based mineral prospectivity mapping can be defined as follows. If $X$ is a set of $n$ evidential maps $X_i$ (where $i=\{1,n\}$) and each map contains between $k$ and $r$ evidential classes denoted as $x_{ij}$ (where $j=\{1,k\leq r\}$), then $n$ fuzzy sets of ordered pairs $A_i$ in $X$, each containing indicators of the presence of target mineralization from a single evidential map, can be defined as

$$A_i = \{(x_{ij}, \mu(x_{ij})) | x_{ij} \in X_i\} \quad (2)$$

where $\mu(x_{ij})$ is the membership value characterizing degree of compatibility of $x_{ij}$ in the fuzzy set $A_i$. $\mu$ is usually defined in the range $[0,1]$, where $\mu(x_{ij}) = 0$ indicates that the class $x_{ij}$ is completely excluded from $A_i$, $\mu(x_{ij}) = 1$ indicates its full membership in $A_i$ and an intermediate value indicates partial membership. The concept of partial membership clearly distinguishes fuzzy sets from Boolean sets characterized by a binary membership scheme of either complete or no membership (equivalent to $\mu(x_{ij}) = \{0,1\}$). The fuzzy membership value $\mu(x_{ij})$ can be estimated on the basis of statistical measures of spatial association, a theoretical mathematical model, expert knowledge or their combination. The membership values can be set individually for each discrete value or categorical class in an evidential map or calculated (for datasets of the ratio, interval and ordinal types) using a fuzzy membership function $\mu_{Ai}$. The function can be linear, Gaussian or any other form deemed appropriate for each dataset (Bonham-Carter, 1994; Porwal et al., 2003a; Carranza, 2009).

The use of the fuzzy set theory helps to minimize information loss (with the corresponding introduction of additional uncertainty) at the intermediate modeling stages compared to models based on Boolean sets. For the latter, each evidential class $x_{ij}$ needs to
be classified as either favorable or unfavorable with respect to the target object type (e.g., a location is either proximal or distal) before data aggregation from multiple evidential maps.

Map integration in fuzzy prospectivity modeling is performed using a fuzzy inference system, or engine. It is designed to simulate a conceptual model of interaction between different components of the natural system considered to be responsible for the formation of the target objects (mineral deposits of a particular type). The inference system constitutes a sequence of parallel and/or serial networks using fuzzy set operators, such as fuzzy sum, product or gamma (An et al., 1991; Bonham-Carter, 1994, p. 301; Porwal et al., 2003a). The evidential maps can then be automatically combined in a raster GIS environment on a cell by cell basis, using map algebra and the fuzzy membership values for the evidential classes to implement the fuzzy inference system. The final output is an estimate of the final fuzzy membership value of each analysis cell in the fuzzy set of the target objects, in the form of a predictive prospectivity map, which can be subsequently reclassified (de-fuzzified) to highlight the areas with relatively high prospectivity (Porwal et al., 2003a; Carranza, 2009). Implementation of a typical fuzzy logic model is illustrated by Fig. 1. For simplicity of illustration, all targeting criteria are assumed to be represented by multi-class (rather than continuous variable) evidential maps.

**4.2. Uncertainty of a fuzzy prospectivity map**

A fuzzy logic prospectivity model explicitly addresses uncertainty due to fuzziness of targeting criteria (and their representations by evidential maps) in its definition in terms of fuzzy sets.
However, this definition does not typically account for the stochastic uncertainty and ambiguity of the evidential classes, which implicitly propagate through a fuzzy inference system into a map of fuzzy prospectivity. Assessment of total uncertainty of such a map is further complicated by the fact that many recent applications of fuzzy logic modeling use a subjective measure of uncertainty as a direct input (often implicit) in calculations of fuzzy membership values. For example, the following linear function has been used to estimate fuzzy membership values (Porwal et al., 2003a; González-Álvarez et al., 2010)

$$\mu(x_{ij}) = \frac{m_i \times w_j \times cf_i}{A}$$

where $m_i$ is a weight assigned to map $i$, $w_j$ is a weight of class $j$ of map $i$, $cf_i$ is a confidence factor and $A$ is a denominator set to constrain $\mu(x_{ij})$ to the range [0,1]. The confidence factor is assigned to an evidential map based on the perceived degree of directness of its representation of an estimated targeting criterion. The evidential map would get a higher confidence factor if it directly maps the exploration criteria and a lower confidence factor if it is based on mapping of an indirect response of the exploration criterion. The confidence factor is also used to account for the uncertainties in the primary GIS datasets used to create a particular evidential map (Porwal et al., 2003a).

In this approach, a measure of uncertainty of a particular evidential map is used as an input in a calculation of fuzzy membership values for all the evidential classes in that map. This may lead to a significantly biased estimate of mineral prospectivity, with some
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locations with coincident favorable evidential classes potentially receiving a low relative ranking only because of a high uncertainty of input factors. In such applications, it can be impractical to distinguish areas with a low overall prospectivity from areas with a high uncertainty, which highlights a danger of combining measures of prospectivity and uncertainty in a single parameter.

It would be difficult to unequivocally interpret relatively low final fuzzy prospectivity membership values in outputs of such applications. Low values could either result from a combination of evidential classes unfavorable with respect to the target objects (no or negative association with mineralization) or be a consequence of missing (or high-uncertainty) dataset(s). This potential ambiguity of interpretation is obviously a highly undesirable property of a predictive fuzzy prospectivity model (An et al., 1991) which may lead to biased decisions.

Therefore, to avoid additional ambiguity of interpretation, measures of relative prospectivity and uncertainty should not be combined in a single parameter (Knox-Robinson, 2000). A quantitative assessment of uncertainty of a prospectivity map would require a model of explicit uncertainty propagation, integrated with a general prospectivity model. For example, a stochastic uncertainty model would assess the resultant stochastic uncertainty of mineral prospectivity $P_D$ at each location given the uncertainties of the present evidential classes of $n$ evidential maps

$$U(P_D) = g(u(x_{1k}), u(x_{2m}), \ldots, u(x_{nj}))$$ (4)

$U(P_D)$ may be represented by variance, or, preferably, by a complete probability distribution of $P_D$ that better characterizes the total uncertainty. $U(P_D)$ as an estimator of the stochastic uncertainty can be calculated analytically, estimated by analytical approximation or modeled using Monte Carlo simulations (Heuvelink, 1998, 1999). Also, Knox-Robinson (2000) suggested a vector algebra model to represent and propagate uncertainty in fuzzy logic prospectivity modeling.

Variance of the final output map of a predictive GIS model, given uncertainties of the input parameters (evidential classes), can be easily estimated analytically only if the input parameters are combined using a simple linear function $F$ (Eq. (1)). However, this is not commonly applicable to fuzzy logic prospectivity modeling. Analytical solutions can also be found for non-linear mathematical operations but they can become very complex for a complex inference system and they have to be specifically formulated for each system. Therefore, precise analytical solutions are not generally applicable. In a more general case, an approximate analytical solution can be found using the Taylor series
method, based on a local linear approximation of mathematical operations (Taylor 1982). While such an approximate solution can sometimes give adequate estimates of variance of final modeling outputs, it also introduces approximation errors which may be difficult to quantify in a general case.

The Evidential Belief Function (Dempster, 1967, 1968; Shafer, 1976; An et al., 1994; Carranza, 2009) can be used to propagate estimates of subjective degree of uncertainty for individual input parameters and estimate combined degree of uncertainty. However, it is questionable if this is an appropriate way to express and model stochastic uncertainty. The resultant measure of uncertainty is not directly comparable to either variance or probability. Another potential drawback of this method is that it would need to be implemented in addition to a fuzzy logic prospectivity model (unless modeling is based entirely on an implementation of the evidential belief function, rather than fuzzy logic), which would create a new source of uncertainty of representativeness. The Evidential Belief Function has rarely been used in practical prospectivity modeling.

Knox-Robinson (2000) proposed to use vector algebra in fuzzy logic modeling, both as a new fuzzy logic combination operator and a means to model uncertainty. In the proposed approach, each input evidential class at each location is represented by a vector. Its direction reflects the fuzzy membership value of the class and the length represents a measure of confidence (the lower the confidence the shorter the vector, reducing to zero length for missing data). The confidence factor represents a combination of perceived relative predictive significance of the evidential class and confidence in the presence of the evidential class at a particular location (which depends on spatial precision and accuracy of classification). The individual evidential classes are combined into a final prospectivity measure by addition of the input vectors. The direction of the resultant vector represents fuzzy prospectivity and its length – a degree of confidence. In essence, the subjective confidence factor in the proposed vectorial fuzzy logic model acts as a weight of each input evidential map in the vectorial aggregation model, diminishing or even excluding influence of factors with high uncertainty. This may bias output results, in the same manner as the approach of Porwal et al. (2003a).

While specific measures of uncertainty, such as variance or degree of uncertainty, could be a valuable complement to a traditional deterministic fuzzy prospectivity map, their practical use in decision making may be not straightforward. For example, masking out areas with high uncertainty, as suggested by Bonham-Carter et al. (1989) for weights of evidence prospectivity maps, may exclude the best potential exploration targets only
because of a lack of an important input dataset or its low resolution. A common implicit assumption of the symmetry of errors around the mean of a distribution may be inappropriate for an output of a series of strongly non-linear operations which may result in a skewed and multi-modal statistical distribution. More powerful interpretations are possible if total uncertainty of a final modeling output $\mu_D$ is characterized not only by an estimate of its variance but also by an estimate of its complete probability distribution $P(\mu_D)$. The latter would allow, for example, the estimation of specific percentiles of the distribution, which can be important in decision making. This can be achieved through Monte Carlo simulations, which has been proposed as a robust method for explicit modeling of error propagation and estimation of total uncertainty of GIS-based modeling in geography and environmental sciences (Huevelink, 1998). A historic practical limitation for the use of Monte Carlo simulations to model complex systems due to the computational cost of running thousands of model iterations necessary to achieve accurate results is no longer applicable, due to the ready availability of fast computing and more efficient simulation algorithms (such as Latin Hypercube Sampling, Helton and Davis, 2003).

Modeling stochastic error propagation using Monte Carlo simulations thus appears to be a preferred choice for assessing total stochastic uncertainty of a fuzzy prospectivity map. Given that both stochastic and systemic (including fuzziness) uncertainties are ubiquitous in every mineral system model, it would be highly desirable to integrate fuzzy logic and probabilistic methods in a unified framework (Cheng and Agterberg, 1999). There are, however, significant questions regarding theoretical validity of applying probabilistic techniques to fuzzy systems (given that the fuzzy set theory has its own methodology typically exclusively used to study fuzzy sets) and practical implementation of those techniques within a fuzzy logic prospectivity model.

5. Proposed method – probabilistic fuzzy logic prospectivity modeling

5.1. Theoretical background and definition

In the classical definition of a fuzzy set (Eq. 2) – and all the previous applications of fuzzy logic prospectivity analysis – fuzzy membership value $\mu(x_i)$ is defined as a real number (e.g., 0.7). However, such a definition this ignores all the uncertainties associated with defining a precise membership value. For example, the membership value of object Ultramafic Rock in a set Metal Source could be defined as 0.8 – on the basis of expert
opinion or estimated by a fuzzy membership function of a measurable property (e.g., metal content in different rock types). In either case, $\mu$ cannot not be estimated precisely, as different experts (and even the same expert in a different situation!) are likely to have different opinions and metal content of any particular rock type is variable. A crisp definition of $\mu$ would preclude capturing this uncertainty and assessing its effect on an output fuzzy prospectivity map.

This limitation of a crisp definition of the fuzzy membership value has been addressed by the introduction of the concept of type-2 fuzzy sets, fuzzy membership values of which are in turn represented by fuzzy sets rather than real numbers (Zadeh, 1975; Mendel and John, 2002). Furthermore, if uncertainty of a fuzzy membership value can be adequately expressed in terms of stochastic uncertainty, then it would be more appropriate to define the fuzzy membership value as a random variable characterized by a probability density function (rather than a fuzzy set) – thus defining probabilistic fuzzy sets (Hirota, 1981; Liu and Li, 2005).

In a probabilistic fuzzy set, each estimate of the input fuzzy membership value $\mu(x_{ij})$ first needs to be represented by a probability distribution $P(\mu(x_{ij}))$ which would adequately reflect both the expected value of $\mu(x_{ij})$ and its uncertainty. In an ideal scenario of the absence of ambiguity of interpretation, uncertainty $u(\mu(x_{ij}))$ can be characterized as a combination of stochastic errors in the spatial dataset(s) which contributed to the definition of $\mu(x_{ij})$. An appropriate probability function can be assigned on the basis of statistical evidence or expert judgment. If $\mu(x_{ij})$ represents a composite input parameter, it should be first disaggregated into the elementary constituent elements, each represented by a probability distribution characterizing its individual stochastic uncertainty. For example, a fuzzy membership value for a distance-based evidential class, such as proximity to a granite, can be represented as a combination of two distinct independent factors: predictive power of the presence of a granite and a function characterizing change of that power with distance. Such disaggregation should minimize the errors of assigning a probability function for a composite factor, which often cannot be adequately represented by a simple theoretical unimodal distribution.

Uncertainty due to ambiguity (e.g., a disagreement on which specific class $x_{ij}$ is present at a given location, as well as non-uniqueness of the fuzzy inference engine itself) can also be represented in terms of a stochastic process. Each possible alternative interpretation, or version of the fuzzy inference engine, can be loosely interpreted as a manifestation of a higher order random process, characterized by its own probability
function. In a simple case of a relatively small number of possible alternatives (for example, several alternative fuzzy inference engines) which can be enumerated, \( P(\mu(D)) \) for each analysis cell can be estimated by mathematical aggregation of the individual alternative probability distributions \( P_n(\mu(D)) \)

\[
P(\mu(D)) = f(P_1(\mu(D)), P_2(\mu(D)), \ldots, P_n(\mu(D))) \tag{5}
\]

Linear pooling of the alternative probability distributions, weighted by their estimated relative probability, can be a robust and simple to implement default method of mathematical aggregation (Genest and Zidek, 1986; O’Hagan et al., 2006)

\[
P(\mu(D)) = \sum_{i=1}^{n} w_i P_i(\mu(D)) \quad | \sum_{i=1}^{n} w_i = 1 \tag{6}
\]

Outputs of this aggregation method reflect the full range of the input distributions and thus clearly characterize additional uncertainty due to the presence of conflicting interpretations or models. Any other aggregation method can be used instead, if deemed more appropriate. This process of aggregation of alternative interpretations can be integrated into the overall fuzzy inference engine. For example, different geological interpretations (none of which is demonstrably invalid) may assign a particular location to different rock types. Instead of choosing only one interpretation and ignoring the others, the contradictory interpretations can be considered as manifestations of uncertainty which needs to be assessed. As the alternative interpretations are all expressed in a probabilistic fuzzy logic model as fuzzy sets characterized by probability distributions of fuzzy membership values, they can be mathematically aggregated (e.g., by linear pooling) into one probability distribution indicating an elevated uncertainty.

In a general form, probabilistic fuzzy prospectivity at each location can be expressed as a probability distribution \( P(\mu(D)) \)

\[
P(\mu(D)) = F(P(\mu(x_{1k})), P(\mu(x_{2m})), \ldots, P(\mu(x_{ij}))) \tag{7}
\]

where \( P(\mu(x_{ij})) \) is a probability distribution of the membership value for the \( j \)th evidential class of the \( i \)th evidential map, which may be represented by a combination of \( k \) constituent parameters or a pool of \( k \) alternative possibilities, each of which is characterized by their individual probability distribution of \( \mu \). \( F \) and \( f_n \) represent a combination of mathematical operations of the fuzzy inference system applied to random variables representing the evidential classes and their constituent or alternative elements (if any), respectively. The operations need to take into account any correlations between the input random variables, as they may have a significant effect on the probability distribution of the output fuzzy prospectivity.
Implementation of the fuzzy inference engine based on random variables would require a Monte Carlo simulation, repeatedly sampling the input probability distributions and applying the mathematical operations of the fuzzy inference engine to the randomly selected values. Analysis can be performed entirely in a GIS software environment, but it would require additional customized tools (Gurdak et al., 2009) to perform Monte Carlo simulations using an adequate choice of theoretical and empirical probability functions. Alternatively, Monte Carlo simulations can be implemented outside a GIS environment, using any suitable general-purpose or specialized statistical software (Brown and Heuvelink, 2007). The outputs can be then brought back into GIS for further spatial analysis and visualization.

![Diagram of a simple probabilistic fuzzy logic prospectivity model.](image

Fig. 2 Structure of a simple probabilistic fuzzy logic prospectivity model.

Analysis can be more efficient if performed for each unique combination of spatially coincident classes of input targeting criteria (unique conditions of Bonham-Carter, 1994), rather than on a cell by cell basis, which can be computationally expensive for a relatively large number of analysis cells. Implementation of a simple probabilistic fuzzy logic model is illustrated by Fig. 2.

5.2. Application example – probabilistic fuzzy logic model for hydrothermal nickel deposits in western Victoria, Australia

5.2.1. Modeling process

The described probabilistic fuzzy logic method was used to model mineral prospectivity for hydrothermal nickel deposits in western Victoria, Australia, and
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uncertainty of the final prospectivity map (Lisitsin et al. 2013). A conceptual mineral system model for hydrothermal-remobilized nickel deposits associated with ultramafic-mafic complexes in a proximity of felsic intrusives was adopted from an earlier study of González-Álvarez et al. (2010). The conceptual and associated exploration targeting model and the corresponding fuzzy inference engine are illustrated by Table 1 and Fig. 3, respectively.

**Table 1.** Conceptual model of hydrothermal-remobilized nickel mineral systems in western Victoria – critical components, targeting elements and GIS proxies.

<table>
<thead>
<tr>
<th>Critical components / processes</th>
<th>Metal source</th>
<th>Mobilization of metal and fluids (Release)</th>
<th>Fluid pathways (Transport)</th>
<th>Metal deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent components / processes</td>
<td>Energy</td>
<td>Fluids</td>
<td>Ligands</td>
<td>Zones of enhanced fluid permeability</td>
</tr>
<tr>
<td>Targeting elements</td>
<td>Ni-rich rocks</td>
<td>1. Magmatic rocks</td>
<td>1. Fractionated granites</td>
<td>1. Fractionated granites</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1. Faults</td>
</tr>
<tr>
<td></td>
<td>2. Metamorphic rocks</td>
<td>2. Rocks with elevated Cl, CO_2, mobile S and C_{org}</td>
<td>2. Fold-related fracture systems</td>
<td></td>
</tr>
<tr>
<td>Targeting criteria (evidential classes)</td>
<td>1. Interpreted geology and lithogeochemistry (Ni content by rock type)</td>
<td>1. Interpreted geology (proximity to intrusive)</td>
<td>1. Interpreted geology (proximity to granites)</td>
<td>Interpreted geology and lithogeochemistry (Ni content by rock type)</td>
</tr>
<tr>
<td></td>
<td>2. Interpreted solid geology (proximity to Ni-rich rocks)</td>
<td>2. Interpreted metamorphic petrology (metamorphic grade)</td>
<td>2. Interpreted metamorphic petrology (metamorphic grade)</td>
<td>2. Interpreted geology and lithogeochemistry (S, C_{org}, CO_2 content by rock type)</td>
</tr>
</tbody>
</table>

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Fig. 3. Fuzzy inference engine (modified from Lisitsin et al., 2013). Potential local-scale metal deposition and fluid transport control factors (e.g., C- and S-rich rocks; minor faults and contacts of rocks with high rheological contrasts) were not included in this scheme, largely due to a lack of sufficiently detailed data with a consistent regional coverage.

The definition of probability distributions of fuzzy membership values for the evidential classes representing the targeting criteria was disaggregated into several discrete steps. This was done to minimize the complexity of tasks and thus reduce the associated uncertainty of largely subjective decisions. (i) For each categorical evidential class representing each targeting criterion, a suitable quantitative attribute was identified, so that it could be used as an indicator of the strength of association between the targeting
criterion and prospectivity. For example, interpreted rock types (categorical values) were characterized as potential sources of nickel on the basis of their nickel content (ratio values). This allowed a better constrained assessment of the expected fuzzy membership values and their uncertainty. (ii) The chosen quantitative attributes for each evidential class were characterized by three statistics: the expected, minimum and maximum values. (iii) Those statistics were transformed into fuzzy membership values using a selected fuzzy membership function. (iv) A probability distribution was fitted to the estimates of the expected, minimum and maximum fuzzy membership values (Lisitsin et al., 2013).

For example, the conceptual model indicated a strong association between hydrothermal nickel deposits and ultramafic-mafic magmatic complexes (particularly ultramafic rocks), which probably were the source of nickel. Therefore, proximity to a favorable rock type was identified as an important targeting criterion. The degree of likely favorableness of a particular rock type could be inferred from its nickel content – a relevant quantitative attribute of this categorical class. Olivine-rich ultramafic rocks (peridotites, dunites) are typically strongly enriched in nickel (2,000 to 3,000 ppm), compared to pyroxenites (~500 ppm), mafic magmatic rocks (~100 to 300 ppm) and intermediate to felsic magmatic rocks and sediments (<50 ppm). Expected, minimum and maximum nickel source fuzzy membership values \( \mu(x_{Ni}) \) for the individual lithological complexes \( x \) were estimated as their average, minimum and maximum nickel contents \( Ni(x) \), divided by an average nickel content of nickel-rich dunites \( (Ni_{(umaf)})_{max} \), accepted here to be equal to 3,000 ppm), thus constraining \( \mu(x_{Ni}) \) to the range [0,1]:

\[
\mu(x_{Ni}) = \frac{Ni(x)}{Ni_{max}(umaf)} \quad (8)
\]

For the evidential maps indicating proximity to a certain geological feature \( y \) (nickel-rich ultramafic and mafic rocks, granites, faults), the expected distance-based fuzzy membership values \( \mu_{y_i}(y) \) at distance \( i \), decreasing with distance, were adapted from expert estimates in González-Álvarez et al. (2010). Those estimates represent subjective probabilities which can be treated with probabilistic methods. To estimate uncertainty of the distance-based values, they were first expressed as a product of a constant \( \mu_{y_i}(y) \) at a zero distance and a variable distance decay coefficient \( d_i(y) \):

\[
\mu_{y_i}(y) = \mu_{y_i}(y) \times d_i(y) \quad d_i(y) \in [0,1] \quad (9)
\]
Ranges for the distance decay coefficients \( d_i(y) \) were subjectively estimated, guided by common alternative power distance decay functions (e.g., linear and inverse distance squared) which would provide realistic estimates of the lower and upper limits of \( d_i(y) \).

Subjective estimates of the expected, minimum and maximum values were interpreted to represent the estimates of the median, 5\(^{th}\) and 95\(^{th}\) percentiles of corresponding probability distributions – to account for typical human biases, such as underestimation of uncertainty (Meyer and Booker, 2001; O’Hagan et al., 2006). Probability functions \( P(\mu(x_{Ni})) \), \( P(d_i(y)) \), etc. were then defined as beta distributions fitted to the percentile estimates. Beta distribution (Krishnamoorthy, 2006; Forbes et al., 2011; Olea, 2011) was used as a default option because of its convenience, flexibility and perceived suitability for modeling uncertainty of the analyzed targeting criteria.

The geology of the vast majority of the study area could only be interpreted from regional geophysical datasets, with extremely limited borehole and surface mapping controls. As a result, GIS proxies for several critical exploration targeting criteria (e.g., the distribution of granites, nickel-rich rocks and faults) were represented by multiple, often contradictory, alternative interpretations. The study did not attempt to explain and reconcile the differences between alternative interpretations, or to choose a single preferred interpretation and disregard all the others. None of them could be unequivocally regarded as a gross error of interpretation incompatible with the available information. The multiple alternatives provided important information on uncertainty due to ambiguity of the primary geological datasets. To assess this uncertainty, the available alternative interpretations (up to four) were used as inputs to derive combined evidential maps through equal-weight linear opinion pooling (Genest and Zidek, 1986; O’Hagan et al., 2006), incorporated as intermediate steps in the fuzzy inference engine.

Finally, a probabilistic fuzzy prospectivity model was implemented by applying the operations of the fuzzy inference engine to the random variables representing fuzzy membership values for the input evidential maps representing targeting criteria using Monte Carlo simulations. GIS operations and visualization of final outputs were performed in ESRI ArcGIS® and Monte Carlo simulations were run in Oracle Crystal Ball™.

5.2.2. Modeling results

The final outputs of the probabilistic fuzzy logic model included a series of probability distributions of the fuzzy prospectivity, each representing a single unique condition, or a single unique spatial co-location of classes of individual targeting criteria maps. Those
probability distributions provided extensive information not only on the expected fuzzy prospectivity at each analysis cell but also on its uncertainty, giving an opportunity to quickly evaluate both downside risk and upside potential at each location. The means and the 90th and 10th percentiles (denoted as $P_{90}$ and $P_{10}$, respectively) of the resultant probability distributions of fuzzy prospectivity are illustrated by maps on Figs. 4 to 6.

The additional information on uncertainty allowed a finer differentiation between identified exploration targets based on the degree of consistency of spatial patterns at different probability levels. This information was also used to identify additional subtle high-risk targets and account for geochemical anomalies likely to be unrelated to potentially economic nickel mineralization. For example, the southernmost group of targets highlighted at all three presented probability levels (target 1, Figs. 4 to 6) includes a prospect with the best exploration results for hydrothermal nickel mineralization obtained to date in the region (including 9.5 m @ 0.3% Ni in drilling, Beaconsfield Gold, 2008). Those detailed exploration results were not used as inputs in the prospectivity analysis which only utilized regional-scale geological datasets. On the other hand, a group of easternmost targets most prominent at the $P_{10}$ level (target 2, Fig. 6) represent regional rock types (mafic igneous rocks) only moderately enriched in nickel and located proximal to granite intrusions.

6. Discussion and conclusions

The proposed method of probabilistic fuzzy logic prospectivity modeling using Monte Carlo simulations to assess uncertainty of model outputs can provide much more information compared to traditional fuzzy logic prospectivity analysis. A key advantage of the proposed approach is that, in addition to identifying exploration targets, it characterizes prospectivity and its uncertainty for each location in a study area, taking into account various identified data and model uncertainties due to stochastic error, fuzziness and ambiguity. This information can be used for a detailed subsequent risk analysis for the identified exploration targets. It can also be used to identify most significant sources of uncertainty of a final mineral prospectivity map, leading to additional targeted data acquisition or research to reduce uncertainty. Probabilistic fuzzy logic prospectivity modeling can be easily implemented using a combination of any standard GIS software suitable for raster spatial data analysis and visualization and statistical software for Monte Carlo simulations.
The reconnaissance regional prospectivity analysis used in this paper to illustrate the proposed approach and some of its potential outputs did not define a complete uncertainty model, focusing only on selected identified sources of uncertainty deemed most significant for model results. Definition of a complete well-defined uncertainty model could result in a much more complex inference system and involve a more challenging and time-consuming process. Such a complete uncertainty model probably would not be warranted in every application of prospectivity modeling, depending on its purpose and requirements. A choice on the desired degree of completeness and sophistication of an uncertainty model will ultimately represent a trade-off between the additional benefits of a more accurate quantified estimate of the prospectivity model uncertainty and the added cost of producing the model. In practice, uncertainty models are likely to always be incomplete. But even a partial definition of the uncertainty model, focusing only on the most important identified sources of uncertainty, with an approximate definition of individual probability distributions and correlations between them, would provide significant additional information at a reasonably small additional modeling cost.

The probabilistic fuzzy logic analysis can be potentially applied to effectively model uncertainty of complex fuzzy systems in any area of geosciences.
Fig. 4. Fuzzy mineral prospectivity (means) map for hydrothermal nickel deposits in western Victoria. Colors correspond to means of fuzzy prospectivity statistical distributions for the individual analysis cells.
Fig. 5. Fuzzy mineral prospectivity \( (P_{90}) \) map for hydrothermal nickel deposits in western Victoria. Colors correspond to 90\(^{th}\) percentiles of fuzzy prospectivity statistical distributions for the individual analysis cells.
Fig. 6. Fuzzy mineral prospectivity ($P_{10}$) map for hydrothermal nickel deposits in western Victoria. Colors correspond to 10th percentiles of fuzzy prospectivity statistical distributions for the individual analysis cells.

References


Chapter 9

DISCUSSION: INTEGRATED REGIONAL MINERAL PROSPECTIVITY ANALYSIS – TOWARDS A SYNTHESIS OF ISOLATED TOOLS AND AREAS OF RESEARCH

1. Introduction

A wide variety of approaches, individual methods and tools have been developed and applied to assess mineral prospectivity of a study area. There have been major advances in the development of statistical methods of geoscientific data and integration for predictive mineral prospectivity modelling (Harris, 1984, Harris and Agterberg, 1981; Agterberg, 1984, 1989; Bonham-Carter, 1994; Carranza, 2009). Mathematical simulation algorithms now allow modelling of certain metallogenic processes, notably deformation and fluid flow, predicting locations of preferred deposition sites for hydrothermal mineralisation. Quantitative mineral resource assessments focus on quantifying probable mineral endowment of large areas – rather than identifying specific deposit-scale targets within them (Allais, 1957; Singer and Menzie, 2010; Guj et al., 2011). Mineral system studies strive to develop a better conceptual understanding of significant geological processes leading to the formation of mineral deposits at different scales.

An apparent limitation of all of the available methods is that, when used in isolation, each of them inevitably focuses only on a specific aspect of mineral prospectivity. While this is not a significant problem for many practical applications, narrowly focused mineral prospectivity assessments would often benefit from utilising knowledge, methods and tools developed in adjoining areas of research. The current research aimed to investigate and demonstrate potential benefits of an integrated approach to assess mineral prospectivity of a region – synthesising disparate methods and tools. The following discussion summarises the major research outputs and lessons learnt.

2. Compilation, analysis and processing of mineral deposit information

The essential first step in any form of mineral prospectivity analysis is a systematic compilation, analysis and pre-processing of all the relevant geological information characterising target deposit type(s) and their likely metallogenic controls. In a region
representing a known mineral province, or its part (such as extensions under cover), information on known mineralisation is critically important. It is by no means the only type of geological information critical to understand mineral systems which operated (or may have operated) in a region and necessary for meaningful prospectivity modelling aiming to predict likely scale and spatial distribution of undiscovered mineral deposits. However, it provides the most direct evidence that one or more mineral systems were actually in operation within the region and information on their nature, likely fertility and direct metallogenic controls. Therefore, in the research described in this thesis, a particular attention was given to dealing with such direct metallogenic information.

Even if relevant and reasonably complete mineral occurrence datasets are readily available (which is generally the case across Australia), it is still a responsibility of a prospectivity assessment team to ensure that the input mineral occurrence data (as well as the other datasets containing mineral system information) are fit for the intended purposes. For many applications, it is the single most important step of analysis, largely pre-determining analysis outcomes. A major part of this research involved a detailed analysis and processing of mineral occurrence data originally sourced from existing mineral occurrence databases of the geological surveys of Victoria and Queensland. The databases were mostly compiled in the 1990-s – early 2000-s, often on the basis of earlier pre-digital compilations and maps. Analysis of the databases revealed significant deficiencies, particularly related to grade and tonnage production statistics for historic mining. Such deficiencies could significantly affect mineral prospectivity assessment results. To minimise this risk, the mineral occurrence data were reviewed and validated using various available published and unpublished sources.

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An important consideration was a consistent definition of metallogenic objects representing desired prediction targets, consistent with the scale and objectives of mineral prospectivity studies and possible practical mineral exploration decisions (McCuaig et al., 2010). The studies conducted as part of this research were of a regional scale, in each case covering areas of tens of thousands of square kilometres. The main focus was mainly on the assessment of the total probable undiscovered endowment of a region and the identification of significant regional metallogenic controls operating at a scale of tens to hundreds of kilometres. Total metal endowment of a mineral province is generally overwhelmingly dominated by a relatively small proportion of larger deposits. Ultimately, a useful predictive modelling outcome would be to identify potential locations and properties of mineral deposits – not mineral occurrences. Accordingly, validated mineral
occurrence data was aggregated (by dominant mineralisation style) to characterise ore fields – clusters of adjacent mineral occurrences of a particular mineralisation style which could ideally developed as individual deposits.

Compilations of spatial and grade and tonnage information for ore fields in central Victoria and north Queensland (Appendices 1-4), as well as the underlying validated mineral occurrence datasets, were extensively used as major inputs in most individual studies completed as part of this research and thus constitute its major outputs which could be used in subsequent studies.

3. Exploratory spatial data analysis

Exploratory spatial data analysis investigates major properties of the spatial distribution of geographic objects within a study area, systematically using a suite of complementary methods of spatial data analysis (Gelfand et al., 2010). Apparently, this type of data analysis is not directly related to predictive modelling in a strict sense, as its many applications only describe spatial patterns of known objects, rather than predict locations and other properties of unknown ones. However, results of such exploratory analysis applied to mineral deposits can provide critical insights into the spatial properties of mineral systems which operated in a region under investigation, with major implications for subsequent predictive mineral prospectivity mapping, quantitative mineral resource assessment and exploration targeting.

Chapter 4 illustrates extensive exploratory spatial data analysis of mineral deposit point patterns in two orogenic gold provinces – in north Queensland and central Victoria (Lisitsin, 2015). The studies demonstrated strong regional spatial heterogeneity in the distribution of gold deposits in both investigated regions. In particular, distinct linear metallogenic zones exist in both the Hodgkinson Province in Queensland and the Bendigo Zone in Victoria. The linear metallogenic zone in the Hodgkinson Province is particularly pronounced, including almost all known significant gold deposits and the majority of gold occurrences. In the Bendigo Zone, the linear metallogenic zone is expressed by an alignment of the largest primary gold ore fields, while smaller ore fields have a much wider regional distribution. Both regional metallogenic zones are oblique to the dominant regional geological structures and could not be related to any of the recognised major faults.

Spatial statistical analysis of mineral occurrences indicates their strong clustering at all scales. However, results of the standard statistical test of clustering are overwhelmingly dominated by local-scale (hundreds to a few thousands of metres) clustering of occurrences
into ore fields. Spatial statistical tests of the distribution of ore fields could be mistakenly interpreted to indicate their regional-scale clustering but are in fact affected by their strong concentration in linear metallogenic zones. Within each zone, the distribution of ore fields is not clustered (as commonly assumed) but random, with possible dispersion tendencies. The latter has potential implications for exploration targeting. While it is intuitively appealing to focus exploration on areas proximal (<20 km) to a known significant ore field, exploration successes following this strategy are likely to result in only incremental discoveries. If a desired target is not an extension of a known ore field or a smaller satellite deposit but another significant ore field, then exploration should focus on more distal areas.

Outputs of the exploratory spatial data analysis (including the recognition of the linear metallogenic zones) informed a subsequent general mineral system analysis (Chapter 5; Lisitsin and Pitcairn, 2015) and quantitative mineral resource assessment (Chapter 6; Lisitsin et al., 2014a). For example, a failure to take into account the existence of the linear metallogenic zone in the Hodgkinson Province and its underlying geological controls could lead to grossly biased results of a quantitative mineral resource assessment and regional exploration targeting, as discussed in Chapter 6. Additionally, an indicated lack of a direct spatial association between gold deposits and recognised major regional faults in both regions also has significant metallogenic and exploration targeting implications.

4. Mineral system analysis

Systematic exploratory data analysis provides a set of powerful tools which may reveal important properties of the spatial distribution of known mineralisation at different scales and highlight spatial associations between mineral deposits and other geological features. However, used without a close cross-validation using broader geoscience knowledge of natural metallogenic processes, the spatial statistical tool set would lack a proper direction and its applications may be at best inefficient and at worst – result in flawed conclusions contradicting a complex reality of a natural system which produced mineralisation. Also, for the purposes of mineral prospectivity analysis and exploration targeting, it is an auxiliary toolset, facilitating but by no means substituting a subsequent geological analysis. A general metallogenic review of target mineralisation within a study region, or, preferably, a more structured mineral system analysis, can guide and validate spatial statistical results – and provide a direct framework for prospectivity analysis.
The main general objective of a mineral system analysis is to identify significant natural processes which jointly led to the formation and preservation of one or more genetically related types of mineral deposits within a region. This includes recognising expressions of the natural processes in geological datasets. While direct results of such an analysis generally allow only a definition of a conceptual model describing the structure and operation of a mineral system, they also may offer a robust framework for a subsequent predictive mineral prospectivity analysis (Knox-Robinson and Wyborn, 1997; Kreuzer et al., 2010; Czarnota et al., 2010; McCuaig et al., 2010).

In this research, a general conceptual mineral system analysis was an essential first step in knowledge-driven GIS modelling of mineral prospectivity of western Victoria for hydrothermal nickel deposits (Chapter 3). It was also integrated into comprehensive regional prospectivity assessments of the Hodgkinson Province in north Queensland and the Bendigo and Stawell zones in central Victoria for orogenic gold mineral systems (Chapters 5-6), linking findings of exploratory spatial statistical analysis (Chapter 4) with quantitative mineral resource assessments and regional exploration targeting.

In particular, this research (Lisitsin et al., 2014a, Lisitsin and Pitcairn, 2015) has indicated that the major regional linear metallogenic zones are related to deep crustal domain boundaries in the Hodgkinson Province (north Queensland) and the Bendigo Zone (central Victoria). In both regions, the crustal domain boundaries have only subtle expressions in the geological datasets traditionally used for mineral prospectivity mapping of orogenic gold mineral systems. While earlier research has previously postulated the existence of the lower crustal domain boundary in the Bendigo Zone (Cayley, 2011) and its potential metallogenic significance (Wilson et al., 2009; Hronsky et al., 2012), the presence of a similar metallogenic control in the Hodgkinson Province has been first documented by this research (Lisitsin et al., 2014a).

5. Mineral prospectivity modelling

Discussions of the processes of aggregating multiple spatial evidential datasets into a single prospectivity map by implementing certain mathematical algorithms in a GIS environment and relative performance of alternative algorithms commonly dominate publications on mineral prospectivity modelling. However, data aggregation should represent only a relatively minor late stage of a much wider mineral prospectivity analysis. The critical importance of the preceding stages (as discussed above) and the extent of their influence on the modelling outputs cannot be overstated.
Regardless of the relative strengths of different prospectivity modelling methods, the choice of one or more methods to be used in a particular study should mostly depend on the main objectives and constraints of the study. For certain practical purposes, such as government regional land use planning, or reconnaissance identification of regional-scale targets for a more detailed subsequent evaluation, a rapid GIS-assisted delineation and classification of broad tracts of land, based on expert judgement supported by general metallogenic considerations and other relevant readily available information, may be adequate. This approach is briefly illustrated by Chapter 2.

Modelling mineral prospectivity for camp-scale exploration targeting within a region with few known mineral occurrences of a target type requires an extensive conceptual mineral system analysis, translated into an appropriate mathematical data aggregation model implemented in a GIS environment. This is illustrated by an implementation of knowledge-driven fuzzy logic prospectivity modelling discussed in Chapter 3.

From a theoretical point of view, high estimated mineral prospectivity, suggesting an elevated probability of occurrence of a target mineral deposit, could be considered the sole critical factor in exploration ground selection. However, it is not sufficient for practical decision making which also needs to take into consideration other factors – such as the presence and thickness of post-mineralisation cover, land use restrictions, proximity to essential infrastructure etc. Such extraneous factors, affecting the probability of discovery and development of any present mineral deposit, can be included in predictive modelling of exploration potential, a broader concept including mineral prospectivity (Chapter 3, Lisitsin et al., 2013).

The evidential datasets to be used in prospectivity mapping need to jointly represent a balanced reflection of a relevant mineral system – consistent with the scale of analysis. Over-representation of individual components of a mineral system (by using multiple related datasets) and mixing datasets characterising a mineral system at significantly different scales (e.g., regional tectonic setting and prospect-scale exploration geochemistry) is likely to lead to biased or unrepresentative models of mineral prospectivity. Regional-scale prospectivity analysis (including quantitative mineral resource assessments) needs to carefully investigate metallogenic implications of potential subtle regional metallogenic controls suggested by exploratory spatial data analysis (Chapter 4) and supported by subsequent regional mineral system analysis (Chapter 5).
6. Quantitative mineral resource assessments

Quantitative mineral resource assessments aim to quantify total undiscovered mineral endowment in relatively large tracts of land. They are quite often conducted independently from GIS-based mineral prospectivity modelling and do not explicitly include extensive spatial data analysis. However, quantitative assessments provide critical additional information, indicating probable properties of undiscovered deposits (if any) and thus supporting analysis of a potential business case for exploration decisions. On the other hand, as shown in Chapter 6, spatial properties of a mineral system may have major implications for a quantitative mineral resource assessment. In particular, a failure to recognise and appropriately account for the spatial trends in the distribution of largescale metallogenic controls can result in strongly biased assessment results. This risk of bias is particularly great when a quantitative mineral resource assessment is based entirely on statistical methods and does not utilise expert judgement as a critical part of the study. An analysis of any internal metallogenic trends and heterogeneities within a study region is recommended at the stage of delineation of permissive tracts in the three-part form of assessment (Singer and Menzie, 2010). This can be significantly assisted by outputs of exploratory spatial data analysis (Chapter 4) and broad mineral system analysis (Chapter 5), informing expert analysts delineating permissive and prospective tracts.

Rank-size statistical models, such as Zipf’s law (Guj et al., 2011, Merriam et al., 2004), can be used for an independent reconnaissance assessment of a likely scale of total natural and residual mineral endowment in a relatively well explored mineral province (as illustrated by Chapter 8). However, such simple statistical models strongly rely on the validity of just one or two critical assumptions. For example, an assessment based on Zipf’s law typically assumes that the largest deposit in the region has been found and adequately evaluated. Thus, in a general case, Zipf’s model could provide a measure of minimum residual endowment. Testing model assumptions using various scenarios can provide a (largely qualitative) measure of uncertainty of prediction results (Chapter 7). Regional-scale predictions for the Mossman and Western Lachlan orogens based on the tested rank-size power-law statistical models are generally consistent with quantitative assessment results based on the three-part form using expert judgment and general density regression model of Singer and Kouda (2011) as discussed in Chapter 6. This provides further confidence in the validity of the obtained quantitative assessment results.

If the main objectives of a mineral prospectivity analysis include broad regional- to camp-scale exploration targeting, it may be advisable to perform at least a high-level
quantitative mineral resource assessment before implementing any more detailed mineral prospectivity modelling. This would explicitly test an assumption that a particular region contains undiscovered deposits of a minimum size consistent with a company strategy. This is typically done implicitly, following empirical qualitative strategies like “elephant country” and “first mover” (Hronsky and Groves, 2008).

7. Uncertainty in mineral prospectivity mapping and quantitative mineral resource assessments

All the inputs of any prospectivity modelling (including the conceptual and mathematical models themselves) are characterised by significant uncertainty, regardless of the choice of a philosophical approach or a specific technique. Error, bias, fuzziness and ambiguity affect all stages of geoscientific work contributing to predictive mineral prospectivity modelling – from collection of primary observations and measurements to automated integration of derivative datasets and interpretation of modelling results. The numerous uncertainties of the input factors and models then propagate into the modelling results complicating their interpretation and use in decision making.

The three-part form of quantitative mineral resource assessment (Singer and Menzie, 2010, illustrated by an application discussed in Chapter 6) is designed to explicitly assess uncertainty of modelling results, greatly facilitating any subsequent decision making. In a stark contrast, other typical applications of mineral prospectivity modelling do not adequately deal with the problem of uncertainty. Some standard GIS-based mathematical models of data integration (such as weights of evidence, Bonham-Carter et al., 1988, Bonham-Carter et al., 1990, and the Dempster-Shafer belief function, Shafer, 1976; Carranza et al., 2008, 2009) provide only partial measures of uncertainty of model outputs. The other models ignore the problem of uncertainty altogether, not giving a decision maker any indications on a range of possible alternative modelling outputs thus impeding a meaningful risk analysis.

This research reviewed main types and sources of uncertainty in mineral prospectivity modelling and developed a new approach to explicitly define uncertainties of individual input factors and propagate them through a computational algorithm to evaluate the combined uncertainty of a prospectivity map - the probabilistic fuzzy logic method (Chapter 8, Lisitsin et al., 2014b).
8. Discussion

Various practical applications of mineral prospectivity assessment have almost universally focused only on a particular aspect of mineral prospectivity using a limited set of methods and tools. Any incremental improvements of existing tools and methods of prospectivity mapping, while necessary, are not sufficient for a major improvement of the effectiveness of exploration targeting.

A common deficiency of the vast majority of current prospectivity modelling methods is their almost universally deterministic nature. They do not explicitly address uncertainty and assume the accuracy and representativeness of the input data, knowledge and mathematical models. This does not only prevent a robust risk analysis but also creates a major risk of biasing modelling results. While the probabilistic fuzzy logic method developed in this research offers a framework for assessing uncertainty in mineral prospectivity mapping, it does not provide a universal way of modelling uncertainty generally applicable in all situations. It is critical to maintain focus on the problem of uncertainty in mineral prospectivity modelling and further research is certainly warranted.

Narrowly focused prospectivity mapping, or a quantitative mineral resource assessment, risks an omission of significant prospectivity factors not recognised by an initial conceptual model and not clearly expressed in the compiled datasets. Such an omission, introducing unrecognised bias, could be prevented by broadening the scope of investigation to consider other aspects and indicators of mineral prospectivity – and utilising a complementary set of methods and tools. This research highlighted a critical metallogenic importance of deep crustal domain boundaries with only subtle expressions in the surface geology as major regional-scale controls on the distribution of orogenic gold mineralisation. They are not related to any recognised crustal-scale faults. The significance of such cryptic deep crustal or lithospheric metallogenic controls has lately received a growing recognition and their early identification should be a major focus of regional exploration targeting in poorly explored geological terranes.

Transforming narrow prospectivity mapping into an exploration targeting system within a unifying mineral system framework (McCuaig et al., 2010) is a major move towards such an integrated mineral prospectivity analysis. The current research has further illustrated potential benefits of an integrated approach to prospectivity analysis as a comprehensive synthesis of currently isolated fields of research and their respective concepts, methods and tools. Further development of such an integrated approach is needed to significantly improve the effectiveness of predictive mineral potential modelling.
and exploration targeting. It will encompass the whole gamut of geological, and even psychological, research areas: traditional economic geology, mineral system studies, exploratory spatial data analysis, mineral potential mapping and data integration, expert judgement and psychology of human decision making.

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MINERAL PROSPECTIVITY ANALYSIS
AND QUANTITATIVE RESOURCE ASSESSMENTS
FOR REGIONAL EXPLORATION TARGETING:
DEVELOPMENT OF EFFECTIVE INTEGRATION
MODELS AND PRACTICAL APPLICATIONS

VOLUME 2: APPENDICES

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<td>Stuart Mill</td>
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<td>2.32</td>
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<td>380</td>
</tr>
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<td>2.33</td>
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<td>2.34</td>
<td>Wildwood</td>
<td>385</td>
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<td>2.35</td>
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</tbody>
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Appendix 1

EPIZONAL OROGENIC GOLD ORE FIELDS IN THE MELBOURNE ZONE, VICTORIA

Presented as originally published (with minor changes) in:

1. Introduction

This appendix (published as GSV Technical Record 2011/2) provides brief summary information on primary epizonal orogenic gold ore fields in the Melbourne Zone in central Victoria. This compilation excludes alluvial gold deposits and numerous primary gold deposits in the Walhalla–Woods Point Belt (including the Foster ore field) in the eastern part of the Melbourne Zone. Those deposits were recently reviewed by Vandenberg et al. (2006).

To ensure consistency and avoid bias in assessing undiscovered endowment, information has been compiled for gold ore fields, defined as areas of mineralisation in which adjacent orebodies are less than 1.6 km apart (Lisitsin et al., 2007, 2010a, 2010b). Their extent is similar (and often identical) to historic goldfields or clusters of goldfields. Gold mineralisation in the ore fields reviewed in this report is characterised by the prevalence of refractory, or ultra-fine (usually <10 μm), gold in sulphide grains (arsenopyrite and pyrite in thin veins and stockworks or disseminated in host rocks), or by free and submicroscopic gold in stibnite–quartz veins. Ores in these deposits have anomalously high concentrations of antimony (usually >100 ppm Sb) and often contain stibnite, either as a minor component in quartz - pyrite - arsenopyrite refractory gold deposits or as a major to dominant mineral in stibnite–quartz veins. Most gold deposits in the Melbourne Zone outside the Walhalla–Woods Point Belt are classified in this report as epizonal orogenic gold deposits. Common properties of these deposits have been reviewed by Lisitsin et al. (2010a, b).

For eight largest ore fields reviewed in this report and used in the grade antonmage model in Lisitsin et al. (2010a), we estimated properties of original pre-mining gold endowment following the process described in Lisitsin et al. (2007, 2010b). Original in situ
ore tonnages (T) and grades (G) were calculated from estimated processed ore tonnages and recovered grades by applying assumed ore dilution and gold recovery factors:

\[ T = \frac{T_{\text{proc}}}{1 + D} \]

where \( T_{\text{proc}} \) is a processed ore tonnage and \( D \) is ore dilution expressed as a proportion, and

\[ G = G_{\text{rec}} \times \frac{1 + D}{R} \]

where \( G_{\text{rec}} \) is a recovered grade and \( R \) is gold recovery expressed as a proportion.

This does not take into account ore loss due to ore le in the ground and ore loss during mining and transportation, thus resulting in a probable underestimation of in situ tonnages and gold contents. Unless deposit-specific information was available, we calculated original in situ grades and tonnages by assuming gold recoveries of 80% and ore dilutions of 10% for historic mining and 30% for recent large-scale open-cut mining.

Recorded sale prices of bullion smelted at epizonal orogenic gold mines in the Melbourne Zone indicate that most of the smelted metal contained 3% to 7% silver. Accordingly, we adjusted original gold endowments and gold grades estimated for the ore fields in the Melbourne Zone to exclude contained silver.

The main sources of information on the spatial distribution of gold deposits and gold production used in this report were corporate databases of the Department of Primary Industries (Victoria) – VicMine (Heap, 1998), VicProd (a database of gold production records compiled from official records of the Government of Victoria and maintained by GSV), GIS datasets of the mineral areas (Weston and Nott, 1993) and mapped auriferous quartz reefs. Additional information was derived from various other published and unpublished sources (referenced in the text) as required – mostly for larger ore fields with > 1 t of total primary gold production. A large part of gold production in the Melbourne Zone took place in the 19th and early 20th centuries. This historic gold production was often poorly documented, especially for smaller goldfields. Consequently, ore field gold grades and tonnages presented in this report are only approximate estimates based on incomplete information of variable quality. For smaller ore fields, the estimates of gold and ore tonnage are almost always conservative and the estimates of ore grades may be unrepresentative as they were based on only partial information.

The coordinates used in this report are based on GDA 94 datum (MGA Zone 55).
2. Ore Fields in the Melbourne Zone

2.1. Acheron

2.1.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 383 499 E, 5 872 900 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality(^2)</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^2\) Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.4</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.1.2. Description

The Acheron ore field contains one mine, (VicMine; O’Shea et al., 1992; Kenny, 1939b). It occurs within the outcrop of the Upper Devonian Walhalla group sediments.

2.1.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>10.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>263</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>41</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

*The largest producer in this ore field is:*

Acheron Mine, (VicMine ID 419216), with recorded production of 10.8 kg gold from 41 t ore.
Appendix 1

2.1.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>10.8</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>10.8</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.1.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs, with possible association to nearby dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 36 m length, 35 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Reef strike 329°, dip 75° E</td>
</tr>
</tbody>
</table>

2.1.5. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, mudstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Acheron ore field
2.2. Alexandra

2.2.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 386 773 E, 5 883 428 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

3 Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.8</td>
<td>7.5</td>
<td>280°</td>
<td>5.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.2.2. Description

The Alexandra ore field contains four named mines, (VicMine; O’Shea et al., 1992; Kenny, 1939a; Kenny, 1940b; Dunn, 1907c). The Galatea and other mines to the west were all assigned to this ore field since they appear to be related to, and either side of, the same anticlinal axis. They lie within the outcrop of the Upper Devonian Norton Gully sandstone.

2.2.3. Production and endowment

Historic production

| Historic gold production, kg | 10.5 |
| Recovered grade, g/t | 85 |
| Processed ore, t | 124 |
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

Estimated pre-mining endowment

| Contained gold, kg | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t | unknown |

Notes on production records

The largest producer in this ore field is Galatea Mine, (VicMine ID 420907) with production of 10.5 kg gold from 124 t ore.

Other mines in this ore field include the Luckie, Homeward Bound and Mysterious lines of reef.
2.2.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>10.5</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>10.5</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft and open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.2.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs, with possible association to nearby dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 60 m length, 137 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Reef strike 339°</td>
</tr>
</tbody>
</table>

2.2.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Alexandra ore field
2.3. Bailieston

2.3.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 325 609 E, 5 932 035 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

* Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3</td>
<td>6.8</td>
<td>330°</td>
<td>6.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

2.3.2. Description

The Bailieston ore field contains thirteen named reefs and mines (VicMine; O’Shea et al., 1992; Edwards et al., 1997).

It occurs within the outcrop of Upper Silurian Broadford Formation and Silurian to Devonian Puckapunyal Formation.

2.3.3. Production and endowment

**Historic production**

| Historic gold production, kg | 675 |
| Recovered grade, g/t | 20 |
| Processed ore, t | unknown |
| Recent gold production (1996–2000) | 329 |
| Current resource / reserve (12/2008) | none |

**Estimated pre-mining endowment**

| Contained gold, kg | 1240 |
| In situ ore tonnage, t | 471,000 |
| In situ grade, g/t | 2.6 |

**Notes on production records**

The overall grade for this field is low due to the diluting effect of the large amount of low-grade ore mined in the 1990’s in the Bailieston open pit.

The main producers listed in VicMine are:

- Hill 158 Bailieston Open Pit (VicMine ID 372184) with a production of 222.5 kg gold;
- London Main Reef (VicMine ID 371986) with a production of 156.5 kg gold;
- Byron Reef (VicMine ID 371968) with a production of 90.3 kg gold;
- Cherry Tree Reefs (VicMine ID 372205) with a production of 43.3 kg gold;

The historic gold production for this ore field is taken from Edwards et al. (1997) and Sebek (1998). Additionally, in 1996–2000, Perseverance Corporation Ltd produced 329 kg of gold from Hill 158 Bailieston Open Pit (VicProd), at a recovered grade of ~0.6 g/t. Assuming 10% dilution, 80% gold recovery and 5% Ag included in produced gold bullion for the historic production and 30% dilution and 75% gold recovery for the modern mining, combined original in situ gold endowment for the Bailiecurston ore field is estimated as 1240 kg Au from 471,175 t ore @ 2.6 g/t.

### 2.3.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>7</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>222.5</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>4</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>548</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>100 m</td>
</tr>
</tbody>
</table>

### 2.3.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 200 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>variable</td>
</tr>
</tbody>
</table>

### 2.3.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, porphyry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Bailieston ore field
2.4. Benalla

2.4.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 404 752 E, 5 949 799 N</th>
</tr>
</thead>
</table>

Ore field data quality\(^5\)  
1

\(^5\) Excludes production data, confined to detail and scope of technical information,  
1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>13.3</td>
<td>315°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.4.2. Description

The Benalla ore field contains fourteen mines and ten identified reefs (VicMine; Ferguson, 1899, O’Shea et al., 1992; Gibson, 1988). It occurs within the outcrop of Silurian and Devonian sedimentary rocks.

2.4.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>186.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>Up to 31 (Royal Mail Extended)</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>7</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

There is recorded production from the:

- Ajax Reef (VicMine ID 362416) with production of 46.6 kg gold;
- Golden Queen mine with production of 31 kg gold;
- Lion Claim (VicMine ID 362414) with production of 0.1 kg gold from 7 t ore;

Other named mines in the ore field include the Benalla, the Standard, the Golden Crown, the Lion (worked to a depth of 64 m), the Golden Queen and the Royal Mail.
However, Gibson (1988) quotes a total production of 186.6 kg from this area (referred to as “Reef Hills”). This later value is accepted as the production for this ore field.

### 2.4.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>14</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>3</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>46.6</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>2</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>77.7</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>70 m</td>
</tr>
</tbody>
</table>

### 2.4.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs and stockworks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length up to 5 km</td>
</tr>
<tr>
<td>Orientation</td>
<td>305° (Benalla)</td>
</tr>
</tbody>
</table>

### 2.4.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, slate, shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.5. Bonnie Doon

2.5.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 397 328 E, 5 900 882 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality(^6)</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^6\) Excludes production data, confined to detail and scope of technical information:
1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>1.7</td>
<td>45(^o)</td>
<td>2.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.5.2. Description

The Bonnie Doon ore field contains two mines (VicMine; Dunn, 1917). It occurs within the outcrop of the Upper Ordovician Mount Easton Shale, the Lower Silurian Jordan River Group and the Upper Devonian Humevale Siltstone.

2.5.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>3.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>197</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>20</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The only producer in this ore field is:

- Bonnie Doon Mine (Dunn, 1917) with production of 3.9 kg gold from 20 t ore. A second, unnamed shaft was sunk to the south of the mine, but did not intersect the reef.

Reported production only refers to the first crushing – presumably a considerable amount of gold mined subsequently went unreported.
2.5.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>2</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>3.9</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>3.9</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>27</td>
</tr>
</tbody>
</table>

2.5.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with Palaeozoic conglomerate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>27 m depth</td>
</tr>
</tbody>
</table>

2.5.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>Amphibolite grade as inferred from the presence of wollastonite</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Bonnie Doon ore field
2.6. CAMBRAVILLE

2.6.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 403 224 E, 5 840 884 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

\(^7\) Excludes production data, confined to detail and scope of technical information, 
1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>minor</td>
<td>320°</td>
<td>6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.6.2. Description

The Cambraville ore field contains five mines (VicMine; Kenny, 1918; Kenny, 1939c). It occurs within the outcrop of the Middle Devonian cathedral Group and the Upper Devonian Norton Gully Sandstone and Montys Hut Formation. The five mines have been combined into a single ore field, despite distances between these mines exceeding 800 m in some cases. Note that the shape is irregular and orientation and dimensions are nominal only.

2.6.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>186.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>30.3</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>6134</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The main producer in this ore field was: The Golden Bower Mine (VicMine ID 421012), with production of 166.4 kg gold from 5009 t ore.

The Cumberland Falls Mine, originally known as Kerwins Reward (VicMine ID 914919), produced about 20 kg gold from 1125 t ore.
Other mines in this ore field include the Sovereign Mine (VicMine ID 914911), the Victorian Mount Morgan Mine (VicMine ID 914920) and the Chester and Lockes Gold Mine (VicMine ID 914917).

2.6.4 Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>8</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>166.4</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>186.4</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.6.5 Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Depth 20 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 343°</td>
</tr>
</tbody>
</table>

2.6.6 Host rocks

| Host rock types                             | Sandstone, dyke                   |
| Metamorphism                                | unknown                           |
| Structural history                          | unknown                           |
2.7. Costerfield

2.7.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 302 405 E, 5 915 488 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

* Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.8</td>
<td>9</td>
<td>340°</td>
<td>7.5</td>
<td>3</td>
</tr>
</tbody>
</table>

2.7.2. Description

The Costerfield ore field contains twenty named reefs and mines (VicMine; Edwards et al., 1998; Price, 1996). It occurs within the outcrop of Upper Silurian McIvor Sandstone and Lower to Upper Silurian Dargile and Broadford Formations.

2.7.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>15–20</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>183 100</td>
</tr>
<tr>
<td>Recent gold production (1995–2009), kg</td>
<td>900</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>331,000 t ore @ 11.4 g/t Au for 3.8 t Au (including 3.3 t Au as Measured and Indicated Resources)</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>7,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>465,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>15</td>
</tr>
</tbody>
</table>

**Notes on production records**

The main producers listed in VicMine are:

- Brunswick open pit (VicMine ID 372183), with production of 197.4 kg gold;
- Bombay Shaft (VicMine ID 371999), with production of 104.7 kg gold;
- Alison Mine (VicMine ID 371991), with production of 99.1 kg gold;
- Minerva Shaft (VicMine ID 372008), with production of 17.9 kg gold.
The most frequently quoted estimate of the total historic (before 1980) production of 2.3 t Au (Bowen, 1974; Whiting & Bowen, 1976; Edwards et al., 1997) is accepted here, although Stillwell (1953) made a slightly higher estimate of 2.462 t Au. Recent production (post 1995) exceeded 900 kg gold (VicProd; Cambrian Resources, 2008; Western Coal Corporation, 2009) and currently (2011) continues. Assuming 10% dilution, 80% gold recovery and 5% Ag included in produced gold bullion for historic production, 30% dilution and 50%–80% gold recovery for modern mining (Cambrian Resources, 2008), total gold production to 2009 is equivalent to the original in situ gold endowment of approximately 4 t Au.

Western Coal Corporation (2009) reported total remaining resources of the Augusta deposit as 331,000 t ore @ 11.4 g/t Au, for 3.8 t of contained gold. This estimate included 85,000 t @ 4.8 g/t Au for 0.4 t of contained gold classified as Inferred Resources and 246,000 t @ 13.43 g/t Au for 3.3 t of contained gold classified as Measured and Indicated Resources (Cambrian Resources, 2008).

Total original in situ gold endowment accepted for the Costerfield ore field in this report is approximately 7 t Au.

This estimate excludes current Inferred Resource and is likely to prove conservative.

Analysis of historic and modern production records and geological descriptions of the Costerfield deposits suggests generally consistent grade characteristics of previously mined and of identified remaining orebodies. Significantly lower mining grades common in recent mining are likely to be a function of using bulk mining techniques (especially open-cut mining), rather than intrinsic differences in mined orebodies. Therefore, an approximate pre-mining ‘global’ gold grade for the Costerfield ore field has been accepted to be 15 g/t – broadly consistent with the data for historic mining and current resource estimates.

### 2.7.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>8</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>197.4</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>3</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>421</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open pit</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>128 m</td>
</tr>
</tbody>
</table>
2.7.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz-stibnite veins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 800 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>340° – 350°</td>
</tr>
</tbody>
</table>

2.7.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.8. Diamond Creek

2.8.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 336 935 E, 5 828 005 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality*</td>
<td>1</td>
</tr>
</tbody>
</table>

* Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.8</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.8.2. Description

The Diamond Creek ore field contains one recorded mine – the Diamond Creek mine (VicMine ID 373675; O’Shea, et al., 1992; Department of Mines, 1870–1884). The mineralisation is within the Lower Silurian Anderson Creek Formation. The ore field as defined here was an area of most significant primary gold production in the early historic Caledonia goldfield, which was largely defined by extensive alluvial gold mining in 1850-s – 1860-s, in a region north of Warrandyte, between Diamond (Back) and Watsons Creeks and extending to the north to St Andrews (Queenstown). Mineralisation at Diamond Creek / Union mine is described by Dunn (1907) and Howitt (1920).

2.8.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (1864–1915), kg</th>
<th>1900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>34</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>56,000</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>45,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>47</td>
</tr>
</tbody>
</table>

Notes on production records

The only significant producer in this ore field was the Diamond Creek mine (including earlier workings – such as mines of the Pioneer and Union companies, the Allendale
mine, etc.), with total historic gold production of approximately 1.9 t (Bowen, 1974; Whiting and Bowen, 1976; Ramsey and Willman, 1988), at an average recovered gold grade of 34 g/t (VicProd; Howitt, 1920; Department of Mines, 1870–1915). Assuming 25% dilution (cf. Howitt, 1920), 85% gold recovery and 5% Ag included in produced gold bullion, combined original in situ gold endowment for the Diamond Creek ore field is estimated as 2100 kg Au from 45,000 t ore @ 47 g/t.

2.8.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>East-dipping quartz veins, often along the contacts between a tabular dyke and sediments, cross-cutting west-dipping bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>The main line of reef was worked for up to 2 km along strike (N–S), mined to a maximum depth of 213 m. The main quartz reef varied in width between 10 cm and 46 cm.</td>
</tr>
<tr>
<td>Orientation</td>
<td>N - S, dip 45° to the east</td>
</tr>
</tbody>
</table>

2.8.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone, mostly along dyke contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Diamond Creek ore field
2.9. Donnybrook

2.9.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 309 462 E, 5 872 184 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality¹⁰</td>
<td>1</td>
</tr>
</tbody>
</table>

¹⁰ Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.7</td>
<td>10°</td>
<td>5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.9.2. Description

The Donnybrook ore field contains seven named reefs and mines (VicMine; O’Shea et al., 1992; Kenny, 1937b). It occurs within the outcrop of Lower Silurian Springfield Sandstone and Chintin Formation and Upper Silurian Kilmore Siltstone.

2.9.3. Production and endowment

**Historic production**

| Historic gold production (1864–1915), kg | 47.3 |
| Recovered grade, g/t                   | 157  |
| Processed ore, t                       | 304  |
| Recent gold production (1983–2008)     | none |
| Current resource / reserve (12/2008)   | unknown |

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

*The main producers listed in VicMine are:*

- Woolfs Lease (VicMine ID 371590) with production of 32.2 kg gold;
- Kilroys Lease (VicMine ID 371591) with production of 15 kg gold.
- O’Shea et al. (1992) quotes production of over 47 kg gold from the Kalkallo mine, but it is unclear as to which mine this refers to, there being no records of a Kalkallo mine in VicMine, in Kenny (1937b) or in Stirling (1899).
2.9.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>7</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>32</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>47.3</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>55 m</td>
</tr>
</tbody>
</table>

2.9.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length 100 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>0°</td>
</tr>
</tbody>
</table>

2.9.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Donnybrook ore field
2.10. Dry Creek

2.10.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 395 037 E, 5 910 874 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

II Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>0</td>
<td>280°</td>
<td>3.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.10.2. Description

The Dry Creek ore field contains two mines (VicMine; Bates and Hughes, 1989). It occurs within the outcrop of the contact aureole of the Strathbogie Granodiorite.

2.10.3. Production and endowment

Historic production

| Historic gold production, kg | 1.3 |
| Recovered grade, g/t        | 3.5 |
| Processed ore, t            | 347 |
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

Estimated pre-mining endowment

| Contained gold, kg | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t | unknown |

Notes on production records

The only producer in this ore field is: Morning Star Mine (VicMine ID 362603), with production of 1.3 kg gold from 347 t ore.

The other mine in this ore field is the Brankeet mine (VicMine ID 362602).
2.10.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>2</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>1.2</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>1.2</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.10.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with hornfels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.10.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>contact</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.11. Dutch Joes Creek

2.11.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 411 217 E, 5 850 091 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality(^\text{12})</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^\text{12}\) Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.11.2. Description

The Dutch Joes Creek ore field contains one mine (VicMine; Kenny and Whiting, 1955; Kenny, 1938b; Kenny, 1939d).

It occurs within the outcrop of the Upper Devonian Norton Gully Sandstone.

2.11.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>8.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>54.2</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>155</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The only producer in this ore field is Lyre Bird Mine (VicMine ID 373738) with production of 8.4 kg gold from 155 t ore.
2.11.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>8.4</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>8.4</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>28 m</td>
</tr>
</tbody>
</table>

2.11.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length about 100 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.11.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, dyke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Dutch Joes Creek ore field
### 2.12. Fontainbleu

#### 2.12.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 319 172 E, 5 941 994 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality&lt;sup&gt;13&lt;/sup&gt;</td>
<td>3</td>
</tr>
</tbody>
</table>

<sup>13</sup> Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>0.8</td>
<td>45°</td>
<td>1.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

#### 2.12.2. Description

The Fontainbleu ore field contains three named reefs (VicMine; O’Shea et al., 1992; Edwards et al., 1998). It occurs within the outcrop of Silurian and Devonian Puckapunyal Formation.

#### 2.12.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>77</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>17.8</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>4354</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The two producers listed in VicMine are:

- Black Reef (VicMine ID 372194) with production of 2 kg gold;
- Doctors Reef (VicMine ID 372095) with production of 0.9 kg gold;

Edwards et al. (1998) lists a number of reefs not listed in VicMine. The gold production for this ore field is taken from the above report.
2.12.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>3</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>2</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>2.9</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>76 m</td>
</tr>
</tbody>
</table>

2.12.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 76 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>90°</td>
</tr>
</tbody>
</table>

2.12.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, slate, shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Fontainbleu ore field
2.13. Gemba

2.13.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 380 999 E, 5 883,000 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality(^4)</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^4\) Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.4</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.13.2. Description

The Gemba ore field contains one mine, (VicMine; O’Shea et al., 1992; Kenny, 1941). It occurs within the outcrop of the Upper Devonian Norton Gully Sandstone.

2.13.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>55</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>14</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producer in this ore field is Gemba Mine, (VicMine ID 420908) with production of 0.8 kg gold from 14 t ore.
2.13.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>0.8</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0.8</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.13.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs, with possible association to nearby dyke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 110 m length, 27 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Reef strike 315°, dip 90°</td>
</tr>
</tbody>
</table>

2.13.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Gemba ore field
2.14. Ghin Ghin

2.14.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 355 817 E, 5 886 685 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^{15}\) Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>minor</td>
<td>0°</td>
<td>3.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.14.2. Description

The Ghin Ghin ore field contains eight named mines (VicMine; Whitelaw, 1895). These lie within the outcrop of the Lower Devonian Humevale Siltstone.

2.14.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>72.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>67</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>1078</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producer (and only one with recorded production) in this ore field is: Providence Mine (VicMine ID 371634) with production of 72.5 kg gold from 1078 t ore.
2.14.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>8</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>72.5</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>72.5</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30</td>
</tr>
</tbody>
</table>

2.14.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with breccias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 1600 m length</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 340°</td>
</tr>
</tbody>
</table>

2.14.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Ghin Ghin ore field
2.15. Graytown

2.15.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 317 253 E, 5 924 803 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality&lt;sup&gt;16&lt;/sup&gt;</td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>16</sup> Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Area of cover (km&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.3</td>
<td>13.6</td>
<td>10°</td>
<td>8.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

2.15.2. Description

The Graytown ore field contains seventeen named reefs and mines (VicMine; O’Shea et al., 1992; Edwards et al., 1998). It occurs within the outcrop of Silurian Dargile and Broadford Formations and the Devonian Puckapunyal Formation.

2.15.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>32.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>9</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>3630</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

The two producers listed in VicMine are:

- Surface Hill (VicMine ID 372238) with production of 15.1 kg gold;
- New Reef (VicMine ID 372025) with production of 1.6 kg gold.
- The gold production for this ore field is taken from Edwards et al. (1998).
2.15.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>17</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>15.1</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>32.6</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30 m</td>
</tr>
</tbody>
</table>

2.15.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz reefs</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length 150 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>320° and 40°</td>
</tr>
</tbody>
</table>

2.15.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Graytown ore field
2.16. Heathcote East

2.16.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55 299 395 E, 5 910 686 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

17 Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.9</td>
<td>2.4</td>
<td>n/a</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

2.16.2. Description

The Heathcote ore field contains four reefs and mines (VicMine; Edwards et al., 1997). It occurs within the outcrop of Lower Silurian Wapentake Formation, the Upper Silurian McIvor Sandstone and the Lower Silurian Dargile Formation sedimentary rocks.

2.16.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>37</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>94</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

| Contained gold, kg            | unknown |
| In situ ore tonnage, t        | unknown |
| In situ grade, g/t            | unknown |

**Notes on production records**

Note that the Heathcote East ore field is quite distinct from the historic Heathcote Goldfield, in that the Goldfield spans the Melbourne–Bendigo Zone boundary, whereas the Heathcote ore field is confined to the Melbourne Zone.

There is recorded production from:

- Antimony Reef (VicMine ID 371829) with production of 2.9 kg gold from 78 t ore;
- Antimony Line of Workings (VicMine ID 372299) with production of 0.9 kg gold from 16 t ore.
2.16.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>4</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>2.9</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>3.5</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.16.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs, associated with antimony</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length 500 m</td>
</tr>
</tbody>
</table>

2.16.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Heathcote East ore field
2.17. Hells Hole

2.17.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 401 812 E, 5 908 784 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality(^{18})</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^{18}\) Excludes production data, confined to detail and scope of technical information, 1 = low, 2 = adequate, 3 = excellent

<table>
<thead>
<tr>
<th>Total area (km(^2))</th>
<th>Area of cover (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.17.2. Description

The Hells Hole ore field contains one mine (VicMine; Bates and Hughes, 1989). It occurs within the outcrop of the Lower Devonian Norton Gully Sandstone.

2.17.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>73</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>21.5</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>3933</td>
</tr>
</tbody>
</table>

Recent gold production (1983–2008) none

Current resource / reserve (12/2008) none

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The only producer in this ore field is: Star of the Glen Mine (VicMine ID 362604) with production of 73 kg gold from 3933 t ore.
### 2.17.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>73</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>73</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.17.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reef associated with hornfels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.17.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>contact</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Hells Hole ore field
2.18. Hoddles Creek

2.18.1. Location and dimensions

<table>
<thead>
<tr>
<th>Nature of data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field centroid</td>
<td>MGA Zone 55: 377 111 E, 5 812 940 N</td>
</tr>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area (km²)</td>
<td>10.2</td>
</tr>
<tr>
<td>Area of cover (km²)</td>
<td>2.3</td>
</tr>
<tr>
<td>Long Axis Direction</td>
<td>320°</td>
</tr>
<tr>
<td>Long Axis Length (km)</td>
<td>4.7</td>
</tr>
<tr>
<td>Short Axis Length (km)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

2.18.2. Description

The Hoddles Creek ore field contains six mines and four reefs (McInnes, 1937; O’Shea et al., 1992; Whitelaw, 1906).

This occurs within the outcrop of the Lower Silurian Anderson Creek Formation and Upper Silurian Melbourne Formation. Although the northern group of mines and reefs are slightly over a mile distant from the southern group of reefs, they are considered to lie within the same ore zone for the purposes of this project.

2.18.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production, kg</td>
<td>95</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>75 (Trinity)</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>3200</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

Two production records were found – an annotation on a map by McInnes (1937), showing production of £4500 of gold in (prior to?) 1901 from the Pioneer Shaft. This is approximately equivalent to 33 kg gold, factoring in the price of gold per oz in $US as $20.71 and the exchange rate between $US and £UK as 0.2052£/$ for 1901. The other production record was from Whitelaw (1906), who reported 62 kg gold production from...
the Trinity Reef. The total is assumed to be a lower limit, since production from the other mines in the ore field is not recorded. The tonnage is calculated at a nominal 30 g/t.

### 2.18.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>5</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>none</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.18.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with stibnite and dyke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>210 m length, 45 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 50°–60°, dip 80° S</td>
</tr>
</tbody>
</table>

### 2.18.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.19. Homewood

2.19.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 351 999 E, 5 881 950 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.3</td>
<td>10</td>
<td>310°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.19.2. Description

The Homewood ore field contains three named mines, with some being reported multiple times (VicMine; Whitelaw, 1895). These occur within the outcrop of the Lower Devonian Humevale Siltstone and other Lower Devonian rocks.

2.19.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>4.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>28</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>171</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

The largest producer (and the only one with recorded production) in this ore field is: Carriers reef (VicMine ID 371764) with production of 4.8 kg gold from 171 t ore. Note that Carriers Reef is also recorded near Yea (Hill, 1860), making the location of this reef within the Homewood ore field uncertain.
2.19.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>3</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>4.8</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>4.8</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30</td>
</tr>
</tbody>
</table>

2.19.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.19.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.20. Kilmore

2.20.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 309 462 E, 5 872 184 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6</td>
<td>2</td>
<td>45°</td>
<td>4.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.20.2. Description

The Kilmore ore field contains three named reefs and mines (VicMine; O’Shea et al., 1992; Kenny, 1937a). It occurs within the outcrop of Lower Silurian Springfield Sandstone and Chintin Formation and Upper Silurian Kilmore Siltstone.

2.20.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>6.7</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>9885</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>2724</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>664,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>4.1 (average)</td>
</tr>
</tbody>
</table>

Notes on production records

The main producers listed in VicMine are:

- Larry Bourkes Reef (VicMine ID 371726) with production of 43 kg gold
- Goldie Mine (VicMine ID 371727) with production of 23 kg gold

A small amount of production is also recorded from Landgridge reef (VicMine)
2.20.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>7</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>3</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>43</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>66</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open pit</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>36 m</td>
</tr>
</tbody>
</table>

2.20.5. Ore bodies and systems

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs in breccia zone</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length 150 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>90° (host breccia)</td>
</tr>
</tbody>
</table>

2.20.6. Host rocks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Kilmore ore field
2.21. Maindample

2.21.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 405 499 E, 5 900,000 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.8</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.21.2. Description

The Maindample ore field contains one mine and three mapped reefs (VicMine; Anon, Undated main Reef Maindample; Kenny, 1921). It occurs within the outcrop of the Upper Devonian Norton Gully Sandstone.

2.21.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>19.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>25</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>755</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producers in this ore field are:

- Lady Hopetoun reef (Kenny, 1921) with production of 4.8 kg gold from 181 t ore;
- Main Reef (VicMine ID 420003) with production of 14.4 kg gold from 729 t ore;

Production shallower than 36 m not recorded.

The historic production statistics are not entirely self-consistent.

2.21.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>14.4</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>19.2</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>73</td>
</tr>
</tbody>
</table>
2.21.5. **Ore bodies and systems**

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs, with possible association to nearby dyke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>over 150 m length, 73 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Reef strike 350°</td>
</tr>
</tbody>
</table>

2.21.6. **Host rocks**

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Maindample ore field
2.22. Mitchellstown

2.22.1. Location and dimensions

<table>
<thead>
<tr>
<th></th>
<th>MGA Zone 55: 325 602 E, 5 920 579 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field centroid</td>
<td></td>
</tr>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6</td>
<td>7.1</td>
<td>330°</td>
<td>5.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>

2.22.2. Description

The Mitchellstown ore field contains ten named reefs and mines (VicMine; O’Shea et al., 1992; Edwards et al., 1998). It occurs within the outcrop of Upper Silurian Broadford Formation.

2.22.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th></th>
<th>3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production, kg</td>
<td></td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>32.7</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>96</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Notes on production records**

O’Shea et al. (1992) reports twenty five reefs from this area, although only ten are recorded in VicMine.

*The producers listed in VicMine are:*

- Try Again Reef (VicMine ID 371865) with a production of 0.3 kg gold
- McBeans Reef (VicMine ID 371866) with a production of 0.2 kg gold.

The gold production for this ore field is taken from Edwards *et al.* (1998).
2.22.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>10</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>0.3</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0.5</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>12 m</td>
</tr>
</tbody>
</table>

2.22.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Less than 0.3 m wide</td>
</tr>
<tr>
<td>Orientation</td>
<td>340°</td>
</tr>
</tbody>
</table>

2.22.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>sandstone, shale</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.23. Nagambie

2.23.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55 342 172 E, 5 926 213 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>3.6</td>
<td>70°</td>
<td>2.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>

2.23.2. Description

The Nagambie ore field contains one mine (VicMine; Edwards et al., 1997). It occurs within the outcrop of Lower Devonian Waranga Formation sedimentary rocks.

2.23.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (pre–1983), kg</th>
<th>none</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>0.6</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>7,270,000</td>
</tr>
<tr>
<td>Recent gold production (1990–2000)</td>
<td>4205</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>6,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>6,000,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Notes on production records

Nagambie Mine (VicMine ID 372182) has production recorded in VicMine as 3431 kg of gold from 5,738,007 t ore.

The accepted production from this ore field is from Edwards et al. (1997): 4205 kg of gold from 7.3 Mt ore, although Panaegis (2008, 2009) and records in VicProd indicate a slightly lower production of 4160 kg of gold.

Production was only from the oxidised zone. An estimated average head grade for the total of 7,311,123 t ore was 0.78 g/t, with metallurgical gold recovery of 73% (Panaegis, 2008, 2009), gold – supergene, very pure (99.9% Au, Gao et al., 1995). Based on this, the contained gold in the oxidised zone only was 5.76 t. Adding only a very minor part...
of remaining sulphide ores and assuming ore dilution of 25%, the total original contained gold endowment is accepted as 6 t, at an average grade of 1 g/t Au.

2.23.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>3431</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>3431</td>
</tr>
<tr>
<td>Mining method</td>
<td>Open pit</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.23.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz stringers and disseminated gold, associated with antimony</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 900 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 70°</td>
</tr>
</tbody>
</table>

2.23.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>Silicic and argylic alteration</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Nagambie ore field
2.24. One Tree Hill

2.24.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid MGA Zone 54: 350 592 E, 5 833 904 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover minor</th>
<th>Long Axis Direction 290°</th>
<th>Long Axis Length (km) 2.5</th>
<th>Short Axis Length (km) 2.2</th>
</tr>
</thead>
</table>

2.24.2. Description

The One Tree Hill ore field contains six reefs and mines (five named; VicMine; Garratt, 1972; O’Shea, et al., 1992; Junner, 1914). Some of the reefs and mines are reported more than once from different sources, with some inconsistencies in location. These occur within the outcrop of the Upper Silurian Dargile Formation and the Lower Devonian Humevale Siltstone.

2.24.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (1854–1940), kg</th>
<th>233</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>Typically, 20–30 g/t</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>About 3300 for Buck Reef</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

The two largest producers in this ore field are:

- Buck reef (VicMine ID 959535) with production of 66 kg gold from 3313 t ore.
- Swedish reef (VicMine ID 373715) with production of 62 kg gold.

2.24.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.24.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reef</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>dip 60°, strike 25° - 30° (Swedish Reef)</td>
</tr>
</tbody>
</table>

2.24.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

One Tree Hill ore field
2.25. Panton Hill

2.25.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 346 984 E, 5 834 717 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.3</td>
<td>minor</td>
<td>45°</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

2.25.2. Description

The Panton Hill ore field (including the Yow Yow area at the northern end of the field) contains thirteen mines (nine named) and seventeen reefs, including Panton Hill Reef, Orams Reef, Carters Reef, Boomers Reef and Jenny Linn Reef (VicMine; Geological Survey of Victoria., Undated. Parish of Greensborough; O’Shea, et al., 1992). Some of the reefs and mines are reported more than once from different sources, with some inconsistencies in location. These occur within the outcrop of the Lower Silurian Anderson Creek Fm and the Upper Silurian Dargile Formation.

2.25.3. Production and endowment

**Historic production**

| Historic gold production (1854–1940), kg | 534 |
| Recovered grade, g/t (Orams Reef only)  | 98.8 |
| Processed ore, t                        | total unknown |
| Recent gold production (1983–2008)      | none |
| Current resource / reserve (12/2008)    | none |

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producers in this ore field are:

- Orams reef, with production of 184 kg gold from 1860 t ore, and 280 kg in total;
- Black Cameron reef (VicMine ID 373711), with production of 20.7 kg gold from 467 t ore in the years 1950–1951 (Mining and Geological Journal 4(2), p 30);
- Carters Reef;
- Boomers Reef.

Other named reefs in the area include Napoleon reef, Doctors reef, Albert reef, Gilman reef and Ironbark reef

### 2.25.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>unknown</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.25.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Up to 120 m depth, 800 m strike length (Orams reef)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>dip west, strike 25° (Orams reef)</td>
</tr>
</tbody>
</table>

### 2.25.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.26. Redcastle

2.26.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 304 671 E, 5 925 033 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.7</td>
<td>13</td>
<td>20°</td>
<td>10.7</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.26.2. Description

The Redcastle ore field contains thirty five named reefs and mines (VicMine; O’Shea et al., 1992; Edwards et al., 1998). It occurs within the outcrop of Upper Silurian McIvor Sandstone and Lower to Upper Silurian Dargile and Broadford Formations.

2.26.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>342</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>29.8</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>11489</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The main producers listed in VicMine are:

- Welcome Reef (VicMine ID 372086), with production of 8.8 kg gold;
- Mary Ann Reef (VicMine ID 372074), with production of 2.5 kg gold;
- Leviathan Reef (VicMine ID 372070), with production of 2.1 kg gold.

The gold production for this ore field is taken from Edwards et al. (1998).
2.26.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>35</td>
</tr>
<tr>
<td>Number of mines recorded</td>
<td>8</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>8.8</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>16.8</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>120 m</td>
</tr>
</tbody>
</table>

2.26.5. Ore bodies and systems

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs, with stibnite</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length 4800 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>345° (typical)</td>
</tr>
</tbody>
</table>

2.26.6. Host rocks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Redcastle ore field
2.27. Reedy Creek

2.27.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 336 277 E, 5 872 765 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.9</td>
<td>0</td>
<td>300°</td>
<td>13</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.27.2. Description

The Reedy Creek ore field contains sixty one named and eleven unnamed mines and ninety four mapped reefs (VicMine; O’Shea, et al., 1992; Garratt, 1977). These lie within the outcrop of the Upper Silurian Dargile Formation and the Lower Devonian Humevale Siltstone. The eastern end of this ore field is also known as the Strath Creek goldfield.

2.27.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>22.5</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>67,000</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

| Contained gold, kg             | 1800 |
| In situ ore tonnage, t         | 61,000 |
| In situ grade, g/t             | 29.5 |

**Notes on production records**

*The largest recorded producers in this ore field are:*

- Langridge Co (VicMine ID 371676), with production of 641 kg gold from 11 261 t ore;
- Doyles Reef Co (VicMine ID 371671), with production of 387 kg gold from 7460 t ore;

Total historic quartz reef production attributed to the Reedy Creek ore field recorded in VicProd is 1421.5 kg Au.
Records for 1308 kg of total gold production contained information on the tonnage of processed ore, which indicated an average recovered grade of 22.7 g/T Au. Total historic gold production accepted for the Reedy Creek ore field is 1500 kg @ 22.5 g/t Au.

2.27.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>28</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>641</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>7</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>1378</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>180</td>
</tr>
</tbody>
</table>

2.27.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs, many associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 180 m length, 90 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.27.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone, strongly associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.28. Reefton

2.28.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 396 712 E, 5 826 684 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0.5</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.28.2. Description

The Reefton ore field is centred around the Reefton mine, although the area is reported to have hosted a number of workings O’Shea, et al., 1992; Department of Mines, 1870–1884). It occurs within the outcrop of the Upper Devonian Norton Gully Sandstone.

2.28.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>116</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>46</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>2500</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

Production records for Reefton (VicMine ID 420896; reported under Central Mining, Reefton, Lee and Carrolls and Young Chandler) covered the period between 1876 and 1884 (Department of Mines, 1870–1884). It is likely that the above is a minimum, since the exact locations of individual mines are unknown and there may have been additional, unrecorded or minor production before 1876 and after 1884.
2.28.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th><strong>Total number of mines</strong></th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of mines with recorded production</strong></td>
<td>none</td>
</tr>
<tr>
<td><strong>Biggest producer</strong></td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Major mines (over 25 kg gold)</strong></td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Total recorded gold production, kg</strong></td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Mining method</strong></td>
<td>shaft s</td>
</tr>
<tr>
<td><strong>Depth of mining</strong></td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.28.5. Ore bodies and systems

<table>
<thead>
<tr>
<th><strong>Character of ore bodies</strong></th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.28.6. Host rocks

<table>
<thead>
<tr>
<th><strong>Host rock types</strong></th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metamorphism</strong></td>
<td>unknown</td>
</tr>
<tr>
<td><strong>Structural history</strong></td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.29. Ringwood

2.29.1. Location and dimensions

<table>
<thead>
<tr>
<th></th>
<th>MGA Zone 55: 345 300 E, 5 813 900 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field centroid</td>
<td></td>
</tr>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>minor</td>
<td>n/a</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.29.2. Description

The Ringwood ore field one mine (Wilkinson, 1971; O’Shea, et al., 1992). This occurs within the outcrop of the Lower Silurian Anderson Creek Formation.

2.29.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>30</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>3500</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

There were several producers in the immediate area of the mine (as listed by Wilkinson, 1971) but they are all aggregated for the purposes of this report under the Ringwood Antimony Mine (not recorded in VicMine). The prime commodity from this mine was antimony, and gold (and silver) are also recorded, but the records for gold are so incomplete as to require a rough estimate as to endowment. Wilkinson (1971) estimates that over 3500 t of antimony ore were mined over the mine’s life. Assays of the (antimony-poorer) quartz-stibnite ore showed over 70 g/t gold and pyrite concentrates showed over 25 g/t gold and 70 g/t silver, with one assay of over 400 g/t silver. It is therefore assumed that gold content would likely have exceeded 30 g/t, implying a total endowment of over 100 kg gold.
2.29.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th></th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>unknown</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>unknown</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>unknown</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.29.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Stibnite, with accessory gold and silver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>300 m length</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 0°, dip 70° W</td>
</tr>
</tbody>
</table>

2.29.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.30. Rushworth

2.31.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 322 177 E, 5 949 418 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>12.5</td>
<td>280°</td>
<td>7.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

2.30.2. Description

The Rushworth ore field contains 84 named reefs and mines (VicMine; Anon, 1954, O’Shea et al., 1992; Garratt, 1985; Edwards et al., 1997; Edwards et al., 1998; Rushworth Chronicle, 1890). It occurs within the outcrop of Lower Devonian Waranga Formation.

2.30.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>3,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>20</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>150,000</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>3700</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>136,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>27</td>
</tr>
</tbody>
</table>

**Notes on production records**

Gold mining at Rushworth took place from 1850-s to 1918 (Edwards et al., 1997, 1998). Most extensive early gold production (before 1885) was very poorly documented. One reference (Rushworth Chronicle, 1890) quotes an estimate of 3110 kg gold production prior to 1883 from the Nuggety Hill - only part of the Rushworth ore field. However, this figure appears to be a personal estimate, with no further information or indications of its sources.

Total primary gold production estimated for the Rushworth ore field by Edwards et al. (1997) (1415.24 kg Au from 70885 t of processed ore) does not include the early
production estimate quoted in the Rushworth Chronicle (1890) but some (admittedly partial) production records reviewed by Edwards et al. (1997) date back to 1860-s.

*The major gold producers recorded in VicMine (as of 2008) were:*

- Specimen Hill Reef (VicMine ID 371954), with a recorded production of 4667 kg gold;
- Nuggety Hill Reef (VicMine ID 372090), with a recorded production of 3184 kg gold;
- Nuggety Reef (VicMine ID 371936), with a recorded production of 1189 kg gold;
- Perseverance Reef (VicMine ID 371940), with a recorded production of 934 kg gold;
- Cockatoo Reef (VicMine ID 371897), with a recorded production of 787 kg gold.

Total gold production for the ore field based on the existing VicMine records is estimated to be 11730 kg Au.

However, this estimate is significantly higher than estimates from any other reviewed sources. The largest published estimate by Phillips (2007) is 6 t of total gold production for the Rushworth - Whroo area (including alluvial gold and >1.3 t of primary gold production from the Whroo ore field as estimated in this report). Sources of VicMine production records are ambiguous. It is likely that production records and various estimates were erroneously assigned to multiple mines recorded in VicMine.

Total primary gold production for the Rushworth ore field is conservatively accepted here to be approximately 3 t Au (Rushworth Chronicle, 1890; M. Hughes, pers. comm., 2009). Average recovered grade accepted for the ore field is taken from Edwards et al. (1997) – 20 g/t Au.

### 2.30.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>84</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>43</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>4667</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>17</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>11 730</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>227 m</td>
</tr>
</tbody>
</table>

### 2.30.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 1000 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>90° (common)</td>
</tr>
</tbody>
</table>
2.30.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, slate, shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Rushworth ore field
2.31. Siberia Reefs

2.31.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55 318 162 E, 5 937 734 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>1.3</td>
<td>n/a</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.31.2. Description

The Siberia Reefs ore field contains two reefs and mines (VicMine; Edwards et al., 1997). It occurs within the outcrop of the Upper Silurian Broadford Formation and Silurian–Devonian Puckapunyal Formation sedimentary rocks.

2.31.3. Production and endowment

Historic production

| Historic gold production, kg | 7.2 |
| Recovered grade, g/t | 29.6 |
| Processed ore, t | 243 |
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

Notes on production records

There is recorded production from:

- Siberia Reefs (VicMine ID 372229) with production of 2 kg gold from 97 t ore.

Edwards et al. (1997) quotes production from Siberia Reefs as 7.2 kg gold from 243 t ore. The accepted production from this ore field is from Edwards et al. (1997).

2.31.4. Recorded mines (VicMine)

| Total number of mines | 2 |
| Number of mines with recorded production | 1 |
| Biggest producer | Siberia Reefs |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | 2 |
| Mining method | shaft |
| Depth of mining | unknown |
### 2.31.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 300 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.31.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Siberia Reefs ore field
2.32. Stewarts Reef

2.32.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 404 752 E, 5 949 799 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>13.3</td>
<td>315°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.32.2. Description

The Stewarts Reef ore field contains one mine (O’Shea et al., 1992; Kenny, 1937c). It occurs within the outcrop of Lower to Upper Silurian Jordan River Group.

2.32.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>27.7</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>181</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

The only recorded production from the:

- Last Fu Mine (VicMine ID 376481) with production of 6.5 kg gold from 181 t ore.

Production records are only available for the years 1902 and 1903.
2.32.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>50 m</td>
</tr>
</tbody>
</table>

2.32.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reef</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 30 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Dip 50° E</td>
</tr>
</tbody>
</table>

2.32.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Stewarts Reef ore field
2.33. Sunbury

2.33.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 301 070 E, 5 834 167 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>minor</td>
<td>315°</td>
<td>2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

2.33.2. Description

The Sunbury ore field contains one mine (Stirling, 1899). It occurs within the outcrop of the Upper Ordovician sedimentary rocks.

2.33.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>62</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>61</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>157 (minimum)</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Notes on production records**

*The only producer in this ore field is:*

- Beatties Reef (VicMine ID 959531) with production of about 62 kg gold from a minimum of 157 t ore.

There were two reported crushings with a total of 9.6 kg of gold recovered from 157 t of ore. The remainder of production was quoted in the absence of an ore tonnage value. Antimony was associated with this deposit.

2.33.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>62</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>62</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>55 m</td>
</tr>
</tbody>
</table>
2.33.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reef, associated with antimony</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 53 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 48°, dip to W</td>
</tr>
</tbody>
</table>

2.33.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Sunbury ore field
2.34. Sunday Creek

2.34.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 330 506 E, 5 867 752 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>minor</td>
<td>80°</td>
<td>2.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.34.2. Description

The Sunday Creek ore field contains eight named mines (VicMine; O’Shea et al., 1992). These lie within the outcrop of the Upper Silurian Kilmore Sandstone and the Lower Devonian Humevale Siltstone.

2.34.3. Production and endowment

Historic production

| Historic gold production, kg | 447 |
| Recovered grade, g/t         | 15  |
| Processed ore, t             | 29740|
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

Notes on production records

The largest producers in this ore field are:

- Golden Dyke mine (VicMine ID 371721), with production of 414 kg gold from 28 095 t ore;
- Rising Sun mine (VicMine ID 371718), with production of 20.5 kg gold from 485 t ore.

2.34.4. Recorded mines (VicMine)

| Total number of mines                       | 8         |
| Number of mines with recorded production   | 5         |
| Biggest producer                           | 414       |
| Major mines (over 25 kg gold)              | 3         |
| Total recorded gold production, kg         | 447       |
| Mining method                              | shafts    |
| Depth of mining                            | 105       |
2.34.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Up to 112 m length, 105 m depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.34.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone, strongly associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Sunday Creek ore field
2.35. Tanjil

2.34.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 428 104 E, 5 791 778 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.6</td>
<td>4.5</td>
<td>350°</td>
<td>13</td>
<td>3</td>
</tr>
</tbody>
</table>

2.35.2. Description

The Tanjil ore field contains ten mines (O’Shea et al., 1992; VicMine; Geological Survey of Victoria, 1915; Geological Survey of Victoria, 1915; Department of Mines, Victoria, 1891). It occurs within the outcrop of Lower to Upper Silurian Jordan River Group and Upper Devonian Walhalla Group sedimentary rocks.

Although this ore field could be divided into a northern and southern section separated by about 2 km, the only comprehensive production record applies to the entire combined area, so the two sections are treated as one.

2.35.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>15</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>3500</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

The ore tonnage is approximated from the net produced gold, assuming a run-of-mine grade of 15 g/t.

There is recorded production from the:

- Empire Mine (VicMine ID 373796), with production of 12.2 kg gold from 47 t ore.

The only production records were for the year 1868.
2.35.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>58 m</td>
</tr>
</tbody>
</table>

2.35.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 1,000 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>335° (dykes)</td>
</tr>
</tbody>
</table>

2.35.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, siltstone, dyke rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Tanjil ore field
2.36. Tea Tree Creek

2.36.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 346 029 E, 5 883 925 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km^2)</th>
<th>Area of cover (km^2)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.36.2. Description

The Tea Tree Creek (also spelled Ti Tree Creek) ore field contains one named mine, (VicMine; O’Shea et al., 1992; Lanzer, 1986), lying within the outcrop of the Lower Devonian Humevale Siltstone.

2.36.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>271.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>27.4</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>10,000</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producer in this ore field is:

- Welcome Mine, also known as Ah Mouy’s (VicMine ID 371620), with production of 271.5 kg gold from 994 t ore. Note that the grade calculated from the records in VicMine is unreasonably high and the grade quoted by Lanzer (1986) of 27.4 g/t appears more realistic. It is likely that the tonnage reported in VicMine is low and the total tonnage is probably nearer 10,000 t (as calculated from the grade and gold production above).
2.36.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>271.5</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>271.5</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>244</td>
</tr>
</tbody>
</table>

2.36.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz reefs, gold antimony, associated with graphitic shale</td>
</tr>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.36.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>siltstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Tea Tree Creek ore field
2.37. The Triangles

2.37.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 346 029 E, 5 883 925 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8</td>
<td>minor</td>
<td>0°</td>
<td>4.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.37.2. Description

The Triangles ore field contains twelve named mines, although there seems to be some confusion between this area and the King Parrot Creek Goldfield to the south (VicMine; Hill, 1895; Cozens, 1986). These lie within the outcrop of the Lower Devonian Humevale Siltstone.

2.37.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>177.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>153</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>1163</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

The largest producers in this ore field are:

- Crown Mine Reefs (VicMine ID 371604), with production of 177 kg gold from 1124 t ore;
- King Parrot Reefs (VicMine ID 371607), with production of 0.6 kg gold from 39 t ore.

Note that there is some confusion over whether the Crown mine mentioned above is located in the Triangles ore field or in the Reedy Creek ore field. There appears to be a mine with this name in both areas (no production recorded from the one in Reedy Creek). Cozens (1986), however, assigns this mine to the Triangles area in the body of his report, although it is designated as located in the Reedy Creek area in the appendix. The production from this mine is tentatively assigned to the Triangles ore field.
2.37.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>12</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>177.7</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>177.7</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30</td>
</tr>
</tbody>
</table>

2.37.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 600 m (Hannigans Reef)</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.37.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

The Triangles ore field
2.38. Three Chums

2.38.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 340 982 E, 5 836 966 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>minor</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.38.2. Description

The Three Chums ore field contains one mine (VicMine ID 963711; Kenny, 1938a). This mine occurs near the anticlinal axis running through the centre of this ore field, which occurs within the outcrop of the Lower Silurian Anderson Creek Formation and the Upper Silurian Dargile Formation.

2.38.3. Production and endowment

*Historic production*

| Historic gold production (1854–1940), kg | 38.3 |
| Recovered grade, g/t                   | 66   |
| Processed ore, t                       | 581  |
| Recent gold production (1983–2008)     | none |
| Current resource / reserve (12/2008)   | none |

*Notes on production records*

There are no other recorded mines in this ore field. Production prior to 1908 was not recorded

2.38.4. Recorded mines (VicMine)

| Total number of mines                  | 1       |
| Number of mines with recorded production | unknown |
| Biggest producer                       | unknown |
| Major mines (over 25 kg gold)          | unknown |
| Total recorded gold production, kg     | unknown |
| Mining method                          | shaft   |
| Depth of mining                        | 78 m    |
2.38.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Up to 78 m depth, 120 m strike length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>dip west, strike 16°</td>
</tr>
</tbody>
</table>

2.38.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Three Chums ore field
2.39. Warrandyte

2.39.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 343373 E, 5 822794 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.2</td>
<td>minor</td>
<td>0°</td>
<td>7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.39.2. Description

The Warrandyte ore field contains 19 recorded mines (15 named) and about 20 reefs - the exact number depends on which of the individually described reefs are actually distinct (VicMine; Garratt, 1972; Murray, 1896; Jutson, 1910; Howitt, 1909; Dunn, 1907a; Forbes, 1898; Murphy, 1859). Some of the reefs and mines are reported more than once from different sources, with some inconsistencies in locations. These all lie within the outcrop of the Silurian Anderson Creek Formation.

2.39.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production (to 1910), kg</th>
<th>693</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>33</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>21044</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>19,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>43.1</td>
</tr>
</tbody>
</table>

**Notes on production records**

*The three largest producers in this ore field are:*

- Caledonia (known previously as the Newhaven; VicMine ID 373694), with production of 397 kg gold from 12653 t ore (between 1905 and 1909);
- Victory reef (VicMine ID 373682), with production of 50 kg gold from 1090 t ore;
○ Pigtail reef (not registered in VicMine, located at the north end of the Consols anticline), with production of about 62 kg gold from 1240 t ore.

There are several additional named mines with recorded production in this ore field (Jutson, 1910; Murray, 1896, Forbes, 1898), all of which contribute to the total above.

2.39.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>none</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.39.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>dip 60°, dip direction 110° (Great Southern); dip 50°, dip direction 290° (Caledonia Consols)</td>
</tr>
</tbody>
</table>

2.39.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Warrandyte ore field
2.40. Whittlesea

2.40.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 334 347 E, 5 831 829 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>minor</td>
<td>330°</td>
<td>3.9</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.40.2. Description

The Whittlesea ore field contains four mines and an area of quartz veining (VicMine; O’Shea et al., 1992; Bowen, 1959). Bowen (1959) refers to the issue of the correct location for the above reefs and mines. These lie within the outcrop of the Upper Silurian Dargile Formation and the Lower Devonian Humevale Siltstone.

2.40.3. Production and endowment

**Historic production**

| Historic gold production, kg | unknown |
| Recovered grade, g/t        | over 39  |
| Processed ore, t            | unknown |
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

**Notes on production records**

*The producers in this ore field are:*

- Timms Reef (1&2) and Kings Reef;
- The Darcy and Barker workings (Ferguson, 1909).

2.40.4. Recorded mines (VicMine)

| Total number of mines | 1 |
| Number of mines with recorded production | 0 |
| Biggest producer | unknown |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | unknown |
| Mining method | shaft |
| Depth of mining | 27 m |
2.40.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Up to 27 m depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.40.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Whittlesea ore field
2.41. Whroo

2.41.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 323 618 E, 5 942 704 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>2.2</td>
<td>280°</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

2.41.2. Description

The Whroo ore field contains thirteen named reefs and mines (VicMine; O’Shea et al., 1992; Edwards et al., 1997; Edwards et al., 1998). It occurs within the outcrop of Silurian and Devonian Puckapunyal Formation.

2.41.3. Production and endowment

Historic production

| Historic gold production, kg | 1350 |
| Recovered grade, g/t        | 12.5 |
| Processed ore, t            | 104,000 |
| Recent gold production (1983–2008) | none |
| Current resource / reserve (12/2008) | none |

Estimated pre-mining endowment

| Contained gold, kg | 1600 |
| In situ ore tonnage, t | 94,000 |
| In situ grade, g/t  | 16.5 |

Notes on production records

The largest producers recorded in VicMine include:
- Balaclava Hill Open Pit (VicMine ID 372092), with recorded production of 734 kg gold;
- Albert Reef (VicMine ID 372091), with recorded production of 36.4 kg gold;
- Carrs Reef (VicMine ID 372093), with recorded production of 28.4 kg gold.

Balaclava Hill mine was by far the most important producer in the field, with total production of more than 1.2 t Au (Bowen, 1974; Bowen and Whiting, 1975; Whiting and Bowen, 1976). Total gold production accepted for the field is based on estimates of Edwards et al. (1997): 1321 kg of gold from 102259 t of processed ore, increased to
1350 kg to account for minor unrecorded production. The average recovered grade is estimated as 12.5 g/t.

### 2.41.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>13</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>7</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>734</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>3</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>970</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open pit</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>91 m</td>
</tr>
</tbody>
</table>

### 2.41.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Character of ore bodies</td>
<td>Quartz veins and stockworks</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Length up 120 m, thickness less than 0.6 m – 0.8 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Mostly 0° or 90° (approximately)</td>
</tr>
</tbody>
</table>

### 2.41.6. Host rocks

<table>
<thead>
<tr>
<th>Character</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone, slate, shale</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Whroo ore field
2.42. Yarrambat

2.42.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 334 347 E, 5 831 829 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>minor</td>
<td>330°</td>
<td>3.9</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.42.2. Description

The Yarrambat ore field contains ten mines (seven named), seven reefs and two areas of quartz veining (VicMine; O’Shea, et al., 1992; Aplin, 1868; Taylor and Etheridge, 1868; Kenny, 1940a). Some of the reefs and mines are reported more than once from different sources, with some inconsistencies in location. These lie within the outcrop of the Upper Silurian Dargile Formation.

2.42.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>11</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>21561</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

Notes on production records

The largest producers in this ore field are:

- Golden Crown mine (VicMine ID2 373669 and 373670) with production of 144 kg gold from 15339 t ore (1939–1950);
- Golden Stairs mine (VicMine ID 373665) with production of 30 kg gold from 2380 t ore (1928–1942).

Other named reefs in the area include Grays reef and Pioneer reef.
2.42.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>9</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>unknown</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Mining method</td>
<td>unknown</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.42.5. Ore bodies and systems

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 42 m depth (Golden Gate mine)</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.42.6. Host rocks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Sandstone and siltstone, some associated with dykes</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Yarrambat ore field
2.43. Yea

2.43.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 55: 358 749 E, 5 881 316 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>2.5</td>
<td>320°</td>
<td>3.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.43.2. Description

The Yea ore field contains three named mines and six mapped reefs (VicMine; O’Shea et al., 1992; Whitelaw, 1895).

These occur within the outcrop of the Upper Silurian Melbourne Fm and the Lower Devonian Humevale Siltstone.

2.43.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>267</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>34</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>7812</td>
</tr>
<tr>
<td>Recent gold production (1983–2008)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2008)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Notes on production records**

The largest producer in this ore field is:

- Providence Mine (VicMine ID 371634), with production of 267 kg gold from 7 812 t ore.

2.43.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>267</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>267</td>
</tr>
<tr>
<td>Mining method</td>
<td>shafts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>180</td>
</tr>
</tbody>
</table>
2.43.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs associated with breccias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 124 m length, 106 m depth</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 300° - 350°</td>
</tr>
</tbody>
</table>

2.43.6. Host rocks

<table>
<thead>
<tr>
<th>Metamorphism</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Yea ore field
3. Summary and Conclusions

The Melbourne Zone (excluding the Walhalla–Woods Point area) yielded a total of 27034 kg gold from about 9,170,000 tonnes ore, mostly distributed over 44 ore fields. There were additional 67 isolated mines (of which four had production records in VicMine) which were not attributed to any particular ore field, generally because they were located more than 800 m away from an ore field cluster and/or had production under 25 kg gold. The later group had an aggregate production of 154 kg gold from 58170 tonnes ore (less than 1% of the production of the defined ore fields) with this production included in the aggregate totals above.

The aggregate area of the ore fields is about 460 km², of which 136 km², about 30%, was under alluvial cover. The total area of the Melbourne Zone is 37 840 km², so the area of gold ore fields represents 1.2% of the total area of the Melbourne Zone.

Most ore fields showed considerable anisotropy in shape, with the ratios of the long to short axes from 1.1 to 4.3, with an average of 2.5 (for the ore fields that showed anisotropy). The orientations of the long axes trend 330° (± 20°) in about one third of the ore fields. Although the orientations of individual ore fields often correspond to the orientations of the individual mineralised structures within them, occasionally there will be a discrepancy, especially where there are multiple lines of mineralisation.

The deepest mine was in the Tea Tree Creek ore field (244 m) and the average depth of the deepest mines for each of the ore fields in the Melbourne Zone was about 80 m.

There were a total of 49 mines in the Melbourne Zone which produced over 25 kg of gold each. Of the 44 ore fields, only 6 had more than one mine which produced more than 25 kg gold.

For 27 of the 44 ore fields, more than half of the recorded mines had no production records at all, with only about a third of mines having any recorded production for the Melbourne Zone as a whole. Where production records were available, they often covered only part of the period of during which an individual mine may have operated. Even if we assume that the mines with no production records tended to be small, this would still imply that the aggregate totals quoted above significantly understate production.
Appendix 1

References


Anon., 1954. Rushworth Goldfield, parishes of Moora and Waranga 20 chains to 1 inch, geological map 2569/G/4.


Department of Mines, Victoria, 1891. Reports of the Mining Surveyors and Registrars. Series published quarterly between the quarters ended 31 March 1864 and 31 March 1891.

Department of Mines, Victoria, 1870–1884. Reports of the Mining Surveyors and Registrars (quarterly).


Ore fields in Melbourne Zone


Francis G., 1864. Map showing the location of Tubbarubba and Bulldog Creeks Gold Diggings, Mornington Peninsula. Plan No 1691/G/2.


Geological Survey of Victoria, 1878. Russells Creek Goldfield 1 mile to 1 inch, geological map. Department of Mines, Victoria.


Hill F.M., 1859. King Parrot Creek Goldfield. Feature plan showing reef locations. Plan No 1123/M/1.

Hill F.M., 1860. Plan of quartz reefs near Yea. Plan No 1124/m/1. Mining Department, Victoria.


Appendix 1


Kenny J.P.L., 1939d. Lyre Bird Mine, Dutch Joes Creek, Cambarville. Plan of adit levels, longitudinal and transverse sections, showing structure, and the positions of reefs, dykes and stopes. Plan No 2363/A/1.


McInnes D.W., 1937. Coronation (Gem Prospecting) Mine, Hoddles Creek. Location / Lease plan showing surface workings; Composite level plan; longitudinal section showing stopes; and transverse section showing reef. Plan No 2330/B/1.

Murphy J., 1859. Map of St. Andrews Mining Division, showing the locations of auriferous reefs and gullies. Plan No 2069/M/1.


Rushworth Chronicle, 1890. Gold mines in Rushworth, Whroo and McCoys Diggings (Bailieston). Department of Natural Resources and Environment Library Collection (unpubl.).

Scanlon E., 1895. Victory Mine, Foster. Composite level plan of workings to 492 foot level off Victory, Gladstone & Jubilee shafts; and Mining Lease plan. Plan No 1709/C/1.


Appendix 2

PRIMARY GOLD ORE FIELDS IN THE BENDIGO ZONE, VICTORIA

Presented as originally published (with minor changes) in:

1. Introduction

This report provides brief summary information on primary mesozonal orogenic gold-quartz vein ore fields in the Bendigo Zone in western Victoria. This compilation, largely focused on ore field grades and tonnages, excludes information on alluvial gold deposits.

To ensure consistency and avoid bias in assessing undiscovered endowment, information has been compiled for gold ore fields, defined as areas of mineralisation in which adjacent orebodies are less than 1.6 km apart (Lisitsin et al., 2007, 2010a, 2010b). Their extent is similar (and often identical) to historic goldfields or clusters of goldfields.

Gold mineralisation in the ore fields reviewed in this report is characterised by free gold in quartz veins, with variable amounts of sulphides and ferroan carbonates. These gold-quartz vein deposits are well studied and described in many reviews (e.g., Junner, 1920, 1921; Bowen and Whiting, 1975; Phillips and Hughes, 1996, 1998; Ramsay et al., 1998; Solomon, 2000; Phillips et al., 2003; Bierlein et al., 2004). They represent the dominant deposit type in the Bendigo Zone. Such deposits were described as ‘gold only quartz vein’, ‘turbidite - hosted quartz - gold’, ‘slate - belt’, ‘mesothermal gold’, etc. They have also been previously classified as mesozonal orogenic (Bierlein et al., 2004; Goldfarb et al., 2005; Moore, 2007), which is the term used in this report. Common properties of these deposits have been reviewed by Lisitsin et al. (2007, 2010b).

The main sources of information on the spatial distribution of gold deposits and gold production used in this report were corporate databases of the Department of Primary Industries (Victoria) – VicMine (Heap, 1998), VicProd (a database of gold production records compiled from Official records of the Government of Victoria and maintained by the GSV), GIS datasets of the mineral areas (Weston and Nott, 1993) and mapped auriferous quartz reefs. Additional information was derived from various other published
and unpublished sources (referenced in the text) as required – mostly for larger ore fields with >1 t of total primary gold production. A large part of gold production in the Bendigo Zone took place in the 19th and early 20th centuries. This historic gold production was often poorly documented, especially for smaller goldfields. Consequently, ore field gold grades and tonnages presented in this report are only approximate estimates based on incomplete information of variable quality. For smaller ore fields, the estimates of gold and ore tonnage are almost always conservative and the estimates of ore grades may be unrepresentative as they were based on only partial information.

The coordinates used in this report are based on GDA 94 datum (MGA Zone 54).
2. Primary gold ore fields in the Bendigo Zone

2.1. Amherst

2.1.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.126</th>
<th>Long: 143.675</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

\(^2\text{Based on detail and scope of available information, 1=low, 2=adequate, 3=excellent}\)

<table>
<thead>
<tr>
<th>Area (km(^2))</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.6</td>
<td>0(^\circ)</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

2.1.2. Description

This ore field contains a series of locally sub-parallel individual lines of reef, some relatively short, all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian – Warendian Castlemaíne Group.

2.1.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>1500(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>13.3 g/t(^4)</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>112,800</td>
</tr>
</tbody>
</table>

\(^3\text{Gold production rounded to the nearest 10 kg}\)

\(^4\text{from VicMine, 1090 kg Au for 77750 t ore}\)

**Notes on production records**

The production records accepted for this ore field are based on VicMine. Given that more than half of the recorded mines do not have an associated production and taking into account other sources, the total production is accepted as 1500 kg.

**Other sources**

- O’Shea et al. (1992) quoted 1353 kg, but this includes the Talbot goldfield;
- Taylor et al. (1999) quoted 1870 to 2490 kg from Amherst, Talbot, Craigie and Majorca ore fields
2.1.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>42 (14 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 20, Ore: 18</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Church Hill (VicMine ID 366360) 303 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>1089 kg from 77750 t ore (14 g/t Au)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>7</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>1018 kg (94% of total production)</td>
</tr>
</tbody>
</table>

*Gold production rounded to the nearest 1 kg*
2.2. Axedale

2.2.1. Location and dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field centroid Lat:</td>
<td>- 36.730</td>
</tr>
<tr>
<td>Ore field centroid Long:</td>
<td>144.487</td>
</tr>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>350°</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.2.2. Gold production

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production, kg</td>
<td>46</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>12.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>560,000</td>
</tr>
</tbody>
</table>

Notes on production records

There is no information on production from this ore field in VicMine, but it is referred to in Weston (1992) and Weston and Nott (1993). Due to this lack of data, this ore field was not used for the grade and tonnage model. However, Cherry and Wilkinson (1994) quote production from the Axedale mine of 46 kg; O'Shea, et al. (1992) quoted production records for Axedale Mine between 1883 and 1887 (3027 t for 1208 oz of recovered gold) and 1909 - 1910 (658 tons for 225 oz), for a total of 45 kg Au. Whitelaw (1925a) reported that the mine was worked between 1867 and 1910. It is possible that further research could add further information on gold production.
Ore fields in Bendigo Zone

Axedale ore field
2.3. Ballarat

2.3.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.604</th>
<th>Long: 143.868</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5°</td>
<td>22</td>
<td>5</td>
</tr>
</tbody>
</table>

2.3.2. Description

The Ballarat ore field contains a series of locally sub-parallel individual lines of reef, with one extensive, dominant line in the centre and south of the ore field, all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup. The Ballarat ore field as defined here includes Ballarat East, Ballarat West, Little Bendigo and South Ballarat - Buninyong historic goldfields. Some minor adjustments were made to the ore field perimeter to eliminate ‘holes’.

2.3.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>88800⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>9.6⁷</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>9,250,000</td>
</tr>
</tbody>
</table>

⁶ Gold production rounded to the nearest 100 kg
⁷ from VicMine 79 500 kg Au for 7 894,000 t ore

**Notes on production records**

- Finlay & Douglas (1992) suggest 76300 kg for the total from Ballarat East, Ballarat West and Little Bendigo fields;
- Bowen (1974) quotes 57900 kg for Ballarat East plus Ballarat West fields;
- Olsen (2003) estimated 77.75 t of primary gold production from Ballarat East and Ballarat West (thus excluding Little Bendigo and South Ballarat / Buninyong);
- Peter D’Auvergne (pers. comm.) quotes 80200 kg gold from this area (which includes East field - 1,582,315 oz; West field – 894,987 oz; Little Bendigo – 188,698 oz; Yorkshire - 1598 oz; South Ballarat/Buninyong – 187,222 oz).

On the basis of all available information, we estimated the total primary gold production for the Ballarat ore field to be 88800 kg.
### 2.3.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number of mines</strong></td>
<td>1 120 (206 unnamed)</td>
</tr>
<tr>
<td><strong>Total number of mines with production records</strong></td>
<td>Gold: 434, Ore: 409</td>
</tr>
<tr>
<td><strong>Biggest Producer</strong></td>
<td>Star of the East Co. No. 1 (Main) Shaft (Vic-Mine ID 381521) 8,000 kg</td>
</tr>
<tr>
<td><strong>Total Recorded Production</strong></td>
<td>79,500 kg from 7,894,000 t ore (10 g/t Au)</td>
</tr>
<tr>
<td><strong>Total producers over 25 kg</strong></td>
<td>158</td>
</tr>
<tr>
<td><strong>Total production over 25 kg</strong></td>
<td>78,200 kg (98% of total production)</td>
</tr>
</tbody>
</table>

* Rounded to nearest 100 kg

* Gold production rounded to the nearest 100 kg

![Ballarat ore field](image)
2.4. Ballarat Reef

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.221</th>
<th>Long: 143.687</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

2.4.1. Description

This ore field contains one mine, lying within the outcrop of the Lancefieldian – Warendian Castlemaine Group. This ore field is covered, in part, by Tertiary and Quaternary sediments.

2.4.2. Gold production

| Historic gold production¹⁰, kg | 4.4 |
| Recovered grade, g/t | 16 g/t¹¹ |
| Processed ore, t (derived) | 280 |

¹⁰ Gold production rounded to the nearest 0.1 kg
¹¹ from VicMine 4.4 kg Au for 280 t ore

Notes on production records

The production records accepted for this ore field are from VicMine.
No references are given for this site.

2.4.3. Recorded mines (VicMine)

| Total number of mines | 1 |
| Total number of mines with production records | Gold: 1, Ore: 1 |
| Biggest Producer | Ballarat Reef (VicMine ID 366625) 4.4 kg |
| Total Recorded Production | 4.4¹² kg for 280 t ore (16 g/t) |
| Total producers over 25 kg | 0 |
| Total production over 25 kg | 0 kg (0% of total production) |

¹² Gold production rounded to the nearest 0.1 kg
Ore fields in Bendigo Zone

Ballarat Reef ore field
2.5. Ballark

2.5.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.726</th>
<th>Long: 144.137</th>
</tr>
</thead>
</table>

| Ore field data quality | 1 |

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>310°</td>
<td>6</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.5.2. Description

This ore field lies within the outcrop of undifferentiated Ordovician sedimentary rocks (Roberts, 1986) and is, in part, covered by Quaternary sediments.

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>50</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>200</td>
</tr>
</tbody>
</table>

**Notes on production records**

There are no VicMine production records for this ore field.

The reference to the only named mine (Powells Reef) appears to be incorrect, referring instead to the Little Secret Mine, on Barrys Reef in the Blackwood gold field.

**Other sources**

Additional 10 mines/shafts/pits were located by Roberts (1986). Some of these were recorded in VicMine, but were not specifically identified as primary deposits and so were initially discarded. These mines were used to help to define the geometry of the ore field.

Kenny (1937a) referred to Powell’s Reef, Ballark. The reef was discovered in 1934; production recorded to the time of writing – 218 oz from 122 t (6.78 kg at 55.6 g/t). Total gold production accepted for the ore field is 10 kg gold at 50 g/t.

2.5.3. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>9 (8 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Ballark ore field
2.6. Bamganie

2.6.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.900</th>
<th>Long: 143.990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>10°</td>
<td>6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.6.2. Description

This ore field is located in the Parish of Bamganie, the Mining District of Steiglitz, within the outcrop of Bendigonian and Lancefieldian Ordovician sedimentary rocks.

2.6.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>735</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>13.4</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>54850</td>
</tr>
</tbody>
</table>

Notes on production records

Official production records (Mines Department Annual Reports) recorded in VicProd, indicate production from the Duke of Wellington mine of 558.52 kg of gold from 46189 t of ore to the end of 1909. Additionally, several smaller mines were operating in the area in the early 1900s, the most significant being the Duke of York Company mine (157.77 kg of Au from 7355 t of ore recorded by the end of 1907).

Information in Herman (1902) indicates continuity of mineralisation within the Bamganie ore field at the 1.6 km scale, thus allowing combining production from these two mines and a number of smaller producers (total recorded was 730.6 kg at 13.4 g/t). All this production was between 1901 and 1909, while the first production recorded in Bamganie was in 1883 - 1884 (39 oz from 18 tons), with Herman (1902) indicating in early 1902 that the goldfield attracted public attention within the previous three years. To allow for unrecorded production from small producers in the 1900’s and before 1901, the total gold production accepted for the ore field is increased to 735 kg at 13.4 g/t Au.
Other sources

Bolger (1977) mentioned the presence of lode workings in Bamganie, “although no persistent lodes were discovered.”

Herman (1902) provided a detailed description of the goldfield:

Full dimensions 3 to 4 miles long (N to S) by 1 mile wide, with the principal mines being 2 to 4 miles from Meredith (which implies that the ore field is actually up to 3 to 4 km east of its current mapped position as per the Mineral Areas database of Weston and Nott, 1992).

Two principal mines reported in the area - the Duke of York in the South and Duke of Wellington in the North (1.5 miles apart). Approximately ¾ miles NE of Duke of York was the Duke of Athol mine which by 1902 had produced about 133 oz down to 100 feet depth and was about to be extended to 200 feet.

Other producers in the area include the Duchess of York (320 to 340 m south of the Duke of York; established in 1901, produced 8 oz 5½ dwt from 15 tons to 1902); Princess May (600 m North of the Duke of York); the Duchess of Cornwall (0.5 mile ENE of Duke of Wellington; produced 218 oz 23 gr from 576 tons).

2.6.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Duke of Wellington (VicMine ID 376811)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Bamganie ore field
2.7. Bendigo

2.7.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.746</th>
<th>Long: 144.268</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>162</td>
<td>5°</td>
<td>21</td>
<td>5</td>
</tr>
</tbody>
</table>

2.7.2. Description

The Bendigo ore field contains a series of locally sub-parallel individual lines of reef, with one extensive, dominant line in the centre and south of the ore field, all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup.

The Bendigo ore field as delineated here includes the Bendigo Goldfield as defined by Johansen (2004) and Johansen et al. (2005) and extends slightly further to the west and north. Consequently, the total historic production from the Bendigo Goldfield as estimated by Bendigo Mining (Johansen, 2004; Johansen et al., 2005) is entirely applicable to the Bendigo ore field.

Some minor adjustments were made to the ore field perimeter to simplify the boundary.

2.7.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production¹³, kg</th>
<th>560,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14.3 g/t¹⁴</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>40,000,000</td>
</tr>
</tbody>
</table>

¹³ Gold production rounded to the nearest 100 kg
¹⁴ from VicMine 79,500 kg Au from 7,894,000 t ore

**Other sources**

- VicMine – grade calculated from the records where both gold production and ore tonnage were available – 14.8 g/t Au (from the total recorded gold production of 199 t Au);
- Thomas (1953) – total estimated gold production to the end of 1951 – 22.36 Moz (694 t);
- Bowen (1974) – grade calculated from production records for major mines – 14.7 g/t (from the total recorded gold production of 130 t Au);
Willman and Wilkinson (1992) – total gold production from the Bendigo goldfield between 1851 and 1954 was quoted as 22 million ounces (684,266 kg), including 5 million ounces from alluvial mining. Accordingly, primary gold production was estimated as approximately 529 t Au. Average recovered grade for the whole goldfield was estimated as 10 - 15 g/t Au;

Cherry and Wilkinson (1994) – total gold production estimated in excess of 684 T Au, including more than 529 t of primary gold production;

Hill (2001) – provides results of a comprehensive compilation and analysis of various sources. For the period until 1954, total primary production was estimated as 18,021,858 ounces (560.5 t); 76% of this production could be attributed to individual gold mines or companies. This estimate of the total primary gold production from the Bendigo goldfield was accepted by the Bendigo Mining NL.

Johansen et al. (2005). Total primary historic gold production – 18.014 Moz from 40,000,000 t of ore at an average recovered grade of 14.3 g/t. Indicated resources of 720,000 t at 10 g/t (236,000 oz) (Johansen, 2004; http://www.bendigomining.com.au/our_operations/reserves_and_resources.htm (as of September 2006));

Buerger (2006) - total historic gold production of 22 Moz, at an average head grade of 17 g/t Au (Buerger, 2006).

Most examined sources estimate total gold production from the Bendigo goldfield in the narrow range of 684 - 697 t.

There is less agreement on the distribution of total gold production between primary and alluvial sources, largely due to uncertainties in estimation of the poorly documented early alluvial production. The alluvial production is estimated between 124 t and 156 t Au. Thus, estimates of the primary gold production range from 530 t (Willman and Wilkinson, 1992; Cherry and Wilkinson, 1994) to 560.5 t (Hill, 2001). In this report, we accepted the historic primary gold production to be 560 t Au.
2.7.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>152 (43 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 69, Ore: 68</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Star of the East Co. No. 1 (Main) Shaft (Vic-Mine ID 381521) 8000 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>79,500 kg for 7,894,000 t ore</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>25 kg: 69</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>78,200 kg (98% of total recorded production)</td>
</tr>
</tbody>
</table>

18 Rounded to nearest 100 kg
19 Gold production rounded to the nearest 100 kg
2.8. Berringa – Rokewood Junction – Smythesdale

2.8.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.727</th>
<th>Long: 143.677</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>136</td>
<td>0°</td>
<td>30</td>
<td>5</td>
</tr>
</tbody>
</table>

2.8.2. Description

This ore field contains a number of sub-parallel major lines of workings (some considered separate goldfields in historical publications) lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup (with some Tertiary and Quaternary cover). This ore field as defined here includes the historic Illabarook and Smythesdale West goldfields.

Some minor adjustments were made to the ore field perimeter to simplify the outline.

2.8.3. Gold production

_Historic production_

<table>
<thead>
<tr>
<th>Historic gold production²⁰, kg</th>
<th>15500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>8 g/t²¹</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1,937,500</td>
</tr>
</tbody>
</table>

²⁰ Gold production rounded to the nearest 10 kg
²¹ from VicMine 15,200 kg Au for 1,898,000 t ore

_Notes on production records_

The production records accepted for this ore field are based on VicMine data, given the uncertainties of goldfield boundaries from other sources. Given the apparent absence of other significant gold-producing areas that could account for more than 300 - 400 kg production within the Scarsdale - Berringa area but outside the Berringa – Rokewood Junction – Smythesdale ore field as defined in this study, the total accepted production has been increased to 15500 kg.

Grade has been determined from VicMine records when both gold production and amount of ore were recorded (8 g/t Au). Geology of Victoria (1988) gives an average recovered grade of 10 g/t Au.
Other sources

- O’Shea et al. (1992) quoted production of 10162 kg Au, but this was for a smaller area of 8 km by 250 m. The same source gives production from the Newtown Goldfield (included within the Berringa ore field in this report) as 1129 kg.

2.8.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>459 (94 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 233, Ore: 229</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Jubilee Co (VicMine ID 379078) 2600(^{22}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>1260(^{23}) kg from 1,898,000 t ore (8 g/t Au)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>32</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>14600 kg (96% of total production)</td>
</tr>
</tbody>
</table>

\(^{22}\) Rounded to nearest 10 kg

\(^{23}\) Gold production rounded to the nearest 100 kg

Berringa – Rokewood Junction - Smythesdale ore field
2.9. Blackwood-Trentham

2.9.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.455</th>
<th>Long: 144.304</th>
</tr>
</thead>
</table>

| Ore field data quality | 1 |

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>0°</td>
<td>14</td>
<td>5</td>
</tr>
</tbody>
</table>

2.9.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Lancefieldian and Bendigonian Castlemaine Supergroup (with some Quaternary cover). A large internal ‘hole’ in the northern section of this area was incorporated in the ore field, given that named shafts from the VicShaft database spans this hole in the west.

2.9.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production²⁴, kg</th>
<th>5500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>23²⁵</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>240200²⁶</td>
</tr>
</tbody>
</table>

²⁴ Gold production rounded to the nearest 10 kg
²⁵ from VicMine 3540 kg Au for 154400 t ore
²⁶ Rounded to nearest 100 t

**Notes on production records**

The total gold production accepted for this ore field is from Ferguson (1906).

**Other sources**

Willman et al. (2002), estimated total recorded production for the mining district including the ore field as 6195 kg Au (after 1864). The district also includes the Greendale, Greendale West, Blakeville and Bullarto South ore fields as defined in this study (with the total estimated gold production of 720 kg). Thus, historic production for the Blackwood - Trentham ore field proper is accepted here as 5500 kg Au.
2.9.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>223 (104 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 32, Ore: 17</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Sultan Mine (VicMine ID 376917) 2050 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>4540 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>21</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>4450 kg (98% of total production)</td>
</tr>
</tbody>
</table>

27 Rounded to nearest 10 kg

28 Gold production rounded to the nearest 10 kg

Blackwood-Trentham ore field
2.10. Blakeville

2.10.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: 37.500</th>
<th>Long: 144.217</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>20°</td>
<td>3.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.10.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Lancefieldian and Bendigonian Castlemaine Supergroup (with some Quaternary cover).

2.10.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production²⁹, kg</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>24.6⁰</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>4470¹¹</td>
</tr>
</tbody>
</table>

²⁹ Gold production rounded to the nearest 1 kg
³⁰ from production recorded in Foster, 1937
¹¹ Rounded to nearest 10 t

**Notes on production records**

The total gold production accepted for this ore field is based on VicMine records.

**Other sources**

- Roberts (1984) reported production for Undaunted Reef as 860 kg Au. This is probably an error, as the original quoted reference (Ferguson, 1906) reported 2762 oz of production, equivalent to 85.9 kg. Foster (1937) also reported production from the Undaunted mine as 2762 oz;

- “The Colbrook Shaft [VicMine ID 547452] yielded good returns at shallow depth from a quartz reef/acid dyke host” (Foster, 1937);

- According to Kenny (1937b), Fortuna company reported production of 550 oz 15 dwt Au from 684 tons (171.3 kg at 24.6 g/t Au) from the Fortuna (Golden Hope) mine between 1907 and 1934, with the mineralisation hosted by a dyke;

- Ferguson (1917) reported several crushings yielding 15 dwt to 2.5 oz per ton, but without giving details of ore tonnage. He also reported production of 200 tons of ore
containing 1 oz 15 dwt Au per ton (for a total production of 350 oz Au). Timing of that production is uncertain, but the report was submitted in October 1911;

- Kenny (1937b) reported total production between 1907 and 1911 as 206.5 tons of ore yielding 339 oz Au. This may refer to the same production reported by Ferguson (1917).

Given the information above and the presence of several other shafts with no recorded production, the accepted production has been increased to 110 kg Au. The grade is accepted from Foster (1937b) as 24.6 g/t Au.

### 2.10.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>5 (1 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Undaunted Reef Workings (VicMine ID 368257) 86(^{32}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>103(^{32}) kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>86 kg (83% of total production)</td>
</tr>
</tbody>
</table>

\(^{32}\) Rounded to nearest 1 kg

\(^{33}\) Gold production rounded to the nearest 1 kg

![Blakeville ore field](image)
### 2.11. Bradshaw

#### 2.11.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.600</th>
<th>Long: 144.194</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 n/a</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.11.2. Description

This ore field lies within mapped undifferentiated Ordovician metasediments, with some Newer Volcanics cover (the Ballan 1:50,000 map - Roberts, 1986).

#### 2.11.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production[^35] kg</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>4.5</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>8180</td>
</tr>
</tbody>
</table>

[^35]: Gold production rounded up to the nearest 1 kg

**Notes on production records**

The total gold production accepted for this ore field is based on records from Department of Mines, Victoria 1939 (p. 23), 1940 (p. 22) and 1941 (p. 20), which describe workings to a maximum depth of 170 ft, mining an orebody approximately 2 ft wide, within a 12 ft wide low-grade ore horizon. Total recorded production was 8151 tons for 1191 oz, at a recovered grade of 4.5 g/t Au.

#### 2.11.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1 unnamed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Bradshaw ore field
2.12. Bullarto South

2.12.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.450</th>
<th>Long: 144.207</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>340°</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

2.12.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Lower Ordovician Castlemaine Supergroup (with some Quaternary cover).

2.12.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>22.5&lt;sup&gt;37&lt;/sup&gt;</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>267</td>
</tr>
</tbody>
</table>

<sup>36</sup> Gold production rounded to the nearest 1 kg  
<sup>37</sup> from VicMine 17 kg Au for 1 100 t ore

**Notes on production records**

The total gold production accepted for this ore field is from VicMine, rounded up to the nearest kg. It is probably a low estimate – 2 mines have no recorded production; production from Abel’s Reef continued after recording 107 t of ore production.

**Other sources**

Ferguson (1906) is the source of production figures in VicMine for the Reilly Mine and Abel’s Reef.

2.12.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Reilly Reef Workings (VicMine ID 368491) 4.2 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>5.4 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
</tbody>
</table>
Bullarto South ore field
Appendix 2

2.13. Camerons-March Reefs

2.13.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.951</th>
<th>Long: 143.697</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>330°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.13.2. Description

This ore field lies within the outcrop of the Lancefieldian Castlemaine Supergroup. The ore field is covered, in part, by Tertiary and Quaternary sediments.

2.13.3. Gold production

Historic production

| Historic gold production, kg | 50 |
| Recovered grade, g/t | 1.6 |
| Processed ore, t (derived) | 30600 |

³⁸ Gold production rounded to the nearest 1 kg
³⁹ from VicMine 50 kg Au for 30600 t ore, rounded to 2g/t

Notes on production records

Judging by the relatively low reported gold grade recovered from the Camerons Reef ore field, this may represent a true run - of - mine grade, rather than the (presumed) usually reported quartz ore grade. Production from this ore field is confirmed by VicProd (Dunolly), as per official production records for 30 Sep. 1890.

The total production accepted for this ore field is from VicMine.

2.13.4. Recorded mines (VicMine)

| Total number of mines | 2 |
| Total number of mines with production records | Gold: 2, Ore: 2 |
| Biggest Producer | Camerons Reef (VicMine ID 362891) 49 kg |
| Total Recorded Production | 50 kg⁴⁰ for 30600 t ore (1.6 g/t) |
| Total producers over 25 kg | 1 |
| Total production over 25 kg | 49 kg (98% of total production) |

⁴⁰ Gold production rounded to the nearest 1 kg
Ore fields in Bendigo Zone

Camerons-March reefs
2.14. Campbelltown

2.14.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.209 Long: 143.979</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>340°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.14.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.14.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production[^41], kg</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>12.9 g/t[^42]</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>10100</td>
</tr>
</tbody>
</table>

[^41]: Gold production rounded to the nearest 1 kg
[^42]: from recorded production for Glengower and Risk Reefs (Amos, 1890), and Harry Lauder, Government Battery and D. Jones after 1890 (DPI production records)

**Notes on production records**

The production records are very incomplete. There are some production records in Lidgey (1898). That report also lists 10 named reefs not recorded in VicMine.

The total gold production accepted for this ore field is based on Lidgey (1898), Amos (1890) and the following production records of the Department of Mines:

- Jones Brothers Reef – 111 oz from 15 tons “after picking out the richest specimens”, for a recovered grade of 230 g/t Au;
- Purtons Reef – shaft 210 feet deep and a tunnel on the surface; 100 oz Au from 200 tons of ore, at a recovered grade of 15 - 20 g/t Au;
- Keenans Reef – 1.2 oz Au from 6 tons - a recovered grade of 6 g/t Au;
- Oliver Cromwells Reef – “a good deal of work has been done by tunnels and open cut” - the lowest grade being 10 g/t Au;
- Half Mile Reef – worked for 30 years before and “has been stoped to a depth of 90 feet on gold - bearing stone from 9 to 12 inches thick”, with a recovered grade of 18 g/t Au (from one crushing);

- Jacksons Reef – worked by a shaft sunk to 382 feet. One crushing from a depth of 200 feet produced 1800 oz from 800 tons – a recovered grade of 70 g/t Au;

- Armers Reef (aka Middle Reef) – worked to 90 feet, with some returns of up to 3 ½ oz per ton. One crushing yielded 4 oz from 7 tons;

- Average gold grade estimated from three largest producers: 62 g/t Au;

Additional information can be found in Amos (1890):

- Glengower and Risk Reefs are located 5 ½ miles west of Yandoit – i.e., close to Campbelltown;

- Glengower Reef was worked by Jackson and party in 1876 - 78 and produced 2343 oz from 5331 t (recorded for 1867 - 1890) - 72.87 kg Au, at a recovered grade of 13.7 g/t Au. The largest production was from a depth of 300 to 400 feet. Given the owner’s name and shaft depth, this reef is apparently identical to Jacksons Reef of Lidgey (1898).

- Risk Reef, at Stockyard Creek, was worked by the Risk Company between 1873 and 1877, by a shaft up to 300 feet deep. Production was 686 oz from 1524 t of ore, with grade calculated as 14 g/t Au.

In addition to the above, quarterly production records of the Department of Mines show production after 1900:

- Harry Lauder mine – 640 t for 12381 g of Au (a recovered grade of 7.6 g/t Au);
- Government Battery, Campbelltown – 292 t for 5726 g of Au (a recovered grade of 19.6 g/t Au);
- D. Jones – 17 t for 1.56 kg of Au (a recovered grade of 90 g/t Au) (Howitt, 1937a; Harris and Thomas, 1948);

Using the above information, the total gold production from the ore field can be estimated as at least 130 kg Au. The average recovered grade, calculated using records in Amos (1890), was 14 g/t Au. Including later production records, the overall average recovered grade was 12.9 g/t Au.
2.14.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>4</td>
</tr>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Harry Lauder (VicMine ID 367207) from other records, but production not recorded in VicMine.</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>0</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

Campbelltown ore field
2.15. Carisbrook-Talbot

2.15.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.192</th>
<th>Long: 143.667</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>20°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.15.2. Description

This ore field contains a series of locally sub-parallel individual lines of reef, some relatively short, all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

The regional structural grain is unrelated to the geometry of this ore field. Based on VicMine and mapped worked reefs, this ore field includes the historic Talbot and Carisbrook goldfields.

2.15.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic production</th>
<th>Recent production</th>
<th>Accepted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production, kg</td>
<td>40⁴³</td>
<td>47⁴⁴</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>15.4 g/t</td>
<td>192</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td></td>
<td>6170</td>
</tr>
</tbody>
</table>

⁴³ Gold production rounded to the nearest 10 kg
⁴⁴ Kingston, 1935

**Notes on production records**

The production records accepted for this ore field are from VicMine, plus the Nuggetty Gully production.

**Other sources**

Nuggetty Gully Central Gold Mine (Kingston, 1935) was not been recorded in VicMine. The recorded production was 47 kg at 19 g/t Au (Kingston, 1935). This was in fact the biggest producer in this ore field. See also Forwood (1984), showing the locations of this and other mines not in recorded in VicMine.
2.15.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>10 (4 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with</td>
<td>Gold: 2, Ore: 2</td>
</tr>
<tr>
<td>production records</td>
<td></td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>All Nations (VicMine ID 366540) 29 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>40 t for 3180 t ore (13 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>29 kg (73% of total production)</td>
</tr>
</tbody>
</table>

\[45\] Gold production rounded to the nearest 1 kg

Carisbrook-Talbot ore field
2.16. Castlemaine

2.16.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.097</th>
<th>Long: 144.249</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>97</td>
<td>0°</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>

2.16.2. Description

The Castlemaine ore field mostly lies within the outcrop of Lancefieldian rocks, in places covered by Tertiary and Quaternary sediments (the covered portions account for less than 50% of the total area). The ore field is well-defined spatially. The Castlemaine ore field as defined here closely corresponds to the historic Castlemaine goldfield as traditionally used in the literature.

2.16.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production⁴⁶, kg</th>
<th>30,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>10.5¹⁷</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>2,857,000</td>
</tr>
</tbody>
</table>

⁴⁶ Gold production rounded to the nearest 100 kg

¹⁷ Willman (1995)

**Notes on production records**

- The estimate of primary gold production is based on data in Willman et al. (2002). 28079 kg of primary historic production can be verified in VicProd records (1864 - 1993). An additional 1921 kg of gold included in primary gold production in this report represents less than 1.5% of the estimated 131,165 kg of undifferentiated production from Castlemaine in 1851 - 1863 – a very low estimate of the likely total primary gold production for that period.

- Willman (1995) reported 27418 kg of gold production (from quartz veins only) from 2,607,985 t of ore at a recovered grade of 10.5 g/t Au (using official records only for 1864 - 1993).
Bowen (1974) reported 23325 kg Au for this goldfield. Tonnage and production data for the 5 largest producers (1226 kg total Au production) allows the calculation of an average recovered grade of 10.5 g/t Au.

VicProd records 28079 kg of gold production for 1864 - 1993 from quartz reefs, quartz tailings and mullock. The calculated average recovered grade (using only production records with both gold production and ore tonnage, but excluding tonnage of tailings and mullock) is 10.5 g/t Au.

### 2.16.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number of mines</strong></td>
<td>1919</td>
</tr>
<tr>
<td><strong>Total number of mines with production records</strong></td>
<td>110</td>
</tr>
<tr>
<td><strong>Biggest Producer</strong></td>
<td>Watt le Gully (10472 kg)</td>
</tr>
<tr>
<td><strong>Total Recorded Production</strong></td>
<td>23358 kg for 2,036,704 t (Note: Some mines only have recorded gold production but not tonnage of ore)</td>
</tr>
<tr>
<td><strong>Total producers over 25 kg</strong></td>
<td>52 (22989 kg production – 98% of total)</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Castlemaine ore field
2.17. Clunes

2.17.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:</th>
<th>Long:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- 37.288</td>
<td>143.785</td>
</tr>
</tbody>
</table>

Ore field data quality 2

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>20°</td>
<td>6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.17.2. Description

This ore field contains what appears to be one major line of reef, lying within the (mostly) subcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.17.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production*, kg</th>
<th>37,200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>12.6 g/t⁴⁹</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>2,953,000</td>
</tr>
</tbody>
</table>

⁴⁸ O’Shea et al., 1992
⁴⁹ from VicMine 32330 kg for 2,566,432 t ore

Notes on production records

The total gold production accepted for this ore field is from O’Shea et al. (1992).

Other sources

- Bowen (1974) reported 37200 kg of Au production. Tonnage and production data for the four largest producers (31177 kg total Au production) allows the calculation of an average recovered grade of 12.9 g/t Au;
- O’Shea et al. (1992) reported 37200 kg gold (from an area of 2.3 km by 0.15 km);
- VicProd shows a recorded production for 1864 - 1867 of 3500 kg of Au, indicating an average recovered grade of 11.6 g/t Au;
- Bush (1995) reported 37300 kg Au production, at an average recovered grade of about 13 g/t Au.
2.17.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 8, Ore: 7</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Port Phillip North (VicMine ID 366379) 15730 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>32820 kg from 2,566,000 t ore (13 g/t Au)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>6</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>32820 kg (100% of total production)</td>
</tr>
</tbody>
</table>

50 Gold production rounded to the nearest 10 kg. The total includes South Clunes United with 489 kg of recorded Au production but with no ore tonnage recorded. 32330 kg Au for 2,566,432 t ore is equivalent to a grade of 12.6 g/t

---

Clunes ore field
2.18. Cochranes Creek North East

2.18.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.683</th>
<th>Long: 143.634</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>350°</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.18.2. Description

This ore field lies within the outcrop of Castlemaine Supergroup and is, in part, covered by Quaternary sediments. VicMine mine locations seem to be displaced by about 300 m to the NE relative to the positions of the respective quartz reefs as mapped at 1:50,000 scale.

2.18.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

There are no production records for this ore field.

2.18.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>5 (4 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Cochranes Creek North East
2.19. Corindhap

2.19.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.870</th>
<th>Long: 143.734</th>
</tr>
</thead>
</table>

Ore field data quality 2

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>330°</td>
<td>3.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.19.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup (with some Tertiary and Quaternary cover). Some minor adjustments were made to the ore field perimeter to simplify the outline.

2.19.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production(^{51}), kg</th>
<th>76</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14(^{52})</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>5400</td>
</tr>
</tbody>
</table>

\(^{51}\) Gold production rounded to the nearest 1 kg  
\(^{52}\) from VicMine 76 kg Au for 5300 t ore

Notes on production records

The production records accepted for this ore field are from VicMine

2.19.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>13 (2 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 6, Ore: 7</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Young Albion Quartz Co. No. 1 Shaft (VicMine ID 381656) 65(^{53}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>76(^{54}) kg for 5 300 t ore (14 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>65 kg (86% of total production)</td>
</tr>
</tbody>
</table>

\(^{53}\) Rounded to nearest 1 kg  
\(^{54}\) Gold production rounded to the nearest 1 kg
Corindhap ore field
2.20. Corindhap West

2.20.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.869</th>
<th>Long: 143.697</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>10°</td>
<td>1.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

2.20.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup and is, in part, covered by Quaternary sediments.

2.20.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>31</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

- The South Golden Birthday was described by Bradford (1904) who reported a grade of 31 g/t Au for what was probably selected ore;
- The Hill mine was described by Lidgey (1895), who reported an estimated grade of about 9 g/t Au. This mine lies on Jacka’s Reef, but Lidgey’s description places this about 3 km to the north of the location registered in VicMine.

2.20.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Corindhap West ore field
2.21. Creswick

2.21.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.419</th>
<th>Long: 143.897</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>10°</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

2.21.2. Description

This ore field contains a number of sub-parallel lines of reef, lying within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup. It includes the Bald Hill and Allendale areas, as based on proximity of worked reefs.

2.21.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production⁵⁵, kg</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14.2⁵⁶</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>28170</td>
</tr>
</tbody>
</table>

⁵⁵ Gold production rounded to the nearest 1 kg
⁵⁶ from VicMine records with both grade and tonnage.

**Notes on production records**

The production accepted for this ore field is based on VicMine. Given the estimate of total primary production from the Creswick Goldfield of 602 kg (Taylor et al., 1999), the accepted production was increased to 400 kg (less than 10 % of the total recorded in VicMine).

**Other sources**

- O’Shea et al. (1992) quotes 272 kg (from New Nuggetty and Niaos Indicator);
- Benn (1990) quotes production identical to VicMine records;
- Baragwanath (1912) quoted a recovered gold grade of 7 to 13 dwt per ton, which is consistent with the current estimate accepted here.
2.21.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>17</td>
</tr>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 12, Ore: 12</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Frenchmans Reef (VicMine ID 366705) 135 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>365 kg (14.2 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>2</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>256 kg (70% of total production)</td>
</tr>
</tbody>
</table>

\(^{57}\) Gold production rounded to the nearest 1 kg

Creswick ore field
2.22. Crusoe

2.22.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.821</th>
<th>Long: 144.214</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>345°</td>
<td>5.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.22.2. Description

This ore field lies within the outcrop of Chewtonian, Castlemainian and Yapeenian Castlemaine Group. The ore field is in part covered by Quaternary sediments.

2.22.3. Gold production

Historic production

| Historic gold production, kg | 750 |
| Recovered grade, g/t         | 25.2 |
| Processed ore, t (derived)   | 29760 |

Notes on production records

This ore field is approximately equivalent to the historic Crusoe Goldfield.

The following reefs are mentioned in O’Shea et al. (1992), but don’t appear in VicMine: New Brunswick, Crusoe, Hit or Miss, Exhibition and Independent Reefs.

The total gold production estimate for this ore field is taken from Cherry and Wilkinson (1994).

In the absence of more detailed data, the average recovered grade for the ore field is calculated using available production statistics for the Break O’Day Reef from official records (1864 - 1867) and Stirling (1899) as 25.2 g/t Au. This estimate is based on less than 10% of the total estimated gold production.

Other sources

○ Cherry and Wilkinson (1994) estimated total gold production from the goldfield as at least 750 kg Au, with the biggest individual producer being Break O’Day (VicMine ID 373310), with recorded production of 404 kg Au;

○ Production records from the Break O’Day Reef in 1864 - 1867 total 7.2 kg at 8.6 g/t Au (Stirling, 1899);
○ Break O’Day: “From 2000 tons of quartz £7000 worth of gold was obtained”. Assuming £4 per oz – about 1750 oz (54.4 kg) at 26.8 g/t Au;
○ Parker’s Claim – very high yields from “indicators”: “from 26 tons, 56 oz. 5 dwt.; 16 tons, 180 oz., with specimens; 16 tons, 20 oz. 15 dwt.; 9 tons, 39 oz.” Caldwell, (1937a), Whitelaw, (1925b).

### 2.22.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>31 (28 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Cruoe ore field
2.23. Daylesford

2.23.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.329</th>
<th>Long: 144.143</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>10°</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

2.23.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Bendigonian, Chewtonian and Castlemainian Castlemaine Supergroup\(^{58}\) (Willman et al., 2002), with some Tertiary and Quaternary cover. The Daylesford ore field as defined here includes the Dry Diggings historic mining area.

2.23.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>23,000(^{60})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>12.5(^{61})</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1,840,000</td>
</tr>
</tbody>
</table>

\(^{58}\) Gold production rounded to the nearest 10 kg

\(^{60}\) Current estimate..

\(^{61}\) from Willman et al. (2002), Amos (1890) and DPI records: 19,635 kg Au for 1,574,571 t ore

**Notes on production records**

- O’Shea et al. (1992) quoted total production as exceeding 19,200 kg (after Amos, 1890, and Baragwanath, 1953);
- Baragwanath (1953) reported that “Production from the quartz mines has exceeded 500,000 oz of gold”;
- Amos (1890) recorded production of 261,648 oz Au from 807,867 t ore;
- Willman et al. (2002) estimated total recorded historic reef production from the Hepburn (Daylesford) Mining Division from 1864 as 24735 kg Au (795,254 oz), 23312 kg Au of which (including 154 kg produced from “quartz and cement”) was also confirmed by VicProd records, which exclude production between October 1891 and June 1897.
At a minimum, an additional 2 tonnes of gold production from the mining division could be assumed between 1891 and 1897. The mining division, in addition to Daylesford, includes Eganstown, Yandoit, and Campbelltown goldfields, with a total combined gold production from those fields unlikely to significantly exceed 1 t Au, as indicated by our current analysis. The best resolution appears to be an upward revision of gold production from the Daylesford goldfield. A brief analysis of available production data for the Daylesford ore field, as defined in this study, is presented below.

Willman et al. (2002) provided production data for 10 significant producers from the Daylesford goldfield. Comparison of the data with VicMine records indicates significant under - reporting in VicMine. Updating VicMine records with the revised production data from Willman et al. (2002) increased total estimated primary gold production from the Daylesford goldfield (as recorded in VicMine) to 20133 kg Au. Also, analysis of Amos (1890) and DPI production records identified additional recorded gold production of 1038 kg Au from 111,863 t of ore coming from some smaller gold reefs located in the Daylesford ore field but not recorded in VicMine.

Including this additional production gives a total estimate of 21171 kg Au for the ore field.

Even this revised estimate should be considered low. Firstly, only officially recorded production was used to compile the estimate, with no production records available for the period before 1864 (10 years of production) and only partial records available for the later production.

About half of all the mines in the Daylesford ore field recorded in VicMine do not have any production records, with many of them worked by shafts up to 230 m deep or by shallow workings with mined length of 150 to 1,000 m. So, total gold production from the Daylesford ore field was probably at least 21200 kg – with 23 - 24 t Au being a reasonable range of estimates.

The average recovered gold grade from the Daylesford ore field was calculated using production records for the largest mines with production in excess of 1 t Au from Willman et al. (2002) and for smaller mines using Amos (1890) and DPI production records (jointly accounting for 92% of the total recorded gold production). The average recovered gold grade is estimated as 12.5 g/t Au.
2.23.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>64</td>
</tr>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 19, Ore: 18</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Ajax (VicMine 367769) 3830kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>17720kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>18</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>17720 kg (100% of total production)</td>
</tr>
</tbody>
</table>

62 Rounded to nearest 10 kg
63 Gold production rounded to the nearest 10 kg

Daylesford ore field
2.24. Dereel

2.24.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.839</th>
<th>Long: 143.765</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5</td>
<td>310°</td>
<td>6.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.24.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the of Lancefieldian Castlemaine Supergroup (with some Tertiary and Quaternary cover).

2.24.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production¹⁴, kg</th>
<th>88</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>15.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>5300</td>
</tr>
</tbody>
</table>

¹⁴ Gold production rounded to the nearest 1 kg

Notes on production records

The total production production accepted for this ore field is based on data from VicMine, increased to 80 kg Au to account for unrecorded production from 18 mines.

In addition, the Oriental mine (VicMine ID 378300) had a recorded production of 280 t at 0.5 oz/t, which is included in the total.

Kenny (1938) reports production from 1909 to 1937 of 1385 oz from 2735 tons (15.5 g/t Au) from the Dereel Mine, with an additional 928 g from 170 t (5.4 g/t) to 10 November 1938 (Kenny, 1939).

2.24.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>30 (7 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 12, Ore: 12</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Golden Reefs Co. Shaft (VicMine ID 377691) 36¹⁵ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>77.4 kg from 5145.7 t ore (15.1 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>36 kg (49% of total production)</td>
</tr>
</tbody>
</table>

¹⁵ Rounded to nearest 1 kg
Dereel ore field
2.25. Dunolly - Goldsborough – Moliagul

2.25.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 36.829</th>
<th>Long: 143.704</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>105</td>
<td>335°</td>
<td>23</td>
<td>8</td>
</tr>
</tbody>
</table>

2.25.2. Description

This ore field contains a series of locally sub - parallel reefs all lying within a restricted and near - continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup, although much of the ore field is covered by Quaternary sediments. The reefs strike approximately north - south near the southern end of the ore field and gradually curve around to a strike of about 325°. The boundary was slightly adjusted to simplify the outline.

2.25.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production[^6], kg</th>
<th>6,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>17.9</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>335,200</td>
</tr>
</tbody>
</table>

[^6]: Gold production rounded to the nearest 10 kg

Notes on production records

- Jubilee reef – recovered gold grades between 3 g/t and 13 g/t Au;
- Taylor (1989) reported recovered gold grades between 17 g/t and 33 g/t Au.

The production records for this ore field are derived primarily from VicMine and VicProd.
2.25.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>118 (1 unknown)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 52, Ore: 49</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Queens Birthday reef (VicMine ID 362753) 3658 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>497068 kg for 275000 t ore (17.9 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>12</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>4674 kg (94% of total production)</td>
</tr>
</tbody>
</table>

*Gold production rounded to the nearest 10 kg*
2.26. Eganstown

2.26.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.363</th>
<th>Long: 144.087</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0°</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

2.26.2. Description

This ore field lies within the outcrop of the Lancefieldian-Warendian and Bendigonian Castlemaine Supergroup (with some Quaternary cover).

2.26.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production⁹, kg</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>38.7</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>10300</td>
</tr>
</tbody>
</table>

⁹ Gold production rounded up to the nearest 1 kg

**Notes on production records**

The following production records were not incorporated in VicMine and derived from Amos (1890), Kenny (1937e), Whitelaw (1920) and Howitt (1909):

- Adelaide Reef - total production in 1898 of 111 tons of ore for 7.2 kg Au, at an average recovered grade of 65.1 g/t Au;
- Alabama Reef - total of 346 tons for 2 kg Au, at an average grade of 5.8 g/t Au;
- Adelaide Reef - 57 tons for 1.5 kg Au, at an average grade of 25.7 g/t Au;
- Oliver & Son - 1897 total of 99 ton for 0.25 kg Au at an average grade of 2.6 g/t;
- Jackson & Co - total production in 1898 of 26 tons for 0.25 kg Au, at an average grade of 9.3 g/t Au;
- Ivesons Reef - total of 510 tons for 57.1 kg Au, at an average grade of 112 g/t;
- Lord Roberts/North Lord Roberts - total production in 1913 - 1915 of 550 tons for 1.6 kg Au, at an average grade of 3 g/t Au;
- Keep It Dark - total of 5564 tons for 161.9 kg Au, at an average grade of 29.1 g/t Au;
○ James & Co. 1907 - total production in 1908 of 320 tons for 4.2 kg Au, at an average grade of 13.2 g/t Au;

○ Keep It Dark - total of 18 tons for 0.6 kg Au, at an average grade of 33 g/t Au;

○ Sullivan - total of 1.7 kg Au\(^{70}\) ('Production over a length of workings of about 180 m. No tonnage reported).

○ Wheal Dorey - total of 36 tons for 0.3 kg Au, at an average grade of 8.4 g/t Au;

○ Lord Tennyson - total of 81 tons for 3.5 kg Au, at an average grade of 42.5 g/t Au;

○ Lord Roberts (before 1913) - total of 457 tons for 9.3 kg Au, at an average grade of 20.3 g/t Au;

○ North Lord Roberts (before 1913) - total of 1524 tons for 62.2 kg Au, at an average grade of 40.8 g/t Au;

○ Black Jack Central mine - total of 25 tons for 0.7 kg Au, at an average grade of 29.4 g/t Au, plus estimated production of 3 kg Au from shallow workings;

The above add up to 10,040 tons of ore for 388.1 kg Au, at an average recovered grade of 38.7 g/t Au.

Total gold production accepted here for the ore field is 400 kg Au.

### 2.26.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Adams (VicMine 368136) 75(^{71}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>121 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>2</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>120 kg (99% of total production)</td>
</tr>
</tbody>
</table>

\(^{71}\) Rounded to nearest 1 kg
Ore fields in Bendigo Zone

Eganstown ore field
2.27. Elaine - Mount Doran

2.27.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  -37.715</th>
<th>Long: 144.0.63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>20°</td>
<td>11</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.27.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the of what is probably Lancefieldian Castlemaine Supergroup, as projected from the Meredith 1:50,000 map (Roberts, 1986.), but mapped as undifferentiated Ordovician on the 1:50,000 Ballan map (with some Tertiary and Quaternary cover) (Bolger, 1980). For the purposes of this study, the Mount Doran ore field includes the Mount Doran, Elaine and Dolleys Creek goldfields. Some minor adjustments were made to the ore field perimeter to eliminate internal ‘holes’.

2.27.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production²⁴, kg</th>
<th>1220</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade²⁵, g/t</td>
<td>30.8</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>39610</td>
</tr>
</tbody>
</table>

²⁴ Gold production rounded to the nearest 1 kg
²⁵ from VicProd 1206 kg Au from 39117 t ore

Notes on production records

The VicMine production records for this ore field are woefully inadequate. The production records accepted for this ore field are based on VicProd.

Other sources

O’Shea et al. (1992) reported 13 kg gold production from the Golden Gate shaft, plus another 326.6 kg Au production from the Minerva mine at Elaine, which is not recorded in VicMine. Based on VicProd records, 1219 kg Au production is attributed to the Elaine - Mt Doran ore field in this study. From VicProd records (using only the records with both grade and tonnage reported; including the records reporting both grades and tonnages for pyrite
concentrates; for tailings and mullock - gold production was included but tonnage excluded to avoid double-counting of tonnage) the calculated average recovered grade was 30.8 g/t Au. The grade for Minerva alone was 49.4 g/t Au.

2.27.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>101 (87 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Golden Gate Shaft (VicMine ID 368694) 1376 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>1377 kg for 400 t ore (32 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

76 Rounded to nearest 1 kg
77 Gold production rounded to the nearest 1 kg

Elaine - Mount Doran ore field
2.28. Elysian Flat (Neilborough)

2.28.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.569</th>
<th>Long: 144.248</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30°</td>
<td>2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.28.2. Description

This ore field is located in the Parish of Neilborough, under cover of Recent alluvium.

2.28.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>32</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>2340</td>
</tr>
</tbody>
</table>

**Notes on production records**

Official production records (Mines Department Annual Reports) report production from the Barkly Reefs in 1867 - 1874 of 68 kg Au at 32 g/t.

Three parallel reefs, Barkly (the largest), Nuggetty and Cannobian, lie within 120 m of each other, beneath alluvium; miners “are said to have left payable gold underfoot when operations ceased” (Kingston, 1937a). Just north of the Barkly mine, the Commonwealth Cooperative worked the reef in 1904 - 1906, with average yields of ½ oz Au per ton; they also located a dyke with up to 2 ½ oz Au per ton. In 1932, Moorhead, Wicks and Crapper Brothers sank a shaft aiming to intersect the Barkly Reef (Kingston, 1937a).

2.28.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Barkly Reef (VicMine ID 373303)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.29. Enfield

2.29.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.771</th>
<th>Long: 143.759</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>270°</td>
<td>4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.29.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of Lancefieldian Castlemaine Supergroup (with some Tertiary and Quaternary cover).

2.29.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production(^7^8), kg</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^7^9), g/t</td>
<td>37</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>3000</td>
</tr>
</tbody>
</table>

\(^7^8\) Gold production rounded to the nearest 10 kg  
\(^7^9\) from VicMine 6.8 kg Au for 185 t ore

*Notes on production records*

The production records accepted for this ore field are from VicMine. Grade calculation excludes the biggest producer because of suspect recorded tonnage. In any event, the grade for this ore field is unusually high.

2.29.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>15 (5 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 6, Ore: 6</td>
</tr>
<tr>
<td>Biggest Producer O’Keefe Brothers (VicMine ID 378287) 100(^8^0) kg</td>
<td></td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>110(^8^1) kg for 1 898000 t ore (37 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>100 kg (91% of total production)</td>
</tr>
</tbody>
</table>

\(^8^0\) Rounded to nearest 1 kg  
\(^8^1\) Gold production rounded to the nearest 10 kg
Note that the mine locations and the associated lines of reef as per recent 1:50,000 geological maps have discrepancies of a few hundred metres.
2.30. Garibaldi Reef (Greendale West)

2.30.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.540</th>
<th>Long: 144.276</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>315°</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

2.30.2. Description

This ore field lies within the outcrop of undifferentiated Ordovician rocks as mapped by Roberts, 1985 (Roberts, 1985), but is along strike with mapped Lancefieldian and Bendigonian Castlemaine Group about 4 km north of this ore field.

2.30.3. Gold production

Historic production

| Historic gold production⁸³, kg | 25 |
| Recovered grade⁸⁴, g/t         | 8.1 |
| Processed ore, t (derived)    | 3090 |

⁸³ Gold production rounded to the nearest 1 kg
⁸⁴ from VicMine 2 kg Au for 125 t ore

Notes on production records

The production data in VicMine refer to the Garibaldi Reef in the Daylesford District (Hepburn), most probably in Yandoit. Production accepted for this ore field is based on official production records of Mining Registrars – 24.4 kg from 3023.6 t of ore (at 8.1 g/t Au). The total gold production accepted for this field was rounded up to 25 kg Au.

2.30.3. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Garibaldi Reef Adit (VicMine ID 367927) ²⁸⁵ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>²⁸⁶ kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

²⁸⁵ Rounded to nearest 1 kg
²⁸⁶ Gold production rounded to the nearest 1 kg
Garibaldi Reef ore field
2.31. Greendale

2.31.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.533</th>
<th>Long: 144.327</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>30°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.31.2. Description

This ore field lies within a within the outcrop of undifferentiated Ordovician as mapped by Roberts (1985), but is along strike with mapped Lancefieldian and Bendigonian Castlemaine Supergroup about 4 km north of this ore field.

2.31.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production³⁷, kg</th>
<th>585</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>10.8</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>54170</td>
</tr>
</tbody>
</table>

³⁷ Gold production rounded to the nearest 1 kg

Notes on production records

Total officially recorded production from the ore field as defined in this study was 583.6 kg Au. The total gold production accepted for this ore field was rounded up to 585 kg Au.

Average recovered grade for the ore field, calculated using the production records with both gold production and tonnage recorded, is 10.8 g/t Au (based on quartz crushings yielding 536 kg of gold).

2.31.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Red, White and Blue Shaft (VicMine ID 368033) 333³⁸ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>534³⁹ kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>2</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>534 kg (100% of total production)</td>
</tr>
</tbody>
</table>

³⁸ Rounded to nearest 1 kg
³⁹ Gold production rounded to the nearest 1 kg
Greendale ore field
2.32. Haddon

2.32.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.595</th>
<th>Long: 143.727</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>40°</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.32.2. Description

This ore field contains three primary gold mines. Most of this ore field is under Tertiary and Quaternary cover, however the bedrock, where exposed, consists of Lancefieldian Castlemaine Supergroup.

2.32.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production⁹⁰</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade⁹¹</td>
<td>6.9</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1488</td>
</tr>
</tbody>
</table>

⁹⁰ Gold production rounded to the nearest 1 kg

⁹¹ from VicMine 4 kg Au for 630 t ore

**Notes on production records**

The production records accepted for this ore field are from VicMine.

2.32.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 2</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Southern Cross Co (VicMine ID 381465) 3³ kg, Gladstone Cooperative Co (VicMine ID 377021) 5.9³ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>10³ kg for 630 t ore (6 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

³ Rounded to nearest 1 kg

² Rounded to nearest 0.1 kg

⁴ Gold production rounded to the nearest 1 kg
Ore fields in Bendigo Zone

Haddon ore field
2.33. Havelock North East

2.33.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.944</th>
<th>Long: 143.801</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0°</td>
<td>2.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

2.33.2. Description

This ore field lies within the outcrop of Castlemaine Supergroup and is, in part, covered by Quaternary sediments. VicMine mine locations seem to be displaced by about 300 m to the NE relative to the positions of the respective quartz reefs as mapped at 1:50,000 scale.

2.33.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

There are no production records for this ore field.

2.33.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2 (both named)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Havelock North East ore field
2.34. Heathcote

2.34.1 Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.953</th>
<th>Long: 144.705</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>300°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.34.2. Description

This ore field lies mainly within the outcrop of Castlemaine Supergroup, but extends into Cambrian sedimentary and volcanic units in the east.

2.34.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>21.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>37900</td>
</tr>
</tbody>
</table>

**Notes on production records**

The total gold production accepted for this ore field is based on VicMine records.

**Other sources**

Official production records of Mining Registrars indicate production from the Heathcote ore field (other than the New Holland Open Cut) of 771.7 kg Au from 36584 t of ore (average grade – 21.1 g/t Au).

The total recorded production, including the New Holland Open Cut, is 1911 kg from 1,648,945 t, at 1.2 g/t Au. Clearly, the overall grade is dominated by the recent production from the New Holland Open Cut, with an average grade of 0.77 g/t Au.

It is a likely that there are two different styles of mineralisation at Heathcote – typical Au - quartz vein (Bendigo) style and the refractory Au style. Analysis of the available geological information and discussions with C. Willman (who had worked on the deposit) confirmed that the mineralisation mined from the New Holland Open Cut does not belong to the mesozonal orogenic gold model, as opposed to the historically mined mineralisation.
The overall gold production for the Heathcote ore field (mesozonal orogenic gold) is accepted as 800 kg Au (3.6% above the recorded historic production), at an average recovered grade of 21.1 g/t Au.

### 2.34.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 15, Ore: 15</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>New Holland Open Cut (VicMine ID 371845) 1140 kg from 1,612,400 t ore.</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>1610 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>3</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>1548 kg (96% of total production)</td>
</tr>
</tbody>
</table>

*To nearest 10 kg  
*To nearest 100 t
2.35. Heathcote South (Tooborac)

2.35.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Long: 144.759</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat: - 37.012</td>
<td></td>
</tr>
</tbody>
</table>

Ore field data quality: 1

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>355°</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

2.35.2. Description

This ore field lies within the outcrop of Castlemaine Supergroup.

2.35.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>158</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>13.8</td>
</tr>
<tr>
<td>Processed ore[^97], t (derived)</td>
<td>11490</td>
</tr>
</tbody>
</table>

[^97]: To nearest 10 t

**Notes on production records**

The VicMine gold production is probably erroneous;

The production records accepted for this ore field are from Lanzer (1986):

- Production from Mundy Gully Reef is quoted as 125 kg from 9330 t (at 13 g/t Au);
- Redan - 7.2 kg Au from 910 t ore (at 8 g/t Au);
- Hagan - 16.3 kg Au from 206 t ore (at 69 g/t Au);
- New Year Venture - 0.9 kg Au from 97 t ore (at 9 g/t Au);
- South New Year Venture (Harknells) - recovered grade of 10 g/t Au;
- Syndicate - 3.2 kg Au from 60 t ore (at 54 g/t Au);
- Mundy Gully - 124 kg Au from 9327 t ore (at 13 g/t Au);
- Mundy Gully South Shaft Tribute - 6.2 kg Au from 886 t ore (at 7 g/t Au).

Total recorded production: 158[^98] kg Au ([^98]: to nearest 1 kg) from 11,490 t of ore (at 14 g/t Au).

Total production for the Tooborac ore field is accepted as per the recorded production above. Undoubtedly, this represents a very conservative estimate as the available production records are incomplete.
### 2.35.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>16 (3 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Mundy Gully Reef (VicMine ID 371645) 299 g from 7570 t ore.</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>2 g</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 (0% of total production)</td>
</tr>
</tbody>
</table>

*To nearest g*

![Heathcote South (Tooborac) ore field](image)
2.36. Inglewood

2.36.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.556</th>
<th>Long: 143.862</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>345°</td>
<td>11</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.36.2. Description

The Inglewood ore field lies mostly within the outcrop of Lancefieldian rocks, in places covered by Tertiary and Quaternary sediments (the covered portions account for less than 50% of the total area). The ore field is well-defined spatially. The Inglewood ore field as defined here closely corresponds to the Inglewood goldfield as traditionally used in the literature (Weston and Nott, 1993; Maher, 1996).

The bulk of mineralisation occurs in several quartz-reef systems striking NNW, hosted by Ordovician sedimentary rocks.

2.36.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production$^{101}$, kg</th>
<th>5900$^{102}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade$^{103}$, g/t</td>
<td>19.5</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>301,100</td>
</tr>
</tbody>
</table>

$^{101}$ Gold production rounded to the nearest 100 kg
$^{102}$ Maher (1996)
$^{103}$ Derived from total grade and tonnage presented in Maher (1996)

**Notes on production records**

- Total primary gold production recorded in VicMine is 4467 kg from 177,846 t of ore. This probably understates true production since VicMine and Maher (1996) report details of 44 primary production centres in the Inglewood goldfield with undefined location and totalling 432 kg of recorded gold production. In addition, some production in VicProd is attributed to the goldfield without being positively associated with any particular mine.

- The total production of 5877 kg is quoted after Maher (1996). Analysis of the associated VicMine database, however, could only confirm 4995 kg. The reason given by Maher (pers. comm.) is that production from the goldfield that could not be reliably
attributed to a particular mine was not included in the VicMine database. Production from spatially referenced production centres recorded in the database accompanying Maher (1996) is 4562 kg (cf O’Shea et al., 1992 with 3600 kg Au).

2.36.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>55</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Maxwells Reef (VicMine ID 362711) 1020 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>4470 kg for 177846 t</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>11</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>4230 kg (95% of total production)</td>
</tr>
</tbody>
</table>

Inglewood ore field
2.37. Kamarooka

2.37.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.506</th>
<th>Long: 144.335</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>350°</td>
<td>5.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.37.2. Description

This ore field lies within the outcrop of Bendigonian and Chewtonian Castlemaine Supergroup and is covered, in part, by Quaternary sediments. Several sources indicate that gold at Kamarooka was primarily disseminated in sediments rather than confined to quartz veins (Bowen, 1974; Cherry and Wilkinson, 1994; Whiting and Bowen, 1976). Consequently, the deposit may not belong to the Au - quartz vein (mesozonal orogenic) deposit model.

2.37.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>19.5</td>
</tr>
<tr>
<td>Processed ore(^{104}), t (derived)</td>
<td>5130</td>
</tr>
</tbody>
</table>

\(^{104}\) To nearest 10 t

Notes on production records

The production records accepted for this ore field are from O’Shea et al. (1992). Production quoted as 6 kg Au from 267 t ore (at 22 g/t Au).

Other sources

Perry (1975) is the original source for O’Shea et al. (1992). This author mentions some reefs not in VicMine, including Jones Reef (about 2 km N of the ore field and Pembroke Reef (probably identical to Pembroke Castle Reef, about 5 km to the NE of the ore field).

Cherry and Wilkinson (1994) report as follows:

“Kamarooka goldfield: The first record of gold in slate from Victoria was made from this goldfield in 1869. Discovered in 1864 the goldfield is located about 30 km north of
Bendigo. The most extensive workings occurred on the Doubtful reef, in a network of spurry quartz which was worked to over 100 m depth. The finely disseminated gold in the slates was difficult to extract, even using cyanide treatment and most of the gold was won from quartz. The principal line of workings stretched nearly 7 km, with a northerly trend. A parallel line, Pembroke Castle, 5.5 km to the east, only had shallow workings over about 500 m. Production is not well documented but the area is known to have produced at least 95 kg”.

Official production records of Mining Registrars:

Records for 1867 - 1869 contain details for 549.87 kg Au from 2817 t (at 19.5 g/t Au) from the Kamarooka area.

Given the sources above, the Kamarooka ore field has been extended to combine the Jones and Doubtful Reefs.

Total production has been increased by 5 kg from 95 kg in Cherry and Wilkinson (1994) to 100 kg. The average grade estimated from officially recorded production is 19.5 g/t Au.

### 2.37.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2 (1 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Kamarooka ore field
2.38. Kingower

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  -36.607</th>
<th>Long: 143.747</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>20°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.38.1. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Group.

2.38.2. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production[^1], kg</th>
<th>71</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>15.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>4700</td>
</tr>
</tbody>
</table>

[^1] Gold production rounded to the nearest 1 kg

Notes on production records

- Grades only were reported for this goldfield in Moon (1895):
  - North Frenchman - 31 g/t Au;
  - South Bon Accord - 62 g/t Au at surface, up to 15 g/t Au on average;
  - North Union - 370 g/t Au at surface, 220 g/t Au at depths between 15 and 45 m, then 370 g/t Au to 55 m;
  - South Walkers (southern extension of Union Reef) - between 26 g/t Au and 62 g/t Au;
  - Hutchinsons - between 62 g/t Au and 155 g/t Au;
  - Smiths Gully Reef - 124 g/t Au at surface, 15 g/t Au at 25 m depth.

Overall, reported grades seem reasonable, but total production appears to be very understated, e.g., the Hutchinsons Reef, averaging over 1 m thick, with the deepest shaft to 20 m and a worked length of 60 m implies that ore tonnage should have been over 2000 t and production in the vicinity of 200 kg gold.

Other sources

Official production records report production of 419.27 kg of gold from 3615 t of ore, mostly from Union and Bon Accord reefs, but not including Hutchison reef. The recorded production for Bon Accord is significantly smaller than that recorded in VicMine, suggesting incomplete official records. Combining production information from VicMine...
and reports of Mining Registrars indicates a total recorded production of 59 kg from 3825 t of ore, with a grade of 15.3 g/t Au.

Caldwell (1937b) reports that in the area around the Union Reef: “…Hutchison is stated to have obtained a patch worth £1700.”

Assuming £4 per oz, this implies production of 425 oz (13.2 kg), while VicMine records just 2.6 kg Au.

“10 - 12 oz produced in March 1933”. “… 120 tons of second - grade ore treated by Jenkins and party averaged 6 dwt. per ton.”

Using officially recorded production for the 1800-s and VicMine data for Bon Accord reef, plus Jenkins production from Caldwell (1937), gives a grade estimate of 15.1 g/t Au for 59.7 kg of gold. Total accepted production, including the estimate from Caldwell (1937) and 13.2 kg for Hutchison, is 71 kg at 15.1 g/t Au.

### 2.38.3. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 2</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Bon Accord Reef (VicMine ID 362921) 18(^{106}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>20(^{107}) kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

\(^{106}\) Rounded to nearest 1 kg

\(^{107}\) Gold production rounded to the nearest 1 kg

Kingower ore field
2.39. Kopke

2.39.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.550</th>
<th>Long: 143.708</th>
</tr>
</thead>
</table>

Ore field data quality | 2

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>280°</td>
<td>2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.39.2. Description

This ore field lies within the outcrop of the Lancefieldian –Castlemaine Supergroup. The ore field is covered, in part, by Tertiary and Quaternary sediments.

Summary of ore field properties:

| Historic gold production\(^{108}\), kg | 0.5 |
| Recovered grade\(^{109}\), g/t | 2.3 |
| Processed ore, t (derived) | 217 |

\(^{108}\) Gold production rounded to the nearest 0.01 kg

\(^{109}\) from VicMine 0.26 kg Au for 114 t ore

Notes on production records

The production records accepted for this ore field are based on VicMine. Given the incomplete nature of available records and three more mines with no production information, the accepted production has been increased to 0.5 kg at the recovered grade of 2.3 g/t Au.

2.39.3. Recorded mines (VicMine)

| Total number of mines | 5 |
| Total number of mines with production records | Gold: 2, Ore: 2 |
| Biggest Producer | Mitchell and Co. (VicMine ID 378112) 0.26 kg |
| Total Recorded Production | 0.26\(^{110}\) kg for 114 t ore (2 g/t) |
| Total producers over 25 kg | 0 |
| Total production over 25 kg | 0 kg (0% of total production) |

\(^{110}\) Gold production rounded to the nearest 0.01 kg
Kopke ore field
2.40. Korweinguboora

2.40.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.466</th>
<th>Long: 144.121</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0°</td>
<td>2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.40.2. Description

This ore field lies within the outcrop of Lancefieldian, Chewtonian and Castlemainian Castlemaine Supergroup. This ore field was extended to the south to accommodate the presence of workings not present in VicMine.

2.40.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>87.5</td>
</tr>
<tr>
<td>Processed ore[^1][^11], t (derived)</td>
<td>1060</td>
</tr>
</tbody>
</table>

[^1]: To nearest 10 t

**Notes on production records**

The production records accepted for this ore field are from VicMine.

2.40.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2, plus two shafts from VicShaft – the Northern Parker and one unnamed, possibly the Parker.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Bradford (VicMine ID 368207) 62[^112] kg from 711 t ore (87.5 g/t)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>93 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>2</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>93 (100% of total production)</td>
</tr>
</tbody>
</table>

[^11]: To nearest 1 kg
Korweinguboora ore field
2.41. Kyneton

2.41.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.285</th>
<th>Long: 144.420</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.41.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup.

2.41.3. Gold production

**Historic production**

| Historic gold production, kg | 62 |
| Recovered grade, g/t        | 57 |
| Processed ore, t (derived)  | 1074 |

**Notes on production records**

The production records accepted for this ore field are from VicMine

**Other sources**

- VicProd records 597.62 kg Au at 56 g/t.
- Ore field geometry likely to be closer to: long axis 310°, 200 m long, >20 m wide (Svanosio and Laughton, 1996), although for the purposes of this report it will be taken as in the table above.

2.41.4. Recorded mines (VicMine)

| Total number of mines                  | 3 |
| Total number of mines with production records | Gold: 1, Ore: 1 |
| Biggest Producer<sup>113</sup>          | Premier Main Shaft (VicMine ID 369394) 62<sup>114</sup> kg Au from 1074 t<sup>115</sup> at a grade of 57 g/t Au (grade recorded in VicMine range between 7 g/t and 889 g/t). |
| Total Recorded Production              | 60 kg |
| Total producers over 25 kg             | 1 |
| Total production over 25 kg            | 1 (100 % of total production) |

<sup>113</sup> O’Shea et al. (1992)

<sup>114</sup> To nearest 1 kg

<sup>115</sup> To nearest 1 t
Kyneton ore field
2.42. Leichardt

2.42.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.686</th>
<th>Long: 144.070</th>
</tr>
</thead>
</table>

| Ore field data quality | 1 |

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>295°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.42.2. Description

This ore field lies within the outcrop of Chewtonian and Lancefieldian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.42.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

O’Shea et al. (1992) stated that “a few reefs were worked on this field with little success”.

2.42.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2 (1 named)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown. Only named mine is Guthries(^1) (VicMine ID 373320), with no recorded production</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

\(^1\) O’Shea et al. (1992)
Leichardt ore field
2.43. Little Hampton

2.43.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.331</th>
<th>Long: 144.300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>70°</td>
<td>2.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.43.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Lancefieldian and Bendigonian Castlemaine Supergroup.

2.43.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production(^n), kg</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^n), g/t</td>
<td>17.8</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1120</td>
</tr>
</tbody>
</table>

\(^n\) Gold production rounded to the nearest 1 kg
\(^n\) From actual recorded production in Ferguson (1906)

The production records in VicMine are sourced from Ferguson (1906), but contain a transcription error (the last 0 in all three VicMine production records, e.g., 1040 oz, were actually the first ‘O’ in ozs. (ounces) in the source (i.e., “104 oz”). The total actual recorded production by the Sugarloaf Company to 1904 was 515 oz Au from 915 tons – with no estimate for the early production. Also, at the time of writing (1904), the company was about to start large-scale stopping from an adit.

Other sources

Ferguson, (1906): for the Sugarloaf (Gambetti) Reef – 515 oz from 915 tons to 1904 (this is the source for VicMine).

However, “This is not a full return of the gold obtained from the mine, but only that won by the present company. Formerly the reef was worked from the surface, mostly on the underlie to, in one place, a depth of 40 feet”. As of the time of writing, a long adit intersected the lode at 110 feet below the surface, and “the company has a long length of auriferous quartz to stope out at the adit level, and has the auriferous ore continuing down under it”.
Cricketer’s Reef – “The last crushing of 5 tons from 60 feet yielded 15 dwts. of gold to the ton”. This is all the production recorded in VicMine, but it is likely that there was more.

Foster, (1937): Little Hampton reefs. Sutton and sons crushed 2 tons of stone for a return of 15 oz. Kitty Wells mine location is uncertain, “approx. 1 mile west of the Blackwood belt” and therefore not in Little Hampton, so its production of 525 oz in 1905 - 1908 is not included here. Using this source, the total recorded production was 169.13 kg Au from 947 t ore (at 17.8 g/t Au). The accepted production is increased to 20 kg to account for the early unrecorded production.

2.43.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Sugarloaf Reef (VicMine ID 419708) 158(^{119}) kg Au</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>158(^{120}) kg – an error (see above)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>158 kg (100% of total production)</td>
</tr>
</tbody>
</table>

\(^{119}\) Rounded to nearest 1 kg

\(^{120}\) Gold production rounded to the nearest 1 kg
2.44. Lockwood

2.44.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.821</th>
<th>Long: 144.130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.44.2. Description

This ore field lies within the outcrop of Chewtonian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.44.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>114</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The production records accepted for this ore field are from O’Shea et al. (1992) and Cherry and Wilkinson (1994).

2.44.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer¹²¹</td>
<td>Alexander Reef (VicMine ID 373297)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>114¹²² kg Au – tonnage/grade unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>114 kg (100% of total production)</td>
</tr>
</tbody>
</table>

¹²¹ Production is not recorded in VicMine
¹²² Gold production rounded to the nearest 1 kg
Lockwood ore field
2.45. Lyell – Myrtle Creek – Redesdale

2.45.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.956</th>
<th>Long: 144.482</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>330°</td>
<td>3.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.45.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments and Newer Volcanics.

2.45.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>22.5</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>11100 (up to 12440 t)</td>
</tr>
</tbody>
</table>

Notes on production records

There are no production records for this ore field in VicMine.

Other sources

Cherry and Wilkinson (1994) report production of 130 kg\(^{123}\) of gold (\(^{123}\) Includes only recorded production between 1871 and 1873 from the Myrtle Creek Co. mine. Several other mines were in production during the same period and from 1889 to at least 1909. Overall production was probably at least double this).

Dunn (1909a) reports production from the main shaft on Linda Reef between 1902 and 1906 of 42 kg Au from 4060 tons of ore. The Horseshoe Bend Reef was worked extensively during the 1860s for a distance of nearly 2 miles both from the surface and by several shafts more than 30 m deep, “…and a very considerable tonnage of quartz must have been crushed.” The reef, running along a fault line, strikes 30° NW and dips 67° W at a slight angle to bedding, striking 40° deg NW and dipping 62° W. The quartz vein was 6 to 8 inches thick. The Amelia and Ben Guy Reefs lie about 20 chains west of the Linda Reef, on the Myrtle Creek. Extensive work on the Amelia Reef in 1860s. 5 chains
east of the Amelia Reef is the Jumping Moses Reef, with shafts more than 30 m deep and “considerable work has been done.” Several other worked reefs described in the vicinity.

Production of 160 kg Au from 4884 t of ore between 1867 and 1914 is reported in VicProd. This includes production by the Myrtle Creek Co. between 1871 and 1873 of 1965 oz (61.1 kg) from 1807 tons. This is significantly less than the production quoted by Cherry and Wilkinson (1994), probably due to incomplete Mining Registrars records. No production was recorded from the Linda mine between 1902 and 1906.

Assuming that the production quoted by Cherry and Wilkinson (1994) is an error, total recorded production from the ore field was 201.6 kg Au. Accepting the production quoted by Cherry and Wilkinson (1994) would give a total recorded production of 270.3 kg Au. Given the incompleteness of officially recorded production, the total production from the ore field is accepted to be at least 250 kg Au – and possibly as high as 280 kg.

The grade accepted for the ore field is from the total recorded production from the Linda mine (Dunn, 1909a) and VicProd - 22.5 g/t Au.

### 2.45.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>12 (10 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer⁹²⁴</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

⁹²⁴ O’Shea et al. (1992)

Lyell - Myrtle Creek ore field
2.46. Majorca

2.46.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.141</th>
<th>Long: 143.795</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>320°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.46.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Lancefieldian – Warrendian Castlemaine Supergroup (with some Quaternary cover). Although it probably extends about 5 km further south, the geometry of the ore field as based on recorded mines is represented below.

2.46.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production[^125]</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade[^126]</td>
<td>73.6</td>
</tr>
<tr>
<td>Processed ore[^127]</td>
<td>1900</td>
</tr>
</tbody>
</table>

[^125]: Gold production rounded to the nearest 1 kg
[^126]: from VicMine 134 kg Au for 1 800 t ore
[^127]: Rounded to nearest 100 t

*Notes on production records*

The production records accepted for this ore field are based on VicMine. Given an additional 8 recorded mines without recorded production, the accepted production was increased to 140 kg. The estimated gold grade appears to be unrealistically high.

2.46.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 2</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Prince Alfred (VicMine ID 367202) 111[^128] kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>134[^129] kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>111 kg (83% of total production)</td>
</tr>
</tbody>
</table>

[^128]: Rouded to nearest 1 kg
[^129]: Gold production rounded to the nearest 1 kg
2.47. Maldon – Muckleford

2.47.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.035</th>
<th>Long: 144.081</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.5</td>
<td>350°</td>
<td>16</td>
<td>7</td>
</tr>
</tbody>
</table>

2.47.2. Description

Although there appear to be a number of distinct reef lines, these occur in a restricted and near-continuous area west of the Muckleford Fault within the outcrop of the Lancefieldian Castlemaine Supergroup. Thus this ore field, as here defined, is deemed to represent a zone of continuous mineralisation at the 1.6 km scale. The ore field includes the historical Maldon and Muckleford Goldfields and lies entirely within the Tarrangower Mining Division.

2.47.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production(^{130}), kg</th>
<th>58,700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^{131}), g/t</td>
<td>27</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>2,174,000</td>
</tr>
</tbody>
</table>

\(^{130}\) Gold production rounded to the nearest 10 kg

\(^{131}\) from VicMine 15,600 kg Au from 577,000 t ore

**Notes on production records**

Most recent company reports seem to refer to the work of Ebsworth and Krokowski DeVickerod (2002) (Alliance Company reports, VIMP Report 75 and other publications) and Willman et al. (2002) as the most authoritative, quoting an orogenic gold production of 1,750,000 oz (54.4 t). Those production estimates are in perfect agreement with the estimate of Bowen (1974) and Bowen et al. (1974). However, the spatial extent of the Maldon Goldfield is not clearly defined in any of those publications.

Ebsworth and Krokowski DeVickerod (2002) reported total historic production for the Maldon Goldfield as 1.75 Moz, but provided details only for the central part of the
goldfield ("Central Maldon Goldfield"), between 238,000E and 240,000E and 5,900,000N and 5,905,000N (AGD 66, Zone 55), with the major reefs:

- Eaglehawk Reef – 491,400 oz (15283 kg)
- Nuggetty Reef – 30,000 oz (9361 kg)
- German Reef – 270,300 oz (8406 kg)
- Beehive Reef – 321,000 oz (7184 kg)
- Victoria and Derby Reefs – 158,950 oz (4943 kg)
- Wilsons Reef – 61500 oz (1913 kg)

Using sparse historic information provided in the report for other reefs in the area, an additional 235 kg of gold production can be assumed as a minimum estimate for the smaller reefs. Using Ebsworth and Krokowski DeVickerod (2002), total historic production from the Central Maldon Goldfield can be estimated as 47325 kg Au.

The largest (by gold production) reef system of the Maldon Goldfield outside the Central Maldon Goldfield of Ebsworth and Krokowski DeVickerod (2002) was the North British Line (Willman et al., 2002), or Perkins Reef. Historic production estimates for the reef range between 6,440 kg Au (Mason and Webb, 1953) and 7540 kg (Bowen, 1974).

Historic records of the Department of Mines, Victoria (Mineral Statistics, Reports of the Mining Registrars, Annual Reports) contain information on 1,099,568 oz (34.2 t) of gold from reef production between 1864 and 1933. Records for 1864 - 1890 are incomplete and reflect only “selected crushings” that could be confirmed by mining registrars. Pre - 1864 production was not recorded.

**Other sources**

DPI records (VicProd) indicate that total gold production from the Maldon Goldfield area from 1962 to July 2005 was 2,201.22 kg Au. Of that total production, 99% was in 1987 - 2004 by Triad Minerals and Alliance. For 1864 - 1960, only 27.6 t of gold production could be confirmed, which is well short of the production reported in Mineral Statistics, Reports of the Mining Registrars and Annual Reports.

Production reported by Willman et al. (2002) (only part of the entire goldfield, between 238,500E and 240,000E and 5,900,000N and 5,905,000N) is 1.6 Moz (± 16,800 oz from other versions of production records). Not all mines in that report are recorded in VicMine.

Production quoted from Cherry and Wilkinson (1994) is “over 55.6 tonnes of gold” (1,787,800 oz). A sketch of the Maldon Goldfield shows an area extending east to the Muckleford Fault, west to Mount Tarrengower and includes the Central Maldon Goldfield.
of Ebsworth and Krokowski DeVickerod (2002), the reefs to the west and the northern part of the Muckleford Goldfield (only part of the entire goldfield, between 237,000E and 241,000E; 5,898,500N and 5,906,000N).

Bowen (1974) estimated total gold production from the Maldon goldfield as 54,425 kg Au at 28 g/t, including 7,540 kg Au from the North British mine.

Production around Fenteman’s Reef (Quinn, 2007) was reported by Nankiwell (1861) as 1784 oz (to 1861, excluding Fentemans Main Shaft). According to VicMine, Fentemans produced 145 oz.

Mason and Webb (1953) reported total recorded production as 1.617 Moz (50.3 t); an average recovered grade estimated for 0.7 Moz of that total production was 27.9 g/t Au.

2.47.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>346 (138 Unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 63, Ore: 61</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>North British (VicMine ID 367301) 3987 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>15553 kg from 577,000 t ore (27 g/t Au)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>30</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>15378 (99% of total production)</td>
</tr>
</tbody>
</table>
Maldon ore field
2.48. Marong

2.48.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.710</th>
<th>Long: 144.146</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0°</td>
<td>4.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.48.2. Description

This ore field lies within the outcrop of Chewtonian and Castlemainian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.48.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The Duke of Edinburgh Reef referred to in O’Shea et al. (1992) doesn’t appear in the VicMine database. According to the description in Cundy (1899), this reef is to the north of the Slate Reef Co, which would put it in the Wilsons Hill ore field.

2.48.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>6 (3 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Appendix 2

Marong ore field
2.49. Maryborough

2.49.1 Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.040</th>
<th>Long: 143.732</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>113</td>
<td>345°</td>
<td>19</td>
<td>12</td>
</tr>
</tbody>
</table>

2.49.2. Description

This ore field contains a series of locally sub-parallel individual lines of reef all lying within a restricted and near continuous zone within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup. A small cluster of gold occurrences to the north of the Maryborough ore field was combined with the main ore field.

2.49.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production¹³⁵, kg</th>
<th>5550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade¹³⁶, g/t</td>
<td>13.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>423660</td>
</tr>
</tbody>
</table>

¹³⁵ Gold production rounded to the nearest 1 kg
¹³⁶ from VicMine records with both production and ore tonnage.

Notes on production records

The production records for this ore field are based on VicMine. Given that more than 150 recorded mines do not have any associated production, plus 69 kg of recent production, the accepted production has been increased to 5550 kg. O’Shea et al. (1992) quotes production of 3100 kg Au.

2.49.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>228 (122 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 75, Ore: 73</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>New Leviathan (VicMine ID 366308) 1825 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>5450¹³⁷ kg for 390000 t ore (14 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>26</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>5075 kg (93% of total production)</td>
</tr>
</tbody>
</table>

¹³⁷ Gold production rounded to the nearest 1 kg
Maryborough ore field
2.50. May Reef

2.50.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.529</th>
<th>Long: 144.530</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$10^9$</td>
<td>2.5</td>
<td>1</td>
</tr>
</tbody>
</table>

2.50.2. Recorded mines (VicMine)

There is no information on this ore field in VicMine, but it is referred to in Weston (1992) and Weston and Nott (1993).
2.51. McIntyre (Matrix Reef)

2.51.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.686</th>
<th>Long: 143.684</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>350°</td>
<td>2.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>

2.51.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup.

2.51.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production ¹³⁸, kg</th>
<th>187</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>147.7¹³⁹</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1260¹⁴⁰</td>
</tr>
</tbody>
</table>

¹³⁸ Gold production rounded to the nearest 1 kg

¹³⁹ though the final recorded crushing indicated a grade of about 24 g/t Au — a much more likely value

¹⁴⁰ or at 24 g/T Au, 7800 t

The production records accepted for this ore field are from VicMine.

**Notes on production records**

- Dunn (1920) reported production of gold worth over £24,000 by two parties. “The last crushing just completed returned 435 oz. smelted gold from 57 tons of quartz. … It [the gold] is of high quality, worth £4 3s. per oz.” Thus, the production can be estimated as over 5,783 oz (180 kg). Note that the paper is dated 22/08/1912; consequently, production in late 1912 – 1913 was not included, but is estimated as an additional 3 kg Au. The mineralisation was described as being on the intersections of the quartz reef and “indicators”, which explains the anomalously high gold grades.

- Official production records indicate 876 oz of Au produced from 145 t of ore in 1910 - 1913, which was probably the source for VicMine. However, ore tonnage was not recorded for 80 oz of gold production. Using only the records with both recorded gold production and ore tonnage would give an average grade of 170.4 g/t Au. Thus, the
overall ore tonnage can be estimated as 160 t. Official production records include another 73 oz from the McIntyres area, with an average recovered grade of 49.2 g/t Au.

- Combining this with the production from the Matrix Reef gives a total production of 29.5 kg at 147.7 g/t Au (from 200 t of ore). Given the uncertainty of location of this additional production, these values can be used as the maximum officially recorded production.

- O’Shea et al. (1992) quote 187 kg Au production, after Dunn (1920);
- Using the sources above, total production is accepted as per O’Shea et al. (1992) – 187 kg Au, at an average recovered grade of 148 g/t Au.

### 2.51.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Matrix Reef (VicMine ID 372710) 27(^1) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>27(^1) kg for 145 t ore (186 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>27 kg (100% of total production)</td>
</tr>
</tbody>
</table>

\(^1\) Rounded to the nearest 1 kg

\(^2\) Rounded to the nearest 1 kg
2.52. Metcalfe

2.52.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.118</th>
<th>Long: 144.451</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>335°</td>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.52.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup.

**Summary of ore field properties:**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>21.7</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>4380</td>
</tr>
</tbody>
</table>

2.52.3. Gold production

**Historic production**

Official production records of Mining Registrars is for 59.4 kg Au at an average grade of 20.7 g/t Au, with no reference to Steads Reef. VicProd contains production details for Steeds Reef (Barfold Ranges, McBinteney or McBritt any and Co.) as 60 tons (61 t) for 1.73 kg Au, probably the source for Steads Reef in VicMine. Combining Officially recorded production and production from Steeds Reef (as per VicProd) gives 61 kg of gold at an average grade of 20.8 g/t. There were several other producers in the Barfold area, with a total recorded production of 31 kg Au from 1315 t of ore. The Green Hill Co. probably operated near the township of Green Hill, about 5 km to the south; Barfold is about 5 km east of Metcalfe. Thus the production could have come from three discreet small deposits, rather than a single ore field.

Overall recorded production 92 kg at a grade of 21.7 g/t from 4250 t ore, with the accepted production for the ore field rounded up to 95 kg Au from 4380 t ore.
### 2.52.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>6 (5 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Steads Reef (VicMine ID 369466) 1.7(^{143}) kg from 60 t ore (28 g/t)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>1.7 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 (0% of total production)</td>
</tr>
</tbody>
</table>

\(^{143}\) To nearest 0.1 kg

---

![Map of Metcalfe ore field](image_url)

Metcalfe ore field
2.53. Mills Reef (Wattle Flat West)

2.53.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.465</th>
<th>Long: 143.923</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>20°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.53.2. Description

This ore field contains two mines lying within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.53.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>7.8</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>320</td>
</tr>
</tbody>
</table>

*Notes on production records*

The production records accepted for this ore field are based on VicMine. Given a second mine with no recorded production (30 m deep, mined over a 40 m length), the accepted production has been increased to 2.5 kg.

2.53.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Mills Reef (VicMine ID 366691) 2 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>2.2 kg for 283 ton ore (7.8 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>
2.53.5. Mills Reef (Wattle Flat West) ore field

Mills Reef ore field
2.54. Monmouth (Garibaldi West)

2.54.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.731</th>
<th>Long: 143.829</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>270°</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

2.54.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup. The ore field is covered, in part, by Quaternary sediments.

2.54.3. Gold production

| Historic gold production\(^{144}\), kg | 6 |
| Recovered grade, g/t                  | 21.3 |
| Processed ore, t (derived)            | 270 |

\(^{144}\) Gold production rounded to the nearest 0.1 kg

Notes on production records

The production records accepted for this ore field are from VicMine.

The production records for this mine appear to be unusually comprehensive and the production is explicitly stated to have come from crushed quartz.

Other sources

Bradford (1903a) reports that this particular site is one of a group of deposits, although these other deposits are not described. The current location of this site does not conform to the description of the location of Bradford (1903a).

2.54.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Monmouth Co (VicMine ID 378116) (^{145}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>(^{146}) kg from 220 t (23 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

\(^{145}\) Rounded to nearest 0.1 kg

\(^{146}\) Gold production rounded to the nearest 0.1 kg
Ore fields in Bendigo Zone

Monmouth ore field
2.55. Mount Egerton-Gordon

2.55.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.586</th>
<th>Long: 144.110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>10°</td>
<td>5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

2.55.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of what is probably Lancefieldian Castlemaine Supergroup, as projected from the Meredith 1:50,000 map (Bolger, 1980), but mapped as undifferentiated Ordovician on the 1:50,000 Ballan map (Roberts, 1986) (with some Tertiary and Quaternary cover). Although it is likely that the Elaine, Mount Doran, Egerton and Gordon goldfields represent parts of the to the same regional mineralised system, here they are treated as two separate ore fields.

2.55.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production ¹⁴⁹, kg</th>
<th>16,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>12</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1,333,000</td>
</tr>
</tbody>
</table>

¹⁴⁹ Gold production rounded to the nearest 10 kg

Notes on production records

The VicMine production records for this goldfield are woefully inadequate. The production accepted for this ore field is taken as the commonly accepted 15.5 -16 t Au (Bradford, 1903b; Kenny, 1936).
2.55.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>42 (25 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 2, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Blackhorse Shaft (VicMine ID 368550) 4780\textsuperscript{150} kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>6650\textsuperscript{151} kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>2</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>6650 kg (100% of total production)</td>
</tr>
</tbody>
</table>

\textsuperscript{150} Rounded to nearest 10 kg

\textsuperscript{151} Gold production rounded to the nearest 10 kg

Mount Egerton - Gordon ore field
2.56. Mt Glasgow-New Years Reefs (Dunach)

2.56.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.184</th>
<th>Long: 143.761</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>0°</td>
<td>3.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.56.2. Description

This ore field contains a series of locally sub-parallel individual lines of reef, all lying within a restricted and nearcontinuous zone within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.56.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^{152}), g/t</td>
<td>8.4</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>518</td>
</tr>
</tbody>
</table>

\(^{152}\) from VicMine 4 kg Au for 500 t ore

Notes on production records

The production records accepted for this ore field are from VicProd, which is generally consistent with VicMine.

2.56.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Mount Glasgow Reef (VicMine ID 366614) 2.5 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>4(^{153}) kg for 500(^{154}) t ore (8 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

\(^{153}\) Gold production rounded to the nearest 1 kg
\(^{154}\) rounded to the nearest 100 kg
Mt Glasgow-New Year Reefs (Dunach) ore field
2.57. Mysia

2.57.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.253</th>
<th>Long: 143.781</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>60°</td>
<td>3.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.57.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup and is, in part, covered by Quaternary sediments.

2.57.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

There are no production records for this ore field

**Other sources**

The original source for this ore field is Edwards et al. (2001). The mines are shown on the map, but there is no other information.

2.57.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>6 (6 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Mysia ore field
2.58. Neilborough East

2.58.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 36.577</th>
<th>Long: 144.281</th>
</tr>
</thead>
</table>

| Ore field data quality | 1 |

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0°</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.58.2. Description

This ore field lies within the outcrop of the Lancefieldian / Darriwillian / Castlemanian / Yapeenian Castlemaine Supergroup sedimentary rocks and is covered in part by Recent alluvium.

2.58.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>24.9</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>400</td>
</tr>
</tbody>
</table>

**Other sources**

Black Rock and Austrian reefs are the only reefs in the area with recorded production. The recorded production of 5.4 kg Au is only for 1867 - 1869. To account for the missing production records, the accepted production is increased to 10 kg Au, which is probably conservative. Information is from Department of Mines, 1891.

2.58.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>15 (6 unknown)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Neiborough East ore field
2.59. North Byron

2.59.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.141</th>
<th>Long: 144.046</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

2.59.2. Description

This ore field lies within the outcrop of Bendigonian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.59.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>504</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>18.6</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>27,000</td>
</tr>
</tbody>
</table>

**Notes on production records**

The production records accepted for this ore field are from VicProd, which is consistent with VicMine.

Official historic production records report cumulative production to the end of 1908 as 504 kg Au from 27046 t ore, at an average recovered grade of 18.6 g/t Au.

2.59.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>North Byron (VicMine ID 367568) 500155 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>500156 kg from 27500157 t (18 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>500 kg (100% of total production)</td>
</tr>
</tbody>
</table>

155 Rounded to nearest 10 kg
156 Gold production rounded to the nearest 10 kg
157 Rounded to nearest 100 t
North Byron ore field
2.60. Rathscar

2.60.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.955</th>
<th>Long: 143.579</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.60.2. Description

There is some dispute as to the geology of this ore field. Although according to the Dunolly 1:50,000 mapsheet, the ore field falls within the Cambrian St Arnaud Group, in the hanging wall of the Avoca fault (i.e., to the west of the fault), observations by D. Moore (pers comm.) seem to indicate that the ore field actually lies in the Lancefieldian Castlemaine Supergroup, within the footwall of the Avoca fault. The latter interpretation is currently accepted.

2.60.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>10</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>3500</td>
</tr>
</tbody>
</table>

**Notes on production records**

Accepted production is 35 kg at 10 g/t Au.

- Howitt (1937b): Production from the Rathscar Mine to 1906 was recorded as 915 oz 14 dwt from 2793 tons of ore. (That paper was submitted in March 1928);
- Howitt (1937c): Production recorded from a new mine west of the old Rathscar mine, to 1931, was 32.3 oz from 58 tons of ore. (That paper was submitted in February 1931);
- Mayne (1937): Recorded production from the Rathscar Mine to June 1906 was 848 oz 6 dwt from 2638 tons of ore. “There is still a large amount of ore in sight, approximately 1750 tons, and though of low grade should pay to take out. With the connection between No. 1 and bottom levels we will also have 1800 tons opened up, which should prove payable.” (That paper was submitted in June 1906).
○ Caldwell (1937d): “Within the last two years 160 tons averaged 6 dwt. of gold to the ton”. (That paper was submitted in January 1936);

○ Mayne (1937) indicated that a large amount of lower-grade ore remained unmined.

From the above, total recorded production was 31 kg from 3059 t (at 10.1 g/t Au).

Production records in VicMine are incomplete for the period to 1906 and are therefore excluded. To account for unrecorded production, total production is accepted as 35 kg at 10 g/t Au, while the total originally contained ore can be estimated as 6000 t at 7 g/t for 42 kg of contained gold.

### 2.60.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Rathscar Mine (VicMine ID 362755)</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>15.6 kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0</td>
</tr>
</tbody>
</table>

158 The inclusion of Burkes Flat Mine is an error in VicMine

![Rathscar ore field](image)
2.61. Raywood

2.61.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.531</th>
<th>Long: 144.208</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>330°</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

2.61.2. Description

This ore field lies within the outcrop of Chewtonian, Castlemainian and Bendigonian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.61.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade ¹⁵⁹, g/t</td>
<td>9.1</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>164840</td>
</tr>
</tbody>
</table>

¹⁵⁹ Recorded production of 877 kg from 96,770 t ore

**Notes on production records**

Cockatoo Reef, mentioned by O’Shea et al. (1992), does not appear in VicMine as lying within this ore field.

The production for Nil Desperandum is taken from Cherry and Wilkinson (1994) - 1142 kg Au (Cherry and Wilkinson, 1994; Forwood, 1980). Additional production from other reefs is taken from the production records of the Department of Mines (20.3 kg Au in 1867 - 1872).

Total recorded production from the above records adds up to 1163 kg Au, but the actual production from the ore field was undoubtedly larger. No production records were found for 19 mines with shafts recorded in VicMine, no records were kept before 1864 and the available production records after 1864 are incomplete. Consequently, the total historic production from the Raywood ore field is deemed to be at least 1170 kg Au.

Simon Maher (unpublished) previously estimated gold production for the historic Raywood goldfield (identical to the Raywood ore field as defined here) as 1500 kg Au. That estimate is accepted for the Raywood ore field.
2.61.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>21 (12 unnamed)</td>
</tr>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer(^{161})</td>
<td>Nil Desperandum Reef</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>1142</td>
</tr>
</tbody>
</table>

\(^{161}\) O’Shea et al. (1992)

Raywood ore field
2.62. Rocklyn

2.62.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  -37.449</th>
<th>Long: 144.064</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>50°</td>
<td>7.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.62.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Bendigonian Castlemaine Supergroup (with some Tertiary and Quaternary cover, Willman et al., 2002). Historically, this area was also referred to as the Korweinguboora goldfield, which covers the Korweinguboora ore field 2 km to the east.

2.62.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production¹⁶³, kg</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade¹⁶⁴, g/t</td>
<td>22.9</td>
</tr>
<tr>
<td>Processed ore¹⁶⁵, t (derived)</td>
<td>3490</td>
</tr>
</tbody>
</table>

¹⁶³ **Gold production rounded to the nearest 1 kg**

¹⁶⁴ **from VicMine using only records with both Au production and tonnage available.**

¹⁶⁵ **Rounded to nearest 10 t**

**Notes on production records**

The production records accepted for this ore field are based on VicMine. Given another 15 mines with no recorded production, the total accepted production is increased to 80 kg Au.

2.62.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 5, Ore: 5</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Try Again (VicMine ID 368200) 37¹⁶⁶ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>61¹⁶⁷ kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>37 kg (61% of total production)</td>
</tr>
</tbody>
</table>

¹⁶⁶ **Rounded to nearest 1 kg**

¹⁶⁷ **Gold production rounded to the nearest 1 kg**
2.63. Rokewood

2.63.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.898</th>
<th>Long: 143.717</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>320°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.63.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup (with some Tertiary and Quaternary cover).

2.63.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production¹⁶⁸, kg</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade¹⁶⁹, g/t</td>
<td>17.6</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>970</td>
</tr>
</tbody>
</table>

¹⁶⁸ Gold production rounded to the nearest 1 kg

¹⁶⁹ from VicMine 17 kg Au for 1000 t ore

**Notes on production records**

The production records accepted for this ore field are from VicMine.

2.63.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Wheel of Fortune Co. (VicMine ID 379424) 17¹⁷⁰ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>17¹⁷¹ kg for 100 t ore (17 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

¹⁷⁰ Rounded to nearest 1 kg

¹⁷¹ Gold production rounded to the nearest 1 kg
Rokewood ore field
2.64. Ross Creek

2.64.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.630</th>
<th>Long: 143.727</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.64.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup. The ore field is covered, in part, by Tertiary and Quaternary sediments.

2.64.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production¹⁷², kg</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>25</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>32</td>
</tr>
</tbody>
</table>

¹⁷² Rounded to nearest 0.1 kg

**Notes on production records**

The production records accepted for this ore field are from VicMine.

2.64.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>British and American Co (VicMine ID 376619) 0.8¹⁷³ kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>0.8¹⁷⁴ kg from 32 t (25 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

¹⁷³ Rounded to nearest 0.1 kg

¹⁷⁴ Gold production rounded to the nearest 0.1 kg
Ross Creek ore field
2.65. Sebastian

2.65.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.606</th>
<th>Long: 144.189</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>340°</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.65.2. Description

This ore field lies within the outcrop of the Castlemainian and Yapeenian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments. Four lines of reef were recognised in this field.

2.65.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production</th>
<th>5,780</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>13.2</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>438,300</td>
</tr>
</tbody>
</table>

Gold production rounded to the nearest 10 kg

Notes on production records

- The production records accepted for this ore field are from O’Shea et al. (1992): 5,780 kg of gold from the Frederick the Great, produced between 1864 and 1912. The Frederick the Great line of reef (O’Shea et al., 1992) includes VicMine IDs 373328, 373341 and 373358.

- The Department of Mines Quarterly reports production records for Frederick the Great and Eureka Reefs from 1864 to 1872 and from 1912. Total recorded gold production was 1042 kg, with a calculated average grade of 14.8 g/t Au.

- Whitelaw (1899) recorded the following about the Frederick the Great mine: “This party, it is stated, in eight years [1864 - 1872] crushed 165,443 tons of quartz, which yielded 73375 ounces of gold...” “The total amount of gold won to date is put down at over 170,000 ounces.” “In fact, the field has not yet been even superficially explored.”
○ The average grade for the Sebastian ore field was calculated using data from Whitelaw (1899) for production between 1864 and 1872 and official production records for later production (2376 kg from 180,177 t), as 13.2 g/t Au.

○ Bowen (1974) reported production from the Frederick the Great mine of 324,498 t of ore, yielding 4286 kg of gold, giving an average recovered grade of 13.2 g/t Au.

2.65.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>10 (3 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Sebastian ore field
2.66. Sebastopol

2.66.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.208</th>
<th>Long: 144.223</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>290°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.66.2. Description

This ore field lies within a restricted and near - continuous zone within the outcrop of the Bendigonian and Chewtonian Castlemaine Group.

2.66.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>115</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^{177}), g/t</td>
<td>8.9</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>12920</td>
</tr>
</tbody>
</table>

\(^{177}\) from VicMine 113 kg Au for 12700 t ore

Notes on production records

The production records accepted for this ore field are based on VicMine, but increased to 115 kg to account for unrecorded production.

2.66.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3 (2 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Sebastopol (VicMine ID 369424) 113(^{178}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>113(^{179}) kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>113 kg (100% of total production)</td>
</tr>
</tbody>
</table>

\(^{178}\) Rounded to nearest 1 kg

\(^{179}\) Gold production rounded to the nearest 1 kg
Sebastopol ore field
2.67. Sedgwick

2.67.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.926</th>
<th>Long: 144.335</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>350°</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.67.2. Description

This ore field lies within the outcrop of Castlemainian and Chewtonian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.67.3. Gold production

Historic production

| Historic gold production, kg | 115 |
| Recovered grade, g/t         | 12  |
| Processed ore\(^{180}\), t (derived) | 9580 |

\(^{180}\) To nearest 10 t

Notes on production records

There are no production records for this ore field in VicMine.

Other sources

- Lenard (1988) quotes 8381 tonnes of ore at 12 g/t Au for the Sedgwick mine, with a total production of approximately 100 kg Au. The workings were reported to have a strike length of 2.6 km. This is unsourced, but may have come from internal WMC documents (M. Lenard, pers comm.). A map of the Sedgwick mine is included in that report.

- Cherry and Wilkinson (1994) quoted production of 107 kg Au by Great Eastern Co. with a recovered grade of 23 g/t between 1895 and 1909, but this is unsourced. Mining also took place in the area before 1870 and intermittently until the early 1950s.

- Dunn (1909b) reported a total yield from the Sedgwick Mine to June 1907 of 8381 tons of ore for 3274 oz 1 dwt of gold. This is probably the primary source for other references. The recovered grade is estimated as 12 g/t Au.
Kingston (1937b) reported that 200 to 300 m of the Great Eastern mine mineralisation consisted of a quartz reef within a fault, close to an anticlinal axis (a saddle reef). Production was reported as 36 oz from 36 ton of ore.

The total gold production accepted for the ore field is based on Cherry and Wilkinson (1994); Dunn (1909b) and Kingston (1937b), increased by 7 kg (6%) to 115 kg Au to account for early unrecorded production before 1870 and between 1909 and the 1950s. The estimated average grade of 12 g/t Au is derived from Dunn (1909b) and Kingston (1937b).

### 2.67.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>12 (8 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer(^{183})</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

\(^{183}\) O’Shea et al. (1992)

Sedgwick ore field
2.68. Shelbourne

2.68.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.795</th>
<th>Long: 144.086</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>350°</td>
<td>8</td>
<td>5.2</td>
</tr>
</tbody>
</table>

2.68.2. Description

This ore field lies within the outcrop of Lancefieldian and Bendigonian Castlemaine Supergroup. The ore field is, in part, covered by Quaternary sediments.

2.68.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>29</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1280</td>
</tr>
</tbody>
</table>

**Notes on production records**

This ore field was part of the Shelbourne East historic goldfield (O’Shea et al., 1992), which included the Alexander Reef mine (now assigned to the Lockwood ore field), the only mine with recorded production.

It is possible that the location of the Alexander Reef in VicMine is incorrect and it actually lies within the Shelbourne East goldfield. In support of this, official production records for the period 1864 to 1867 indicate production from “Alexander and Wallaby Reefs” and production from the Mechosk Reef by the Alexander Reef Co. It is puzzling that the Alexander Reef is more than 3 km away from the Mechosk Reef and is isolated, while the (apparently minor?) Mechosk Reef is a part of a cluster of 11 mines.

VicProd records production for Mechosk Reef as 42 oz, 22 dwt from 45 tons of ore, with a calculated grade of 29.3 g/t Au and for Alexander and Wallaby Reefs of 113 oz, 9 dwt, 18 gr from 165 tons of ore, with a calculated grade of 21.1 g/t Au.

O’Shea et al. (1992) reported production of 34 kg Au from the Wallaby Reef. The accepted production (which must be regarded as a minimum) is 37 kg Au at 29 g/t. If
Alexander Reef is deemed to lie within the Shelbourne East ore field, the production should be increased to 155 kg Au.

### 2.68.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>11 (9 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

![Shelbourne ore field](image)
2.69. Simson

2.69.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.001</th>
<th>Long: 143.799</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>60°</td>
<td>2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.69.2. Description

This ore field lies within the outcrop of Lancefieldian – Warendian Castlemaine Supergroup and is, in part, covered by Quaternary sediments.

2.69.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

There are no production records for this ore field

2.69.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3 (all unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Simson ore field
2.70. Smith and Taylor

2.70.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.824</th>
<th>Long: 143.609</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.70.2. Description

This ore field contains one mine. It is entirely covered by Newer Volcanics basalt and is very close to the Avoca fault, probably on the footwall (eastern) side.

2.70.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>3.6</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>6100</td>
</tr>
</tbody>
</table>

*Notes on production records*

The production records accepted for this ore field are based on VicMine.

2.70.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Smith and Taylor (VicMine ID 379239) 22.4 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>22184 kg for 6 165 ton ore (3.6 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (100% of total production)</td>
</tr>
</tbody>
</table>

184 Gold production rounded to the nearest 1 kg
Smith and Taylor ore field
2.71. Springmount

2.71.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.415</th>
<th>Long: 143.934</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.71.2. Description

This ore field contains one mine, lying within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.71.3. Gold production

**Historic production**

| Historic gold production\(^{185}\), kg | 40 |
| Recovered grade\(^{186}\), g/t | 9.5 |
| Processed ore, t (derived) | 4210 |

\(^{185}\) Gold production rounded to the nearest 1 kg

\(^{186}\) from VicMine 38 kg Au for 4000 t ore

**Notes on production records**

The production records accepted for this ore field are based on VicMine.

**Other sources**

- Benn (1990), which is identical to VicMine records.
- Caldwell (1937c) reported on the New Madam Berry Syndicate’s reef, Allendale. This mine, located ½ mile north of Spring Mount, had a shaft 70 feet deep, with cross - cuts at 45, 57 and 65 feet, with some stoping done. No production details are available. However, given the existence and scale of this mine and a mapped worked reef, the production recorded in VicMine has been increased to 40 kg Au.
2.71.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Springhill Reef (VicMine ID 367266) 38 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>38 kg for 4000 t ore (9.5 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>38 kg (100% of total production)</td>
</tr>
</tbody>
</table>

\[ ^{187} \text{Gold production rounded to the nearest 1 kg} \]

Springmount ore field
2.72. Steiglitz

2.72.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.868</th>
<th>Long: 144.181</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>0°</td>
<td>10</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.72.2. Description

This ore field lies within the outcrop of Castlemainian, Yapeenian and Darriwillian Age rocks (in places covered by Tertiary and Quaternary sediments).

2.72.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>7800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>38</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>200,000</td>
</tr>
</tbody>
</table>

188 Gold production rounded to the nearest 100 kg

189 Grade taken from North Birmingham mine (record of average grade from substantial production)

*Notes on production records*

The gold production estimate for this ore field from O’Shea et al. (1992) was 3910 kg Au.

Bradford (1904) reported approximately 250,000 oz, or 7800 kg Au, which is accepted in this report. It is possible, however, that this estimate includes some alluvial production.

*Other sources*

Mine locations are from Geological Survey of Victoria (1909). This map incorporates face notes showing grades of 11 g/t Au and 31 g/t Au from two reefs. From Forbes (1897):
<table>
<thead>
<tr>
<th>Mine</th>
<th>Grade</th>
<th>Tonnage</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Princess Alice</td>
<td>Up to 156 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernhardt</td>
<td>Up to 62 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Native Youth</td>
<td>Up to 93 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tam O’Shanter</td>
<td>5 g/t</td>
<td>70 (selected parcel)</td>
<td>0.35 kg (selected parcel)</td>
</tr>
<tr>
<td>Elsie Average</td>
<td>39 g/t (pyrite concentrate 31 g/t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whipshaft</td>
<td>Up to 311 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Mariners Shaft</td>
<td>No gold produced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanover Average</td>
<td>9 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Birmingham Average</td>
<td>38 g/t (grade range 30 - 220 g/t)</td>
<td>2627 (total – probably handpicked quartz ore)</td>
<td>101 kg (total prod)</td>
</tr>
<tr>
<td>Albion United line&lt;sup&gt;191&lt;/sup&gt; (includes following 2)</td>
<td>Over 620 g/t (Average 62 g/t&lt;sup&gt;192&lt;/sup&gt;)</td>
<td></td>
<td>1500 kg</td>
</tr>
<tr>
<td>Boxing</td>
<td>Up to 1520 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yankee Smith</td>
<td>Up to 1240 g/t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Mariners&lt;sup&gt;193&lt;/sup&gt;</td>
<td></td>
<td></td>
<td>850 kg</td>
</tr>
</tbody>
</table>

<sup>191</sup> Dividend of £100,000 + £100,000 wages implies production of over 1500 kg Au (assuming Au at £4 /oz) from handwritten, un- attributed comment on report hardcopy.

<sup>192</sup> Bradford (1904).

<sup>193</sup> Bradford (1904). £110,000 worth of Au is approximately 850 kg

### 2.72.4. Recorded mines (VicMine)

There are no production records for this ore field in VicMine
Steiglitz ore field
2.73. Sulky

2.73.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -37.473</th>
<th>Long: 143.864</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>60°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.73.2. Description

This ore field (generally regarded as part of the historic Creswick Goldfield) contains a series of locally sub-parallel individual lines of reef, some relatively short, all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup.

2.73.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production°, kg</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade°, g/t</td>
<td>14.3</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>3920</td>
</tr>
</tbody>
</table>

° Gold production rounded to the nearest 1 kg
°° from VicMine 54 kg Au for 3750 t ore

**Notes on production records**

The production records accepted for this ore field are based on VicMine. Given three other primary mines with no recorded production and a number of shafts in the area, the accepted production has been increased to 56 kg.

2.73.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4 (3 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Seymore shaft (VicMine ID 366505) 54 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>54°° kg for 3750 t ore (14.3 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (100% of total production)</td>
</tr>
</tbody>
</table>

°° Gold production rounded to the nearest 1 kg
Sulky ore field
2.74. Sunday Morning Reef (Kingower North)

2.74.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 36.544</th>
<th>Long: 143.716</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>n/a</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

2.74.2. Description

This ore field lies within the outcrop of the Lancefieldian Castlemaine Supergroup. The ore field is covered, in part, by Quaternary sediments.

2.74.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^{197}), g/t</td>
<td>165.8</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>122</td>
</tr>
</tbody>
</table>

\(^{197}\) from VicMine 20 kg Au for 170 t ore

Notes on production records

The production records accepted for this ore field are from VicMine, although the mined tonnage is suspect.

2.74.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 1, Ore: 1</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Sunday Morning Reef (VicMine ID 362809) 20 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>20(^{198}) kg for 120 t ore (170 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>

\(^{198}\) Gold production rounded to the nearest 1 kg
Sunday Morning Reef (Kingower North) ore field
2.75. Taradale - Lauriston - Drummond – Malmsbury

2.75.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 37.188</th>
<th>Long: 144.362</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>0°</td>
<td>15</td>
<td>6</td>
</tr>
</tbody>
</table>

2.75.2. Description

This ore field contains one mine, lying within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup. This ore field is covered, in part, by Quaternary sediments. The ore field includes the historic Taradale, Lauriston and Malmsbury goldfields.

2.75.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>7,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>21</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>333,300</td>
</tr>
</tbody>
</table>

**Notes on production records**

- Willman et al. (2002) report 7,175 kg of primary gold production from the Taradale Mining Division (confirmed by VicProd). In addition to the Taradale - Lauriston - Malmsbury ore field as defined in the current study, the Mining Division also includes the Metcalfe and Little Hampton goldfields and the area around the Premiere mine near Kyneton, with a combined recorded production of 170 kg and a total probably not exceeding 200 kg Au. The approximate share of the total recorded production for the Taradale - Lauriston ore field should therefore be at least 6900 kg Au. The accepted production has been increased to 7,000 kg Au to account for production missing from official records.

- Production originally assigned in VicMine to the Caledonia Shaft (2514 kg Au) represents a database error.

- O’Shea et al. (1992) report the total primary production as 6608 kg Au.

Ramsay and Willman (1988) estimated the average recovered grade as 21 g/t Au.

2.75.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>282</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 44, Ore: 44</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Russells Reef (VicMine ID 369419) 1432 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>7963199 kg for 1000 t ore (5.5 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>20</td>
</tr>
</tbody>
</table>

199 Caledonia Shaft (VicMine ID 369136) with 2514 kg Au production recorded in VicMine – a database error.

Taradale – Lauriston – Drummond – Malmsbury ore field
2.76. Tarnagulla

2.76.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.772</th>
<th>Long: 143.865</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>350°</td>
<td>15</td>
<td>6</td>
</tr>
</tbody>
</table>

2.76.2. Description

The Tarnagulla ore field lies mostly within the outcrop of Lower Ordovician rocks, in places covered by Tertiary and Quaternary sediments (less than 50% of the total area). When using standard 800 m buffers around the recorded primary gold mines recorded in VicMine, the ore field is represented by two main clusters: Tarnagulla and Newbridge, with 12 t and 1.8 t of estimated gold production, respectively, and several additional small ore fields with an aggregate recorded production of 142 kg Au. Using additional data from Marlow and Bushell (1996a, 1996b) on lines of worked quartz reefs in the area, the Tarnagulla, Newbridge and adjacent smaller ore fields can be combined into a single ore field. Using this definition, the Tarnagulla ore field is almost identical to the Tarnagulla goldfield of Maher (1996). The Tarnagulla Goldfield of Krokowski de Vickerod et al. (2001) also includes the Waanyarra Goldfield, but no production data was available for the latter.

2.76.3. Gold production

Historic production

| Historic gold production²⁰⁰, kg | 17800 |
| Recovered grade²⁰¹, g/t      | 59.6  |
| Processed ore, t (derived)   | 298,660 |

²⁰⁰ Cuffley et al. (2001) – 17453 kg, plus 293 kg of production south of Corfu Reef (VicMine), plus 48 kg of additional recent production from Tarnagulla (DPI Statistical Reviews).

²⁰¹ Derived from total grade and tonnage as reported in Cuffley et al. (2001). Cuffley et al. (2001) reports total reef production to 2001 as 17453 kg; this production figure is probably an underestimate. The total does not include any production south of Corfu Reef, from the Llanelly Zone, while VicMine includes details of production for 5 mines: Tarnagulla, American, Kangaroo, Irvinies and Woolshed Reefs, with a total production of 293 kg Au.
Notes on production records

- Total primary gold production from mines with established locations recorded in VicMine is 13967 kg from 186,195 t of ore. These values probably understate actual total gold production.

- The production estimate of 17800 kg quoted here is derived by using the most recent estimate of Cuffley et al. (2001), plus 293 kg Au of production south of Corfu Reef (VicMine), plus 48 kg Au of additional recent production from Tarnagulla (DPI Statistical Reviews). This estimate probably still understates the actual production, since there are no production records for another 11 recorded mined reefs.

Other sources

- Maher (1996) states that the total quoted historic production was 14991 kg Au. Analysis of the associated VicMine database, however, could only confirm 14466 kg. The reason given by S. Maher (pers comm.) is that the production from the goldfield that could not be reliably attributed to a particular mine was not included in the VicMine database. Adding 1696 kg Au of recent production in 1996 – 2003 gives a total of 16687 kg Au.

- O’Shea et al. (1992) reports 12450 kg Au production.


2.76.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of recorded primary mines</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of recorded primary mines with recorded production</td>
<td>31</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Poverty Reef (10880 kg)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>10 (13840 kg production – 99% of total)</td>
</tr>
<tr>
<td>Total recorded production</td>
<td>13967 kg from 186,195 t</td>
</tr>
</tbody>
</table>
Tarnagulla ore field
2.77. Toolleen

2.77.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.758</th>
<th>Long: 144.705</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>20°</td>
<td>3.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.77.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Cambrian metabasalts and sedimentary rocks (with some Quaternary cover). Its position is approximate, due to some uncertainty in the locations of individual mines.

2.77.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>15,000</td>
</tr>
</tbody>
</table>

Notes on production records

The production accepted for this ore field is a total of 99 kg gold of historic production (Ramsay and Willman, 1988), 99 kg gold of recent production from MIN 5096, plus approximately 5% to account for incomplete historic production records.

Other sources

- Thomas (1942) states in reference to the Toolleen gold mine: “It differs from the mines of this field … in that the country rock is an ancient volcanic rock of Cambrian age. Instead of being the usual type of quartz reef it is a mineralized shear zone in which quartz veins play a subsidiary part”. Production in 1939 - 1942 (to 9th February) was 1941.33 oz from 6212 t (at 9.6 g/t Au), plus 215.51 oz from 1880 t extracted by cyanidation. The shear zone strikes north-east.
- Stillwell (1942) reported: “Gold particles (1 - 35 microns) are strongly associated with pyrite. All 37 observed grains were inside or adjacent to pyrite and/or arsenopyrite grains.”
Foster et al. (1998) reported that the age of sericite from pervasively altered wall rock to a gold-bearing quartz vein from the Toolleen mine is 382±3 Ma: “The mean age probably reveals the time of alteration and mineralization at Toolleen and/or may also record a phase of deformation and recrystallization within the Heathcote Fault zone.”

Cundy (1899) reported that mineralisation is in a series of numerous auriferous reefs (“… there is no lack of quartz in the area under notice”) striking NW (348°), within a zone one mile wide in Ordovician turbidites. Gullies worked for alluvial gold were “though payable, without any rich results. One piece of gold weighing 4 ozs. was, however, secured”. Crushings from 2 areas gave grades of 2.5 – 3.5 oz/ton.

The information above indicates the existence of two distinct styles of mineralisation – Au-Qtz veins in NW-striking reefs (Cundy, 1899) and refractory gold mineralisation in the NE-striking shear zone. Most of the recorded gold production is probably of the latter type.

2.77.4. Recorded mines (VicMine)

There are no recorded primary gold mines in VicMine for this ore field.
2.78. Waanyarra

2.78.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.837</th>
<th>Long: 143.795</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>345°</td>
<td>9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.78.2. Description

This ore field contains a series of locally sub-parallel reefs all lying within a restricted and near-continuous zone within the outcrop of the Lancefieldian Castlemaine Supergroup. Two occurrence clusters were combined to form this ore field. The separation of the two occurrence clusters was small enough and the local geology similar enough to regard them as continuous.

2.78.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production(^{202}), kg</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade(^{203}), g/t</td>
<td>25</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>4,000</td>
</tr>
</tbody>
</table>

\(^{202}\) Gold production rounded to the nearest 1 kg

\(^{203}\) from VicMine 53.5 kg Au for 1647.5 t ore

**Notes on production records**

Recovered grades of 17 - 33 g/t Au were reported by Taylor (1989).

VicProd records 51.04 kg Au at 19.3 g/t for the Waanyarra area and the Horseshoe Reef. Information for the Horseshoe reef is identical to that in VicMine, while for other mines in VicMine a different source of information was probably used.

No individual record in VicProd had a recovered gold grade in excess of 66 g/t, with cumulative crushings larger than 60 t having grades in the range of 7.7 to 26.7 g/t Au. On the other hand, the two biggest mines recorded in VicMine, with 32.6 kg of gold production, have estimated recovered grades of 93 g/t and 110 g/t Au. These two sources of production data cannot be easily reconciled and additional analysis is required. It is
likely that the overall production from the Waanyarra ore field was in excess of 100 kg of gold.

### 2.78.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 7, Ore: 7</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Almeida reef (VicMine 362623) 19 kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>54(^{204}) kg for 1650 t ore (33 g/t)</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^{204}\) Gold production rounded to the nearest 1 kg

[Diagram of Waanyarra ore field]
2.79. Wedderburn

2.79.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.368</th>
<th>Long: 143.609</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5°</td>
<td>19</td>
<td>8</td>
</tr>
</tbody>
</table>

2.79.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup (in places covered by Tertiary and Quaternary sediments).

2.79.3. Gold production

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14.3</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>45450</td>
</tr>
</tbody>
</table>

**Notes on production records**

Production records are inconsistent between various sources. O’Shea et al. (1992) suggests that total production for this field is 238 kg (although the limits of the field are not identical to the ore field limits as defined in this study).

Edwards et al. (2001) gives a total production for the Wedderburn goldfield (which here includes the Wytchitella South East, Wytchitella South West, Wytchitella South, Wedderburn North West, Wedderburn and Korong Vale historic goldfields, as well as other isolated mines in the area) of 456 kg. Analysis of additional sources (VicProd, Department of Mines, Victoria, 1870 - 1953) suggests that total primary gold production was approximately 650 kg Au at an average recovered grade of 14.3 g/t.
### 2.79.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>59 (4 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 36, Ore: 30</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>Kanaka Reef (VicMine ID 373175) 57(^{205}) kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>274(^{206}) kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>4</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>160 kg (58% of total production)</td>
</tr>
</tbody>
</table>

\(^{205}\) Rounded to nearest 1 kg  
\(^{206}\) Gold production rounded to the nearest 1 kg

![Wedderburn ore field](image)
2.80. Wehla

2.80.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 36.624</th>
<th>Long: 143.621</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>345°</td>
<td>6.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.80.2. Description

This ore field lies within the outcrop of Lancefieldian Castlemaine Supergroup.

2.80.3. Gold production

**Historic production**

| Historic gold production, kg | 1910 |
| Recovered grade, g/t         | 11.3 |
| Processed ore, t (derived)   | 168,590 |

\(^{207}\) Gold production rounded to the nearest 1 kg

**Notes on production records**

Production records accepted for this ore field are based on VicMine, rounded up to 1910 kg Au to account for minor unrecorded production. Average recovered gold grade could not be correctly determined from aggregated VicMine records.

For German Reef (the largest gold producer), no grade information is available for 93% of total production. Using all estimated gold production and partial recorded tonnage results in an obviously incorrect grade of 119 g/t Au. Using only production records with both gold production and tonnage information recorded gives a much more realistic grade estimate of 11.3 g/t Au.

2.80.4. Recorded mines (VicMine)

| Total number of mines | 9 |
| Total number of mines with production records | Gold: 5, Ore: 5 |
| Biggest Producer | Reef (VicMine ID 362670) 1880 kg |
| Total Recorded Production | 1905 kg |
| Total producers over 25 kg | 1 |
| Total production over 25 kg | 1880 kg (99% of total production) |

\(^{208}\) Rounded to nearest 1 kg

\(^{209}\) Gold production rounded to the nearest 1 kg
Ore fields in Bendigo Zone

Wehla ore field
2.81. Welshs Reef

2.81.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.491</th>
<th>Long: 143.886</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Area (km²)</td>
<td>Long Axis Direction</td>
<td>Long Axis Length (km)</td>
</tr>
<tr>
<td>2</td>
<td>n/a</td>
<td>1</td>
</tr>
</tbody>
</table>

2.81.2. Description

This ore field contains one mine, lying within the outcrop of the Lancefieldian – Warendian Castlemaine Supergroup, covered in part by Quaternary sediments.

2.81.3. Gold production

**Historic production**

| Historic gold production[^10], kg | 5 |
| Recovered grade[^11], g/t | 5.4 |
| Processed ore, t (derived) | 1,000 |

[^10]: Gold production rounded to the nearest 1 kg
[^11]: from VicMine 5.47 kg Au for 1004 t ore

**Notes on production records**

The production records accepted for this ore field are from VicMine.

2.81.4. Recorded mines (VicMine)

| Total number of mines | 1 |
| Total number of mines with production records | Gold: 1, Ore: 1 |
| Biggest Producer | Welshs Reef (VicMine ID 372321) 5 kg |
| Total Recorded Production | 5[^12] kg for 1000 t ore (5.4 g/t) |
| Total producers over 25 kg | 0 |
| Total production over 25 kg | 0 kg (0% of total production) |

[^12]: Gold production rounded to the nearest 1 kg
Welshs Reef ore field
2.82. Wilsons Reef

2.82.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: -36.742</th>
<th>Long: 144.108</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>n/a</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

2.82.2. Description

This ore field lies within the outcrop of the Bendigonian - Chewtonian Castlemaine Supergroup, covered, in part, by Quaternary sediments.

2.82.3. Gold production

*Historic production*

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>1,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>14.7</td>
</tr>
<tr>
<td>Processed ore[^13] t (derived)</td>
<td>68,000</td>
</tr>
</tbody>
</table>

[^13] Rounded up to nearest 500 t

*Notes on production records*

O’Shea et al. (1992) quotes production as 974 kg gold, which includes Wallaby Reef with a production of 34 kg gold.

The production records accepted for this ore field are from O’Shea et al. (1992), increased by 25 kg and rounded to 1000 kg Au to account for unrecorded production from minor mines. The grade is estimated from available records (Department of Mines, 1891; VicProd) as 14.7 g/t Au.

2.82.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>11 (9 unnamed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>0</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>0 kg (0% of total production)</td>
</tr>
</tbody>
</table>
Ore fields in Bendigo Zone

Wilson's Reef ore field
2.83. Yandoit

2.83.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat: - 37.230</th>
<th>Long: 144.082</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>10°</td>
<td>11</td>
<td>3</td>
</tr>
</tbody>
</table>

2.83.2. Description

This ore field lies within a restricted and near-continuous zone within the outcrop of the Lancefieldian and Bendigonian Castlemaine Superroup.

2.83.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production²¹⁴, kg</th>
<th>525</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade²¹⁵, g/t</td>
<td>18.3</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>28670</td>
</tr>
</tbody>
</table>

²¹⁴ Gold production rounded up to the nearest 10 kg; tonnage rounded up to the nearest 100 t
²¹⁵ From VicMine; 64 kg Au for 3700 t ore

Notes on production records

Kenny (1937c) reported total production from 1861 to 1933 as 4096 oz 17 dwt from 9016 tons (127.4 kg Au at 13.9 g/t). No production was recorded between 1862 and 1863, during which period there was active reef mining in the area. To estimate unrecorded production, an interpolation was carried out based on annual production in 1861, 1864 and 1865 (37, 20 and 46 kg, respectively). This is consistent with the estimate of 5500 oz by Amos (1890) for cumulative production to 1890.

In Willman et al. (2002), the production for Glamorgan reef is estimated as 155 kg Au.

Amos (1890) reported the following:

- All Nations Reef produced 688 oz Au from 478 tons;
- Chance Reef produced 66 oz from 203 tons;
- Christmas Reef produced 1286 oz from 4119 tons;
- Glamorgan Reef produced 5500 oz;
- Malcolm’s Reef produced 904 oz from 491 tons in 1859 - 1860, plus 191 oz from 640 tons from 1867 to 1890, for a total of 1,095 oz from 1152 tons;
Sardines (Sardinia) Reef produced 298 oz from 273 tons;

Pioneer (Steeles Pioneer) Reef produced 1128 oz from 559 tons. Before the first recorded production (203 tons for 900 oz Au between 1860 and 1861), the reef had been worked for 9 months with “large returns”. Mining continued through 1860s with no recorded production. (VicMine recorded 573 oz from 1212 t, probably in addition to that reported by Amos, 1890);

Hamburg Reef produced 2000 oz at an average grade of 4.4 oz per ton, plus 87 oz from 112 tons, for a total of 2087 oz from 564 tons;

Total gold production recorded or estimated by Amos (1890) is 450.73 kg Au. Both gold production and ore tonnage are available for 279.68 kg of this (11,325 t, at an average grade of 24.7 g/t Au).

In addition, records of the Department of Mines give details of another 657.48 kg of gold from 5,362 t produced after June 1890 and in 1870. (The total includes 17,846 g of Au from 1576 t produced at the Government Battery in Clydesdale).

Kenny (1937a) recorded production from the Glamorgan Reef in 1931 - 1933 of 3.2 kg Au at 7.7 g/t.

Kenny (1937d) referred to the Eliza May mine, 300 feet east of the Steel’s Pioneer mine, on the Eastern Reef, with recorded production of 27 oz Au from 27 tons ore.

From the above, total recorded production for the Yandoit ore field can be estimated as 521 kg Au. Given that another 12 worked reefs within the Yandoit ore field recorded in VicMine do not have any production records, total production from the Yandoit ore field can be estimated as at least 525 kg Au. The average grade is estimated from recorded production as 18.3 g/t Au.

### 2.83.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 3, Ore: 3</td>
</tr>
<tr>
<td>Biggest Produce&lt;sup&gt;217&lt;/sup&gt;:</td>
<td>German (VicMine ID 368369) 39&lt;sup&gt;218&lt;/sup&gt; kg</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>64&lt;sup&gt;219&lt;/sup&gt; kg</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>1</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>39 kg (61% of total production)</td>
</tr>
</tbody>
</table>

<sup>217</sup> According to VicMine, although VicMine has no production record for Glamorgan reef, which is in fact, probably the biggest producer

<sup>218</sup> Rounded to nearest 1 kg

<sup>219</sup> Gold production rounded to the nearest 1 kg
2.84. Yankee Creek

2.84.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>Lat:  - 36.719</th>
<th>Long: 144.424</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>325°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.84.2. Description

This ore field lies within the outcrop of Castlemainian, Bendigonian, Chewtonian and Lancefieldian Castlemaine Supergroup and is, in part, covered by Quaternary sediments. Note that the outline of this ore field (other than area) was defined here by excluding the outlier mine site in the NW of the ore field. Although this mine is registered as primary, it is located in an area of alluvial cover and may be alluvial.

2.84.3. Gold production

Historic production

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>26</td>
</tr>
<tr>
<td>Processed ore, t (derived)</td>
<td>1200</td>
</tr>
</tbody>
</table>

Notes on production records

The production records accepted for this ore field are from Roberts, 1994.

The production is quoted as 1,000 oz (31 kg) from 1200 t ore at a grade of 26 g/t. Other reports indicate grades of 3 - 4.5 g/t. This report includes a good map of the goldfield.

Other sources

Bendigo Mining NL (1995) quotes production as 4.75 kg Au from 50 t of ore at a grade of 95 g/t. This source includes a map showing the locations of mines not in VicMine, including Greaves Original Find, Greaves Later Find, Ryans Claim, Heines Claim and Slingo and Simpsons Shaft (Whitelaw, 1900).
2.84.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>9 (7 unnamed)</td>
</tr>
<tr>
<td>Total number of mines with production records</td>
<td>Gold: 0, Ore: 0</td>
</tr>
<tr>
<td>Biggest Producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Total Recorded Production</td>
<td>unknown</td>
</tr>
<tr>
<td>Total producers over 25 kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Total production over 25 kg</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Yankee Creek ore field
3. Summary and Conclusions

The Bendigo Zone yielded approximately 900 t gold from 66 Mt ore from primary gold-quartz vein mesozonal orogenic deposits, distributed over 85 primary gold ore fields. There were an additional 229 isolated mines (of which 5 had production records) which were not attributed to any particular ore field, generally because of their isolated locations and small gold production (under 25 kg gold). The latter group had an estimated aggregate production of 878 kg gold from about 27300 tonnes ore (less than 0.1% of the production of the defined ore fields) with this production included in the aggregate totals above.

Most ore fields showed considerable anisotropy in shape, with the ratios of the long to short axes mostly in the range of 1.5 to 3, with an average of 2.2. The orientations of the long axes trend N-S (± 20°) in about half of the ore fields. Although the orientations of individual ore fields often correspond to the orientations of the individual mineralised structures within them, occasionally there is a discrepancy, especially where there are multiple lines of gold mineralisation.

There was a total of 507 mines within ore fields in the Bendigo Zone which produced over 25 kg of gold each. Of the 85 ore fields, 21 had more than one mine which produced more than 25 kg gold.

For 25 ore fields defined in this study, there were no production records at all in VicMine. Production estimated for these were derived from other sources. Where production records were available, they often covered only part of the period of during which an individual mine may have operated. Even if we assume that the mines with no production records tended to be small, this would still imply that the aggregate totals quoted above may significantly understate total production from primary gold deposits.

The total production for the ore fields studied, as registered in VicMine, was about 308 t gold – about a third of what was found in the quoted references and allocated to the individual ore fields.
### 4. Mesozonal orogenic gold ore fields in the Bendigo Zone

The following table ranks (by estimated gold endowment) the mesozonal orogenic gold - quartz ore fields defined in the Bendigo Zone and lists the characteristics of each ore field. This compilation excludes refractory gold deposits, for example, the Fosterville ore field (>60 t Au, Lisitsin et al., 2010a, 2010b).

<table>
<thead>
<tr>
<th>Gold production rank</th>
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References


Appendix 2

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Appendix 2


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APPENDIX 3

GOLD ORE FIELDS IN THE STAWELL ZONE

Presented as originally published (with minor changes) in:

1. Introduction

This report provides brief summary information on primary mesozonal orogenic gold-quartz vein ore fields in the Stawell Zone in western Victoria, largely focusing on primary ore field grades and tonnages and excluding alluvial gold deposits.

To ensure consistency and avoid bias in assessing undiscovered endowment, information has been compiled for gold ore fields, defined as areas of mineralisation in which adjacent orebodies are less than 1.6 km apart (Lisitsin et al., 2007, 2009, 2010). Their extent is similar (and often identical) to historic goldfields or clusters of goldfields. Gold mineralisation in the ore fields reviewed in this report is characterised by free gold in quartz veins, with variable amounts of sulphides and ferroan carbonates. These gold–quartz vein deposits are well studied and described in many reviews (e.g., Junner, 1920, 1921; Bowen and Whiting, 1975; Phillips and Hughes, 1996, 1998; Ramsay et al., 1998; Solomon, 2000; Phillips et al., 2003; Bierlein et al., 2004). They represent the dominant deposit type in the Stawell Zone. Such deposits were described as ‘gold only quartz vein’, ‘turbidite-hosted quartz-gold’, ‘slatebelt’, ‘mesothermal gold’, etc. They have also been previously classified as mesozonal orogenic (Bierlein et al., 2004; Goldfarb et al., 2005; Moore, 2007). The spatial distribution of gold–quartz vein deposits is described by the Stawell–Ararat pyrite-arsenopyrite mineralogical domain and the Landsborough–Percydale silver–lead mineralogical domain of Hughes et al. (1997), Phillips et al. (2003) and Hughes (2004). Those deposits are classified in this report as mesozonal orogenic gold deposits. Common properties of these deposits have been reviewed by Lisitsin et al. (2009, 2010).

For the eight largest ore fields reviewed in this report and used in the grade and tonnage model in Lisitsin et al. (2009), we estimated properties of original pre-mining gold endowment following the process described in Lisitsin et al. (2007, 2010). Original in situ
ore tonnages (T) and grades (G) were calculated from estimated processed ore tonnages and recovered grades by applying assumed ore dilution and gold recovery factors:

\[ T = \frac{T_{\text{proc}}}{1 + D} \]

where Tproc is a processed ore tonnage and D is ore dilution expressed as a proportion, and

\[ G = G_{\text{rec}} \times \frac{1 + D}{R} \]

where Grec is a recovered grade and R is gold recovery expressed as a proportion.

This does not take into account ore loss due to ore left in the ground (unless included in the current mineral resources) and ore loss during mining and transportation, thus resulting in a probable underestimation of in situ tonnages and gold contents. Unless deposit-specific information was available, we calculated original in situ grades and tonnages by assuming gold recoveries of 85% and ore dilutions of 10% for historic mining.

Recorded sale prices of bullion smelted at historic gold mines in the Stawell Zone indicate that most of the smelted metal contained 10% to 30% silver. Accordingly, we adjusted original gold endowments and gold grades estimated for the ore fields in the Stawell Zone to exclude contained silver.

The main sources of information on the spatial distribution of gold deposits and gold production used in this report were corporate databases of the Department of Primary Industries (Victoria) – VicMine (Heap, 1998), VicProd, GIS datasets of the mineral areas (Weston & Nott, 1993) and mapped auriferous quartz reefs. Additional information was derived from various other published and unpublished sources (referenced in the text) as required – mostly for larger ore fields with greater than one tonne of total primary gold production. Much of the gold production in the Stawell Zone took place in the 19th and early 20th centuries. This historic gold production was often poorly documented, especially for smaller goldfields. Consequently, ore field gold grades and tonnages presented in this report are only approximate estimates based on incomplete information of variable quality. For smaller ore fields, the estimates of gold and ore tonnage are almost always conservative and the estimates of ore grades may be unrepresentative as they were based on only partial information.

The coordinates used in this report are based on GDA 94 datum (MGA Zone 54).
2. Ore fields in the Stawell Zone

2.1. Ararat

2.1.1. Location and dimensions

Historic production

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 670 320 E, 5 871 992 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2</td>
</tr>
</tbody>
</table>

<sup>2</sup> Excludes production data, confined to detail and scope of technical information, 1=low, 2=adequate, 3=excellent

<table>
<thead>
<tr>
<th>Total area (km&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Area of cover (km&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>3.6</td>
<td>290&lt;sup&gt;o&lt;/sup&gt;</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.1.2. Description

The Ararat ore field contains eighteen mines, two of which are unnamed (VicMine; Bradford, 1894; Cayley and Taylor, 2001; Cayley and Taylor, undated. Geology and prospectivity of the Ararat-Grampians; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Department of Mines, Victoria, Undated. Goldfields of Victoria: Reports of the Mining Registrars. Series published quarterly between the quarters ended 30 June 1884 and 31 December 1889; Department of Mines, Victoria. Undated. The Goldfields of Victoria Quarterly Returns; Inan, 1989a; Inan, 1989c; Inan, 1990; King, 1979; Krause, 1875b; Plans., undated c. Dead mining lease plan 145; Ramsay and Vandenberg, 1986; Stirling, 1898c; Walker, 1988). The reefs and mines all occur within the outcrop of the Silurian Moornambool Metamorphic complex and the Cambrian St Arnaud Group.
2.1.3. Production and endowment

<table>
<thead>
<tr>
<th>Historic gold production, kg</th>
<th>41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>43</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>892</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes on production records

Pyrite concentrate returned almost 400 g/t Au near Golden Hope Reef (VicMine ID 431656).

2.1.4. Recorded mines (VicMine)

None of the individual mines are reported to have produced more than 10 kg gold each. The more prominent mines were the Royal Standard (VicMine ID 431684), Mitchells Reef (VicMine ID 431702) and the Caledonia (VicMine ID 431863).

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>10</td>
</tr>
<tr>
<td>Biggest (single(^3)) producer</td>
<td>Royal Standard</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>No individually named mine(^4)</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>41</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>110 m (Mitchells Reef)</td>
</tr>
</tbody>
</table>

\(^3\) Aggregate production from ‘Various Parties’ was reported as 712 oz by Cayley and Taylor (2001), but the largest production from a single mine (non-alluvial) was from the Royal Standard.

\(^4\) Cayley and Taylor (2001) reported that no individual mine produced more than 10 kg gold.
2.1.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>800 m long (Mitchells Reef)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Dip 83°, dip direction 62° (Mitchells Reef)</td>
</tr>
</tbody>
</table>

2.1.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Turbidite, slate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>greenschist</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.2. Armstrong

2.2.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 665 564 E, 5 880 581 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.2</td>
<td>5.8</td>
<td>310°</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

2.2.2. Description

The Armstrong ore field contains thirty nine mines, all named (VicMine; Anon, 1899; Anon, 1946; Bartrop, 1983; Bell, Cochrane and Associates Pty Ltd., 1988; Bradford, 1894; Cayley & Taylor, 2001; Cayley & Taylor, undated; Department of Mines & Water Supply, Victoria, Undated; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Department of Mines, Victoria, Undated. Gold production card index; Department of Mines, Victoria, Undated. Goldfields of Victoria: Reports of the Mining Registrars. Series published quarterly between the quarters ended 30 June 1884 and 31 December 1889; Inan, 1989b; Inan, 1990b; Krause, 1875; Krause, 1875b; Murray, 1898; Plans., Undated a; Plans., Undated b; Stirling, 1898; Taylor, 1878; Walker, 1988; Walker, 1988b). The reefs and mines all occur within the outcrop of the Silurian Moornambool Metamorphic complex and the Cambrian-Ordovician St Arnaud Group.
2.2.3. Production and endowment

Historic production

| Historic gold production (1854-1940), kg | 46  |
| Recovered grade, g/t                   | 14  |
| Processed ore, t                       | 3335|
| Recent gold production (1983-2007)     | 0   |
| Current resource / reserve (12/2007)   | 0   |

Notes on production records

The Taylor mine (VicMine ID 431617) is probably incorrectly located and is confused with W Taylor (VicMine ID 431711) with a total production of 2.7 kg gold rather than the 28.4 kg recorded in VicMine. For the latter, grades ranged between 15 and 29 g/t Au (Inan, 1989).

2.2.4. Recorded mines (VicMine)

Eaglehawk (VicMine ID 431639) produced 17 kg gold at a grade of 9.5 g/t, although pyrite concentrates were reported to assay 1124 g/t from a sample of 2.7 kg.

Native Youth (VicMine ID 431678) produced 15.4 kg gold from 362 t of ore for a grade of 44 g/t. Native Youth South (VicMine ID 431677) produced 4.4 kg gold from 350 t of ore at a grade of 13 g/t.
The other mines with production records include Smart and Whitten, Golden Gate, Taylor, Collings Tribute, Morgan and Howard, Moore and Party, New Eaglehawk, Hospital Hill/Reef and Jubilee Reef mines, as well as twenty four named mines with no recorded production – including the Gladstone, with workings of 1,000 m in length and Simpsons, with workings over 1,000 m length and a depth of 40 m.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>15</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Eaglehawk</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>73</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>91.5 m (Eaglehawk), 40 m (Phoenix and Eldorado)</td>
</tr>
</tbody>
</table>

2.2.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>2000 m (Eaglehawk), 1700 m (Gladstone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Dip 69° W, strike 155° (Eaglehawk); dip 80° E, strike 155° (Simpsons)</td>
</tr>
</tbody>
</table>

2.2.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Slate, turbidites, greenstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>Up to amphibolite</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.3. Avoca

2.3.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 722 746 E, 5 891 162 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km$^2$)</th>
<th>Area of cover (km$^2$)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.2</td>
<td>7.5</td>
<td>310°</td>
<td>8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.3.2. Description

The Avoca ore field contains eighteen mines and seven reefs (VicMine; Cayley, 1995; Wohlt et al., 2000), all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.

2.3.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (1854-1940), kg</th>
<th>179</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>7.4</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>24064</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>0</td>
</tr>
</tbody>
</table>
2.3.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>4</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Hogs reef</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>Hogs reef, Township/Hogs reef, Monte Christo reef</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>179</td>
</tr>
</tbody>
</table>

Notes on production records

Beehive (VicMine ID 366644; Moon, 1897) - 0.3 to 0.5 m thick, about 90 m long; average recovered grade of about 15 g/t Au. Reef contains stibnite.

Bung Bong/Star of the East reef (VicMine ID 366643; Moon, 1897, Whitelaw, 1894). Strike 330°/dip 75° W, length about 180 m. Grades of up to 186 g/t Au, although more typically 17 g/t.

Callinans (VicMine ID 432533; Moon, 1897). Strike 340°/dip 70° W, about 0.3 m thick. Grade of over 120 g/t Au at the surface.

Hogs Reef (VicMine ID 432531; Kenny, undated; Kenny, 1938; Nott, 1985). The reef varied from 45 to 61 cm thick and at surface yielded up to 150 g/t Au. Crushings averaged 90 g/t Au down to 20 m where grades decreased. An average grade of 11 g/t Au can be assumed (Kenny, 1938). The deepest working was 84 m. A prospecting shaft was sunk to a depth of 61 m without success. This is part of a reef complex with five reefs lying within a width of 30 m. Includes Beavis reef, 18 m to the west. Monte Christo (VicMine ID 432534; Moon, 1897; Cayley, 1995). Strike 335°/dip 78° E, 0.3 to 0.6 m thick, over 180 m long and worked to a depth of 45 m. Grade about 30 g/t. There are two other nearby reefs associated with the main reef.

Morning Star (VicMine ID 366645; Moon, 1897). Strike 355°/dip 65° E. Worked to a depth of 21 m, with a grade between 3 and 9 g/t Au.

No. 2 Shaft Hogs Mine (VicMine ID 432532; Nott, 1985; Kenny, undated; Kenny, 1941; Kenny, 1938). Shaft was originally sunk on a reef occurring 11 m W of Hog’s. A number of reefs were prospected from the shaft.

Township/Hogs (VicMine ID 432530, Moon, 1897). Strike 342°/dip 80° W, length about 800 m and up to 1.8 m thick. Grades ranged between 6 g/t to over 90 g/t Au.
2.3.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.3.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Deep marine turbidites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.4. Beaufort

2.4.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 714 916 E, 5 863 845 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>113.5</td>
<td>36.4</td>
<td>350°</td>
<td>22</td>
<td>6</td>
</tr>
</tbody>
</table>

2.4.2. Description

The Beaufort ore field contains one mine registered in VicMine (the Camp Hill adit), another one hundred and thirty three shafts (many probably prospecting shafts) and five hundred and sixty four mapped reefs, of which forty five are reported as having been worked (VicMine; Cayley, 1995; Swensson, 1988; Geological Survey of Victoria, undated. Parish of Beaufort; Bond, undated; Allan, undated; Department of Mines, Victoria, 1891; Nott, 1985) all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.
2.4.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | unknown |
| Recovered grade, g/t                  | unknown |
| Processed ore, t                      | unknown |
| Recent gold production (1983-2007)    | none    |
| Current resource / reserve (12/2007)  | none    |

**Notes on production records**

Although recorded hard rock production from this ore field is low, given the substantial production of alluvial gold (about 8 t Au recorded in VicMine; more than 30 t Au estimated by Phillips, 2007, 2010), which was, ultimately derived from the numerous thin quartz reefs, the Beaufort area is defined as an ore field.

2.4.4. Recorded mines (VicMine)

| Total number of mines                        | One, although mapped reefs also appear to have been worked |
| Number of mines with recorded production     | 0 |
| Biggest producer                             | Possibly Camp Hill adit |
| Major mines (over 25 kg gold)                | 0 |
| Total recorded gold production, kg           | 0 |
| Mining method                                | shaft |
| Depth of mining                              | unknown |

Camp Hill adit (VicMine ID 432578; Nott, 1985; Department of Mines, Victoria, 1891; Cayley, 1995). Production/grade unknown.

Other named sites: Babylon reef (VicMine ID 860545 – recorded as a placer deposit, probably in error; Allan, undated; Cayley, 1995); Red Hill/Brinkers reef (Cayley, 1995) is located just to the east of this ore field.

2.4.5. Ore bodies and systems

| Dimensions            | unknown |
| Orientation           | unknown |

2.4.6. Host rocks

| Host rock types       | unknown |
| Metamorphism          | unknown |
| Structural history    | unknown |
2.5. Berrimal

2.5.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 719 541 E, 5 953 621 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2.9</td>
<td>0°</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

2.5.2. Description

The Berrimal ore field contains twenty seven mapped reefs (some of which may be duplicates; Beckett, 1880; Krokowski de Vickerod, 1997), all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.
2.5.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 0 |
| Recovered grade, g/t | 0 |
| Processed ore, t | 0 |
| Recent gold production (1983-2007) | 0 |
| Current resource / reserve (12/2007) | none |

**Notes on production records**

There are no production records for this ore field.

2.5.4. Recorded mines (VicMine):

| Total number of mines | 0 |
| Number of mines with recorded production | 0 |
| Biggest producer | unknown |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | 0 |
| Mining method | unknown |
| Depth of mining | unknown |

2.5.5. Ore bodies and systems

| Dimensions | Average reef length 190 m |
| Orientation | Typically 350° |

2.5.6. Host rocks

| Host rock types | Deep marine turbidites |
| Metamorphism | unknown |
| Structural history | unknown |
2.6. Burkes Flat

2.6.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 728 187 E, 5 939 110 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>2.4</td>
<td>350°</td>
<td>4.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

2.6.2. Description

The Burkes Flat ore field contains two mines and six reefs (VicMine; Bannear, 1994; Bradford, 1903c; Caldwell, 1936; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Marlow and Bushell, 1996a; Marlow and Bushell, 1996b; Marlow and Bushell, 1996c; Marlow and Bushell, 1996d; Cotton, 1986; Foster, 1991; Moon, 1898). The mines lie within the outcrop of the Cambrian St Arnaud Group.
2.6.3. Production and endowment

**Historic production**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>1600</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>21.2</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>76,000</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>2100</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>69,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>30</td>
</tr>
</tbody>
</table>

**Notes on production records**

Burkes Flat mine (Fones Reef) was reported to have produced 74350 t of ore at a recovered grade of 21.2 g/t, for a total of 1573 kg gold, mined mostly from a single ore shoot 1 m to 5 m thick, continuously stoped down-dip for 304 m and 45 m along strike, between 1860 and 1884 (Caldwell, 1936; Callow, 1981; Ando Minerals NL, 1986; Foster, 1991). This probably includes production from the nearby Lilliputian Reef. Tailings were treated in the early 1900-s by gravity separation and cyanidation but no records of gold production have been found. Additional reefs and mines in this area are reported by Moon (1898). These include Forsters Reef (and an adjacent reef), Camerons Reef or Donald Reef (and an adjacent reef).. Detailed mapping by CRA indicated a number of unnamed old quartz workings which extended for more than 5 km to the south and over 2 km to the north of Burkes Flat (CRAE, 1986).

Most of the workings follow two NNW trends about 300 m apart. Other nearby reefs at Burke’s Flat: Black Reef, Morning Star, Evening Star, Deadlock, David’s, Greek’s, White Horse, Tay, Gladstone, Bedford (Mining Department, Victoria, 1865-1869; Department of Mines, Victoria, 1870).

Official production records captured in VicProd indicate total production from the Burkes Flat Goldfield after 1864 of over 900 kg at a recovered grade of 18.3 g/t. The largest recorded producers were Fone’s and Lilliputian Reefs.

These account for at least 700 kg of Officially recorded production captured in VicProd. The relationship between the two reefs is uncertain. In 1870s – 1880s they were probably mined from the same shaft.
The original head gold grade of ore mined from the Fone’s Reef was estimated to be 31.2 g/t (Ando Minerals NL, 1986). This value is likely to include recoverable silver, which is typical for historically reported gold grades in Victoria (Lisitsin et al., 2009). For the entire Burkes Flat ore field, the average in situ gold grade (excluding silver) is conservatively accepted to be 30 g/t.

The location of most worked auriferous reefs at Burkes Flat is uncertain, but it is likely that most of them form a NNW-trending cluster continuous at the 1.6 km scale. The production from the ore field is conservatively accepted to be 1600 kg of gold.

2.6.4. Recorded mines (VicMine)

○ Existing VicMine records grossly underestimate historic gold production from the Burkes Flat ore field, as discussed in the previous section.

○ Fones Reef (VicMine ID 362980), with a total production of 219 kg.

○ Burkes Flat (VicMine ID 362798), with a total production of 18 kg.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Fones Reef</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>2</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>275</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>263 m</td>
</tr>
</tbody>
</table>

2.6.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Fones Reef – a narrow ore shoot in a quartz reef cutting the bedding on the western limb of a tight anticline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Fones Reef: About 150 m long (the richest ore shoot – only 45 m long), 1-5 m thick, mined down-dip for 304 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Dip 60°, dip direction 265°</td>
</tr>
</tbody>
</table>

2.6.6. Host rocks

| Host rock types | siltstone |
2.7. Emu

2.7.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 719 421 E, 5 932 727 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.7</td>
<td>9.7</td>
<td>0°</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

2.7.2. Description

The Emu ore field contains seven mines, seventeen mapped reefs (some of which may be duplicates) and nine areas of quartz veining (Geological Survey of Victoria, undated Parish of Kooreh; Krokowski de Vickerod, 1997; Barber, 1987), all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.

Emu ore field
2.7.3 Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | unknown |
| Recovered grade, g/t (Royal George; Barber, 1987) | up to 29 |
| Processed ore, t | unknown |
| Recent gold production (1983-2007) | 0 |
| Current resource / reserve (12/2007) | 0 |

**Estimated total endowment**

| Contained gold, kg | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t (Royal George; Barber, 1987) | up to 29 |

**Notes on production records**

There are no production records for this ore field

2.7.4. Recorded mines (VicMine)

| Total number of mines | 7 |
| Number of mines with recorded production | 0 |
| Biggest producer | unknown |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | unknown |
| Mining method | shaft (Barber, 1987) |
| Depth of mining | unknown |

- Enterprise (VicMine ID 363735; Krokowski de Vickerod et al., 1997)
- Royal George (VicMine ID 363659; Barber, 1987)
- Royal George South (VicMine ID 363736; Hughes, 1987)
- Prince George mine (VicMine ID 363639; Barber, 1987)
- Prince George Extended mine (VicMine ID 363738; Krokowski de Vickerod et al., 1997)
- South Whip mine (VicMine ID 363737; Krokowski de Vickerod et al., 1997)
- Isabelle Reef mine (VicMine ID 363602; Bannear, 1994) – this may have been confused with this Isabelle mine 5.2 km to the east.

2.7.5. Ore bodies and systems

| Dimensions | unknown |
| Orientation | unknown |
2.7.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Deep marine turbidites.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.8. Glenpatrick

2.8.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 708 111 E, 5 887 847 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.7</td>
<td>0.6</td>
<td>330°</td>
<td>5.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.8.2. Description

The Glenpatrick ore field contains four mines and four reefs, although there is some ambiguity as to the locations of Percy’s and McLaughlin’s reefs (VicMine; Department of Mines, Victoria, 1891; Foster, 1899; Foster, 1899b; Lidgey, 1899; Nott, 1985; Cayley, 1995). The reefs and mines lie within the outcrop of the Ordovician to Cambrian St Arnaud Group.
2.8.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (1854-1940), kg</th>
<th>&gt;3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>4.6</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>&gt;650</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

5 Mountain Hut mine

Notes on production records

The only mine with recorded production in VicMine is the Mountain Hut (VicMine ID 363498). It is likely that the production from this ore field is under-reported. Lidgey (1899) reported an aggregate production of over 2.8 kg from McLaughlin’s and Cohens Reefs as well as unknown production from Percy’s Reef, worked over a period of 17 years, indicating that there must have been significant production to maintain activity over this length of time.

2.8.4 Recorded mines (VicMine)

Mountain Hut (VicMine ID 363498), with a total production of under 100 gm.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>McLaughlins reef</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>3</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30 m (Cohens)</td>
</tr>
</tbody>
</table>

2.8.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>1900 m long (Cohens Reef)</th>
</tr>
</thead>
</table>

6 This may have been confused with Cohens reef, Walhalla

2.8.6. Host rocks

| Host rock types         | sandstone, slate, quartzite |
2.9. Glenshee

2.9.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 699 964 E, 5 888 232 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.3</td>
<td>9.1</td>
<td>100°</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

2.9.2. Description

The Glenshee ore field contains seventy five reefs (some of which are reported more than once, depending on the source). None of these reefs are reported to have yielded gold, however the high number of quartz reefs mapped in a well defined area indicates that this is an area where mineralising processes similar to those in other ore fields have been active (Cayley, 1995; Geological Survey of Victoria, undated. Parish of Eversley; Foster, 1899). These reefs all lie within the outcrop of the Cambrian-Ordovician St. Arnaud Group.

![Glenshee ore field](image-url)
2.9.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th></th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>unknown</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

No mines have been recorded within this ore field. However, it was considered that this ore field should be included in this compilation to illustrate that an area which has undergone apparent orogenic gold style mineralization processes may, in fact, contain no gold.

2.9.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>0</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0</td>
</tr>
<tr>
<td>Mining method</td>
<td>unknown</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.9.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Typical reef strike appears to be 330°, but ranges from 300°-350°.</th>
</tr>
</thead>
</table>

2.9.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.10. Golden Jacket

2.10.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 723 391 E, 5 964 505 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>1.4</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.10.2. Description

The Golden Jacket ore field contains one mine (VicMine; Bibby and Moore, 1998; Caldwell, 1938). The mine lies within the outcrop of the Cambrian St Arnaud Group.

2.10.3. Production and endowment

The calculated high grade is probably suspect.

*Historic production*

| Historic gold production (1854-1940), kg | 43 |
| Recovered grade, g/t                   | 251|
| Processed ore, t                       | 171|
| Recent gold production (1983-2007)     | 0  |
| Current resource / reserve (12/2007)   | unknown |
2.10.4. Recorded mines (VicMine)

Golden Jacket (VicMine ID 737410), with a total production of 42.9 kg.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Golden Jacket</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>43</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>Over 46 m</td>
</tr>
</tbody>
</table>

2.10.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>About 84 m long; 0.2-0.3 m wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Strike 320°, dip 79° W</td>
</tr>
</tbody>
</table>

2.10.6. Host rocks

| Host rock types | Slate and sandstone |
2.11. Homebush

2.11.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 724 491 E, 5 897 595 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.7</td>
<td>5</td>
<td>30°</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

2.11.2. Description

The Homebush ore field contains five mines and seven reefs (VicMine; Geological Survey of Victoria, undated. Parish of Glenmona; Wohlt et al., 2000; Taylor et al., 2000; Nicholas, undated; Department of Mines, Victoria, Undated; Annual report - series published since 1874 under various departmental names), all lying within the outcrop of the Cambrian St Arnaud Group.
Appendix 3

2.11.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 493 |
| Recovered grade, g/t                  | 29 |
| Processed ore, t                      | 3385 |
| Recent gold production (1983-2007)    | 0  |
| Current resource / reserve (12/2007)  | unknown |

**Estimated total endowment**

| Contained gold, kg | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t | 29 |

2.11.4. Recorded mines (VicMine)

| Total number of mines | 6 |
| Number of mines with recorded production | 5 |
| Biggest producer        | Excelsior mine |
| Major mines (over 25 kg gold) | 2 |
| Total recorded gold production, kg | 493 |
| Mining method           | Open cut (Dreadnought, Raws reef), shaft (Excelsior, Vales Reef, Frying Pan reef) |
| Depth of mining         | 46 m (Frying Pan reef)  |
|                         | 152 m (Excelsior mine) |
|                         | 85 m (Vales reef) |

**Notes on production records**

- Excelsior mine (VicMine ID 366635; Taylor et al., 2000; Nicholas, undated; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated -Annual report)
- Dreadnought mine (VicMine ID 366636; Howitt, 1912). Dip 75° W. Slates adjacent to quartz reefs had gold grades of over 10 g/t. Total gold production is slightly greater than quoted in VicMine – about 5 kg.
- Raws reef (VicMine ID 366641; Ramsay and Nott, 1986) Frying Pan reef (VicMine ID 366638; Whitelaw, 1894; Department of Mines, Victoria, Undated. Gold production card index; Moon, 1897). Worked over a 40 year period. Between 0.3 and 0.6 m wide. Strike 13°/dip 70° E. Length about 100 m. Deepest working about 30 m. Grade up to 180-250 g/t Au.
- Vales reef (VicMine ID 366637; Moon, 1897; Whitelaw, 1894; Department of Mines, Victoria, 1891). There are four distinct reefs in this complex: Vales reef, east reef, west reef and Yankee Bills reef. Strike 23-28°/dip 70-88°W. Up to 0.6 m wide. Length over 300 m, maximum depth over 80 m. Grade varied between 30 and 160 g/t with yields of over 800 g/t reported. Total production was estimated as 193 kg (cf VicMine with a recorded production of 61 kg). The final production for this ore zone was increased by 132 kg to allow for this discrepancy. Yorkies reef (not registerd in VicMine; Moon, 1897). 30 m long, strike 20°/dip 85° E, maximum depth 16 m. Production over 0.4 kg gold.

2.11.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>unknown</th>
</tr>
</thead>
</table>
| Orientation | Vales reef, dip 70°, dip direction 118° - varies within reef system  
Frying Pan reef dip 70°, dip direction 283°  
Yorkies reef dip 85°, dip direction 110° |

2.11.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone and slate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>contact</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.12. Isabelle

2.12.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 723 328 E, 5 930 944 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total area (km²)</strong></td>
<td><strong>Area of cover (km²)</strong></td>
</tr>
<tr>
<td>5.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

2.12.2. Description

The Isabelle ore field contains three mines (VicMine; Barber, 1987), all lying within the outcrop of the Cambrian St Arnaud Group.

2.12.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 18.8 |
| Recovered grade, g/t                    | 22   |
| Processed ore, t                        | 854.5|
| Recent gold production (1983-2007)      | 0    |
| Current resource / reserve (12/2007)    | unknown |
Estimated total endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t (Isabella mine)</td>
<td>22</td>
</tr>
</tbody>
</table>

Notes on production records

There are no production records for this ore field.

2.12.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Isabelle mine</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>18.8</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>40 m (Barber, 1987)</td>
</tr>
</tbody>
</table>

- Isabelle (VicMine ID 363446; Bannear, 1994)
- Cruikshank Reef (Barber, 1987)
- Round Hill Cyanide mine (VicMine ID 363745; Krokowski de Vickerod et al., 1997)

2.12.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Saddle reef, only one leg auriferous (Cruikshank reef)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>20 m wide, 500 m long (Cruikshank reef)</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.12.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Deep marine turbidites.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.13. Kewell

2.13.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 619 683 E, 5 969 569 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>345°</td>
<td>5.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.13.2. Description

The Kewell ore field is entirely under cover and was defined by drilling (Perseverance Corporation Ltd., 2007). The dimensions of this ore field are speculative.

Kewell ore field
2.13.3. Production and endowment

Historic production

| Historic gold production (1854-1940), kg | 0 |
| Recovered grade, g/t                   | 0 |
| Processed ore, t                       | 0 |
| Recent gold production (1983-2007)     | 0 |

Notes on production records

There has been no production from this ore field.

2.13.4. Recorded mines (VicMine)

| Total number of mines                     | 0 |
| Number of mines with recorded production | 0 |
| Biggest producer                         | 0 |
| Major mines (over 25 kg gold)             | 0 |
| Total recorded gold production, kg        | 0 |

2.13.5. Ore bodies and systems

| Character of ore bodies | Volcanogenic sediment and basalt-hosted quartz reefs |
| Dimensions             | About 4000 m long                                      |
| Orientation            | Strike of structure about 345°                         |

2.13.6. Host rocks

| Host rock types | Volcanogenic sediments and basalt |
2.14. Kingston

2.14.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 687 821 E, 5 899 295 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>0</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.14.2. Description

The Kingston ore field contains one mine (VicMine; Bradford, 1903b; Department of Mines & Water Supply, Victoria, Undated. The Goldfields of Victoria; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Department of Mines, Victoria, Undated. Gold production card index; Department of Mines, Victoria, Undated. The Goldfields of Victoria Quarterly Returns; Inan, 1989c; Jenkins, 1902; Stephens, 1929; Watchorn, 1986).

The mine lies within the outcrop of the Cambrian St Arnaud Group.
2.14.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>65</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>7.5</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>8667</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Estimated total endowment

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>100,000+7</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

7 Stephens, 1929

Notes on production records

Grades for the Kingston mine varied considerably, with some very rich grades reported – over 800 g/t Au. Silver grades varied up to about 215 g/t and the ore contained significant Pb.

2.14.4. Recorded mines (VicMine)

Wimmera (VicMine ID 432552), with a total production of about 140 gm.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Kingston</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>65</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>91 m</td>
</tr>
</tbody>
</table>

2.14.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Up to 12 m thick</td>
</tr>
</tbody>
</table>

2.14.6. Host rocks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>turbidite</td>
</tr>
</tbody>
</table>
2.15. Kooreh South

2.15.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 717 510 E, 5 939 779 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.7</td>
<td>4</td>
<td>90°</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

2.15.2. Description

The Kooreh South ore field contains twenty five mapped reefs (some of which may be duplicates; Geological Survey of Victoria, undated Parish of Kooreh; Krokowski de Vickerod, 1997), all lying within the outcrop of the Cambrian St Arnaud Group.

![Kooreh South ore field](image)

2.15.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production (1854-1940), kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>unknown</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>
Estimated total endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

There are no production records for this ore field

2.15.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>none</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0</td>
</tr>
<tr>
<td>Mining method</td>
<td>unknown</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.15.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Average reef length 260 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Typically 355°</td>
</tr>
</tbody>
</table>

2.15.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Deep marine turbidites.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.16. Landsborough

2.16.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 690 172 E, 5 904 678 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.9</td>
<td>11.3</td>
<td>330°</td>
<td>6.5</td>
<td>5</td>
</tr>
</tbody>
</table>

2.16.2. Description

The Landsborough ore field contains twenty mines (fifteen named) and forty one reefs (VicMine; Anon, undated. Landsborough, County of Kara Kara; Krokowski de Vickerod et al., 1997; Department of Mines, Victoria, 1891; Reilly, 1899; Bradford, 1903b; Caldwell, 1928; Caldwell, 1933; Canavan, 1988). Some of the reefs and mines are reported from different sources, with some inconsistencies in location. These all lie within the outcrop of the Cambrian St Arnaud Group.

![Landsborough ore field](image-url)
2.16.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Historic gold production (1854-1940), kg</th>
<th>&gt;1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>4</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>&gt;439</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Estimated total endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

Two mines have recorded production in VicMine in this ore field:

- Empire Co (VicMine ID 363404) with production of 1.1 kg gold from 410 t ore
- Powers (VicMine ID 363634) with production of 0.7 kg gold from 28 t ore.

There are a further twelve named and six unnamed mines in this ore field, as well as eleven named reefs, some of which are associated with the above mines.

2.16.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Empire Co</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>4.2</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft s, open cuts, adits</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>29 m (Argonaut Mining Syndicate)</td>
</tr>
</tbody>
</table>

2.16.5. Ore bodies and systems

| Orientation                   | Dip direction 270° (Empire Co, Powers, Stawell); 230° (Flagstaff Syndicate, with dip of 65°); 90° (Lennons, Grahams, Kellys, Tramway, Naracoorte) |

2.16.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>turbidite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.17. Leggetts Reef

2.17.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 725 527 E, 5 956 419 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>0.8</td>
<td>30°</td>
<td>2.8</td>
<td>1</td>
</tr>
</tbody>
</table>

2.17.2. Description

The Legget’s Reef ore field contains two reefs (Beckett, 1880; Panaegis Gold, 2007(?)), only one of which is named (Legget’s Reef), all lying within the outcrop of the Cambrian St Arnaud Group.
2.17.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | unknown |
| Recovered grade, g/t                  | unknown |
| Processed ore, t                      | unknown |
| Recent gold production (1983-2007)    | 0 |
| Current resource / reserve (12/2007)  | unknown |

**Estimated total endowment**

| Contained gold, kg  | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t   | unknown |

**Notes on production records**

There are no production records for this ore field.

2.17.4. Recorded mines (VicMine)

| Total number of mines | 1 |
| Number of mines with recorded production | 0 |
| Biggest producer | Presumed to be Leggett’s Reef |
| Major mines (over 25 kg gold) | unknown |
| Total recorded gold production, kg | unknown |
| Mining method | unknown |
| Depth of mining | unknown |

2.17.5. Ore bodies and systems

| Dimensions | Leggett’s Reef 280 m long |
| Orientation | 320° |

2.17.6. Host rocks

| Host rock types | Deep marine turbidites and hemipelagic sediments |
| Metamorphism    | unknown |
| Structural history | unknown |
2.18. Linton

2.18.1. Location and dimensions

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>142.1</td>
<td>57.1</td>
<td>0°</td>
<td>21</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 725 752 E, 5 828 052 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

2.18.2. Description

The Linton ore field as defined here includes the Linton, Snake Valley and Happy Valley historic goldfields. It contains 119 recorded mines (76 named) and 337 mapped reefs (VicMine; Department of Mines, Victoria, 1891; Mining Department Victoria, undated; Department of Mines, Victoria, Undated. The Goldfields of Victoria Quarterly Returns; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Fitches, 1908; Department of Mines, Victoria, Undated. Goldfields of Victoria: Reports of the Mining Registrars; Department of Mines, Victoria, Undated. Reports and Statistics of the Mining Department; Bierlein et al., 2001; Lynch, 1902; Roberts, 1901; Anon, Undated. Dickers Mining Record; Anon, undated. Plan showing leads shafts and topography; Robertson, 1927; Kenny, 1937c; Whitelaw, 1898; Baker, 1916a; Baker, 1916b; Krause, 1898; Wallace, 1933; Baragwanath, 1946; Dunn, 1909; Department of Mines & Water Supply, Victoria, Undated; Geological Survey of Victoria, 1903; Dunn, 1890; Baragwanath, 1923; Kenny, 1937d; Department of Mines, Victoria, Undated. Mining and Geological Journal; Krause, 1898b; Finlay et al., 1992a and 1992b; Baragwanath, 1917; Krause, 1889; Adcock, 1912) all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.

Two main mineralised areas – the Britannia Reef and four adjacent reefs south of Snake Valley in the north and around the Port Arthur mine in the south-east, on the hanging wall of the Avoca Fault.
2.18.3. Production and endowment

Historic production

| Historic gold production (1854-1940), kg | 880  |
| Recovered grade, g/t                  | 9.3  |
| Processed ore, t                      | 94,000 |
| Recent gold production (1983-2007)    | None |
| Current resource / reserve (12/2007)  | None |

Estimated pre-mining endowment

| Contained gold, kg                  | 1,000 |
| In situ ore tonnage, t              | 86,000 |
| In situ grade, g/t                  | 12    |
Appendix 3

2.18.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>52</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Britannia QM Co.</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>4</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>903</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft, open cuts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>335 m (Western Star Co. Main Shaft)</td>
</tr>
</tbody>
</table>

Most other shafts less than 50 m deep

Notes on production records

Production from 1864 to 1913 Officially recorded by mining registrars – approximately 700 kg at an average recovered grade of 10.6 g/t (VicProd; Mines Department, Victoria, 1864-1869; Department of Mines, Victoria, 1870-1913).

Port Arthur GM Co (VicMine ID 378363; Dunn, 1909; Baragwanath, 1923; Department of Mines, Victoria, Undated.

Annual report. Series published since 1874; Kenny, 1937d) is located a few hundred meters west of the eastern boundary of the Stawell Zone. Average grade was 21 g/t Au.

Britannia Quartz Mining Co Shaft No. 1 - Main Shaft (VicMine ID 377551; Mining Department Victoria, Undated. Reports of the Mining Surveyors and Registrars; Department of Mines, Victoria, 1891; Anon, Undated. Dickers Mining Record.; Kenny, 1937c; Krause, 1898). Grades reported as 217 g/t for the Britannia reef (Krause, 1898) but more typically around 25 g/t.

New Britannia Co (VicMine ID 378184; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Goldfields of Victoria; Kenny, 1937C; Geological Survey of Victoria, 1903). This was on the Result reef line, with an average grade of about 8 g/t (VicMine grade calculation) or alternatively 23 g/t as reported in Krause, 1898.

Homeward Bound Co (VicMine ID 377905; Department of Mines, Victoria, Undated. Annual report. Series published since 1874) This is approximately along strike and 6.5 km SSW of the above two mines. Grade reported as 12 g/t.

Based on the value of extracted gold recorded for approximately 200 kg Au, mostly from the Port Arthur mine (Department of Mines, Victoria, 1906-1907), an average silver content of produced gold is estimated to be approximately 12%.
2.18.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Worked length: 306 m (Port Arthur GM Co), 107 m (Britannia Quartz Mining Co). Average width: About 0.76 m (Britannia Quartz Mining Co)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>dip 88° to 270° (Port Arthur GM Co)</td>
</tr>
</tbody>
</table>

2.18.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>shale and sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.19. Mannibadar

2.19.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 725 691 E, 5 814 843 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>3.4</td>
<td>290°</td>
<td>2.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.19.2. Description

The Mannibadar ore field contains four mines and one reef (VicMine; Taylor, 1996; Kenny, 1937a; Kenny, 1937b; Department of Mines, Victoria, Undated. The Goldfields of Victoria Quarterly Returns; Finlay et al., 1992), all lying within the outcrop of the Cambrian St Arnaud Group, although this is assumed to be the case for the reef.
2.19.3. Production and endowment

*Historic production*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production</td>
<td>49</td>
</tr>
<tr>
<td>(1854-1940), kg</td>
<td></td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>6</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>7653</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

*Estimated total endowment*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>6</td>
</tr>
</tbody>
</table>

2.19.4. Recorded mines (VicMine)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>4</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>3</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Linton GM Co</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>49</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>61 m (Linton GM Co)</td>
</tr>
<tr>
<td></td>
<td>24 m (Gribble)</td>
</tr>
<tr>
<td></td>
<td>28 m (Corbett’s)</td>
</tr>
</tbody>
</table>

*Notes on production records*

- Linton GM Co (VicMine ID 378029; Anon, undated; Baragwanath, 1946; Department of Mines, Victoria. Undated. Mining and Geological Journal; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Kenny, 1940; Kenny, 1937b). Recovered gold grades reported as 1 to 7 g/t, but there may be some confusion with Gribbles mine.

- Gribbles mine (VicMine ID 377013; Kenny, 1937a; Kenny, 1937b; Department of Mines, Victoria, Undated. The Goldfields of Victoria Quarterly Returns). Grade reported as 12 g/t.

- Corbett’s Freehold GM Co (VicMine ID 376740; Kenny, 1936; Kenny, 1937a; Kenny, 1937b; Anon, 1937). Grade reported as 16 g/t. Thickness 0.6 m to 2.7 m.
2.19.5. Ore bodies and systems

| Dimensions       | Worked length: 21 m (Linton GM Co)  
|                  | Variously reported as 21 m or 28 m (Corbett's Freehold GM Co) |
| Orientation      | Dip 49° to 118° (Linton GM Co)       
|                  | Dip to 90° (Gribble)                 
|                  | Shaft variously reported as dip 50° to 135°, dip 60° to 140° and dip 90° to 270° (Corbett's Freehold GM Co) |

2.19.6. Host rocks

| Host rock types               | Slate and sandstone |
| Metamorphism                  | contact              |
| Structural history            | unknown              |
2.20. Moonambel-Redbank

2.20.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 700 751 E, 5 907 462 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.2</td>
<td>13.5</td>
<td>290°</td>
<td>15</td>
<td>4</td>
</tr>
</tbody>
</table>

2.20.2. Description

This ore field contains 32 mines (27 named) and 86 reefs (VicMine; Whitelaw et al., 1903; Krokowski de Vickerod, 1997; Herman & Baragwanath, undated; Walker, 1894; Walker, 1894b; Byrne, 1861; Nott, 1983; Bradford, 1903; Department of Mines, Victoria, 1891; Krokowski de Vickerod et al., 1997; Bannear, 1994; Howitt, 1899; Department of Mines, Victoria,

Undated. Annual report. Series published since 1874; English, 1861; Byrne, 1861b; Byrne, 1861c; Jenkins, 1901; Hunter, 1897; Caldwell, 1935; Hunter, 1898; Byrne, 1861d; Hunter, 1894; Byrne, 1861e; Lennard, 1988). Some of the reefs and mines are reported more than once from different sources, with some inconsistencies in location. These all lie within the outcrop of the Cambrian St Arnaud Group.

Moonambel - Redbank ore field
2.20.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>760</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>30</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>25300</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>44</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>840</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>24,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>34.9</td>
</tr>
</tbody>
</table>

**Notes on production records**

The four largest producers in this ore field are:

- Pyrenees reef (VicMine ID 363642) with production of 49 kg gold from 1684 t ore (recorded in VicMine).
- Slaughteryard (VicMine ID 363680) with production of 25 kg gold from 224 t ore.
- All England reef (VicMine ID 363330) with production of 18 kg gold from 225 t ore.
- Tormeys (VicMine ID 363705) with production of 16 kg gold from 409 t ore.

There are a further eight named mines with recorded production in this ore field.

Historic records indicate that total production from the Pyrenees Reef between 1861 and 1915 was more than 600 kg Au and, possibly, as high as 900 kg Au, with an average recovered grade of more than 31 g/t (Walker, 1894; Baragwanath, 1917; McKenzie, 1981). Additionally, Krokowski de Vickerod et al. (1997) estimated total gold production from the ore field outside the Pyrenees Reef to be 156 kg (including 44 kg of recent production in 1989-1990). Based on the value of gold produced in 1864-1866 (Mines Department, Victoria, 1864-1866) and in 1909-1915 (213 kg Au, Department of Mines, Victoria, 1909-1915), the average silver content of gold produced from the Moonambel-Redbank ore field is estimated to be approximately 10%.

Total production accepted for the Moonambel-Redbank ore field is 800 kg (90% purity), at an average recovered grade of 30 g/t.
2.20.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>12</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Pyrenees reef</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>2</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>127</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shafts, open cuts</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>130 m (Pyrenees reef)</td>
</tr>
</tbody>
</table>

2.20.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>dip 58°, dip direction 251° (Pyrenees reef); dip 65°, dip direction 65° (Moonambel)</td>
</tr>
</tbody>
</table>

2.20.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Turbidite (Pyrenees reef)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.21. Moores Reef

2.21.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 673 148 E, 5 879 078 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.3</td>
<td>6.1</td>
<td>0°</td>
<td>10.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.21.2. Description

The Moores Reef ore field (named after the main mapped reef running through this ore field) contains twelve mines and three reefs – two named (VicMine; Anon, Undated. Kingston Gold Mining Co Shaft; Bradford, 1894a; Cayley & Taylor, 2001; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Reports and Statistics of the Mining Department; Inan, 1989b; Inan, 1989c; Inan, 1990; John Taylor & Sons., 1968; Krause, 1875a; Krause, 1875b; Motton, 1989; Taylor, 1878; Walker, 1988a). The mines lie within the outcrop of the Cambrian St Arnaud Group.
2.21.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>12.6</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>7.9</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>1594</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated total endowment**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The Prospectors claims (VicMine ID 431676) shows an unusually high grade of nearly 83 g/t Au, but this is probably because this is an agglomeration of several small
claims working selected ore. Although this is registered as one site, it in fact consists of small workings over a strike length of nearly 2,000 m. The largest individual producers in this ore field are from this series of prospectors’ claims.

2.21.4. Recorded mines (VicMine)

The largest mine, Claim No. 4 and 5 South (VicMine ID 431668), produced just over 3 kg of gold at a grade of 13.4 g/t

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>10</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Claim No. 4 and 5 South</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>12.6</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>61 m (Noahs Ark)</td>
</tr>
</tbody>
</table>

2.21.5. Ore bodies and systems

| Dimensions                | 100 m long (Moores Reef) |

2.21.6. Host rocks

| Host rock types | Turbidites, slate |
2.22. Moyston

2.22.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 656 232 E, 5 869 815 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>2.9</td>
<td>350°</td>
<td>3.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.22.2. Description

The Moyston ore field coincides with the historic Moyston goldfield. It contains 46 recorded mines, 10 of which are unnamed (VicMine; Anon, 1899; Anon, Undated. Dickers Mining Record; Cayley and Taylor, undated; Department of Mines & Water Supply, Victoria, Undated. The Goldfields of Victoria; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Gold production card index; Dunn, 1909c; Forwood, 1987; Geological Survey of Victoria, undated. Ararat plan showing leads and reefs; Inan, 1989c; Krause, 1875; Mining Department Victoria, Undated. Reports of the Mining Surveyors and Registrars; Murray, 1892; Smyth, 1869; Stirling, 1898b; Whiting, 1959). The reefs and mines all occur within the outcrop of the Cambrian Moornambool Metamorphic complex and Nargoon Group.
2.22.3. Production and endowment

Historic production

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>2400</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>22.5</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>107,700</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated total endowment

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>2600</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>98,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Notes on production records

The Taylor mine (VicMine ID 431617) is probably located on Campbells Reef rather than in the Armstrong ore field (Inan, 1989a) and its production is thus included in this ore field.
Total primary production from the Moyston Goldfield has been consistently estimated by numerous researchers to be 76,000 oz (2360 kg) from approximately 100,000 t of processed ore at an average recovered grade of 22 – 23 g/t (Krause, 1875; Whiting, 1959; Bowen, 1974; Bowen & Whiting, 1975; Whiting & Bowen, 1976; Ramsey & Willman, 1988; O’Shea et al., 1991; Bush et al., 1995; Cayley & Taylor, 2001). This estimate is consistent with total gold production apportioned to recorded mines (2117 kg at an average recovered grade of 21 g/t). The difference is probably due to a fact that some recorded gold production from the Moyston ore field could not allocated to registered mines. The original estimate of 76,000 oz was made for primary gold production in the period from 1857 to 1875 (Krause, 1875; Stirling, 1898; Whiting, 1959). An additional 47.3 kg of gold was recorded for cyanide treatment of mine tailings in 1897-1898 (Department of Mines, Victoria, 1897-1898). The average Ag/Au ratio of the gold recovered by cyanide treatment is estimated to be 15%. Gold produced in 1860-s is estimated to have been 90% pure (based on bullion prices reported by Mines Department, Victoria, 1864-1865).

The ore field production statistics are accepted after Inan (1990) and Cayley and Taylor (2001), plus the minor recorded gold production from cyanide treatment.

### 2.22.4. Recorded mines (VicMine)

Total gold production apportioned to recorded mines is 21117 kg at an average recovered grade of 21 g/t Au.

- Kangaroo mine (VicMine ID 431614) produced 585 kg gold at a grade of 18 g/t, This was the major mine on Campbells reef with other large producers including:
  - Smarts (VicMine ID 431615) which produced 379 kg gold at a grade of 82 g/t (ore tonnage probably under-reported), North Star (Vicmine ID 431606) which produced 270 kg gold at a grade of 14 g/t, and Southern Cross (VicMine ID 431607) which produced 230 kg gold at a grade of 17 g/t.

Other major producers include the Perseverance (VicMine ID 431609), Extended Southern Cross (VicMine ID 431608), Invincible (VicMine ID 431612), Consolidated (VicMine ID 431602), Extended North Star (VicMine ID 431600), Prospect (VicMine ID 431618), Three Crowns (VicMine ID 431603) and Hutt ons (VicMine ID 431597), all of which produced in excess of 25 kg gold each.
### Appendix 3

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>28</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Kangaroo</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>12</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>2 117</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>177 m (Extended Southern Cross), 171 m (Kangaroo) 159 m (Sir Bowen)</td>
</tr>
</tbody>
</table>

#### 2.22.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz veins in steep east-dipping fault planes. Campbells reef is laminated. East Spur reef very thin (.02 m) but rich</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Individual reefs up to 1 km along strike, up to 1.8 m thick (average – about 0.5 m - Campbells reef), mined to a depth of up to 180 m.</td>
</tr>
<tr>
<td>Orientation</td>
<td>Dip 90o E, strike 340o (Campbells reef); dip 80o E, strike 155o (Simpsons)</td>
</tr>
</tbody>
</table>

#### 2.22.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>schist, greenstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>Up to amphibolite</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.23. Nine Mile

2.23.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 723 391 E, 5 964 505 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>0.4</td>
<td>n/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.23.2. Description

The Nine Mile ore field contains one recorded mine (VicMine; Bibby and Moore, 1998; Hunter, 1900; Hunter, 1904).

The mine lies within the outcrop of the Cambrian St Arnaud Group.

![Nine Mile ore field](image)

2.23.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 507 |
| Recovered grade, g/t                  | 11.5 |
| Processed ore, t                      | 44,000 |
| Recent gold production (1983-2007)    | none |
| Current resource / reserve (12/2007)  | none |
Appendix 3

**Estimated pre-mining endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

Total Officially recorded production to the end of 1910 was 506,750 g (16292 oz 8 dwt) (Department of Mines, Victoria, 1903-1910). Ore tonnage was not recorded for the last 131 oz (4 kg). The total amount of processed ore was calculated from the total recorded gold production (506.8 kg) and the average recovered grade of 11.5 g/t recorded for 43573 t of ore production.

Silver content of total produced gold (from the value of 272 kg of production in 1903-1910) is estimated to be approximately 5%.

**2.23.4. Recorded mines (VicMine)**

Nine Mile (VicMine ID 373408), with a total production of about 505 kg.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Nine Mile</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>505</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>130 m</td>
</tr>
</tbody>
</table>

**2.23.5. Ore bodies and systems**

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Complex of three reefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>About 300 m long</td>
</tr>
<tr>
<td>Orientation</td>
<td>Strike 326°, dip 80° E</td>
</tr>
</tbody>
</table>

**2.23.6. Host rocks**

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Slate and sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>Cordierite grade</td>
</tr>
</tbody>
</table>
2.24. Percydale

2.24.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 715 177 E, 5 900 616 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>9.5</td>
<td>350°</td>
<td>6.5</td>
<td>5</td>
</tr>
</tbody>
</table>

2.24.2. Description

The Percydale ore field contains twenty five mines and thirty reefs (some of which are reported more than once, depending on the source), of which most are related to the registered mines (VicMine; Cayley, 1995; Geological Survey of Victoria, undated. Parish of Yehrip; Moon, 1897; Department of Mines, Victoria, 1891; Nott, 1985; Dunn, 1890; Whitelaw, 1895b; Bradford, 1903; Nott, 1985b; McKenzie, 1981; McKenzie, 1980; Apthorpe, 1981; Bradford, 1904; Anon, 1908; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Cayley and McDonald, 1995; Bierlein et al., 2000; Walker, 1894; Whitelaw, 1899; Bradford, 1903) all lying within the outcrop of the Cambrian-Ordovician St Arnaud Group.
2.24.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>150</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>11.5</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>12372</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Estimated total endowment**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

Some gold was slate-hosted (Fiddlers Creek, and in the vicinity of 714,000 E 5,895,000 N), occurring as thin films on cleavage planes, but the grade of the latter occurrence was low, averaging 3 g/t Au (Bradford, 1903), over a width of about 5 m.
2.24.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>15</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Barnes</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>2</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>150</td>
</tr>
<tr>
<td>Mining method</td>
<td>Tunnel, shaft and open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>90 m (Barnes)</td>
</tr>
</tbody>
</table>

- Barnes (VicMine ID 432518; Whitelaw, 1895b; Moon, 1897; Nott, 1985; Department of Mines, Victoria, 1891; Bradford, 1903). 41.4 kg gold was produced from 1405 tons of ore for a grade of 29 g/t. Initial grade was 62 g/t but the grade declined below 60 m.

- Perseverance (VicMine ID 432508; Whitelaw, 1895b; Moon, 1897; Nott, 1985; Department of Mines, Victoria, 1891; Dunn, 1890; Bradford, 1903). 34.4 kg of gold was produced from 3672 t of ore for a grade of 9 g/t, although other sources estimate the grade at 15 g/t (Whitelaw, 1895b).

Other named sites with production records:

- West of England (VicMine ID 432512). Initial grade of 78 g/t Au, declining to 6 g/t. Also known as Hancocks.

- Fiddlers Reef (Roberta) (VicMine ID 432509). Grade to 10 m depth was over 120 g/t, at 15 m the grade was 31 g/t, at 45 m the grade had dropped to 6 g/t, which was at the economic limit at the end of the 19th century. This was probably an extension of Perseverance reef, which would make this reef system about 1,000 m long. The reef is subparallel to bedding and occurs within a W-dipping reverse fault system and the ore shoot pitches 18° S. The gold was difficult to extract at depth due to the presence of fresh sulphides, occasionally in massive concentrations.

- Lucks All (VicMine ID 432515).

- Union Jack (VicMine ID 432516). Grade of over 30 g/t until the reef was worked out.

- Poverty/Bannisters (VicMine ID 432511).

- Honeycomber – reef and mine (VicMine ID 432502) – possibly confused with the Honeycomb reef, reported to lie about 1 km to the SE (Geological Survey of Victoria, undated. Parish of Yehrip).

- Donkey Hill (VicMine ID 432506) - grade of 16 g/t Au.

- Sliding Rock Reef (VicMine ID 432507).

- Darling (VicMine ID 432504).
Bullocky (VicMine ID 432513). Grade started at 8 g/t and became uneconomic at a depth of 150 m.

Halls (VicMine ID 432517). Average grade of 8 g/t, with patches up to 120 g/t.

Compensation (VicMine ID 432503).

Magenta (VicMine ID 432505).

Wards (VicMine ID 432510). Probably produced over 6 kg of gold (Whitelaw, 1895b). Given the previously unregistered production of over 6 kg of gold from Wards reef and the unrecorded production from Hannans and Victoria reefs (Whitelaw 1895b) the production from this ore field is increased from 142 kg to 150 kg, which is still probably conservative.

2.24.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 m wide at 15 m depth range</td>
<td>0.3-2.4 m</td>
</tr>
<tr>
<td>4.6 m wide (Halls reef)</td>
<td></td>
</tr>
<tr>
<td>0.8 m (Barnes reef)</td>
<td></td>
</tr>
<tr>
<td>0.3 m wide (Perseverance reef)</td>
<td></td>
</tr>
<tr>
<td>0.1 m (Wards)</td>
<td></td>
</tr>
<tr>
<td>0.5 m wide, 150 m long (West of</td>
<td></td>
</tr>
<tr>
<td>England reef)</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td></td>
</tr>
<tr>
<td>Fiddlers reef strike 325°</td>
<td></td>
</tr>
<tr>
<td>West of England reef 330°, dip</td>
<td></td>
</tr>
<tr>
<td>60° W</td>
<td></td>
</tr>
</tbody>
</table>

2.24.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Sandstone, slate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.25. Port Curtis-Bourkes

2.25.1. Location and dimensions

<table>
<thead>
<tr>
<th>Total area (km$^2$)</th>
<th>Area of cover (km$^2$)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>4.4</td>
<td>0°</td>
<td>5.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.25.2. Description

The Port Curtis-Bourkes ore field (named after its largest producing mine) lies partially over granite. Mines outside the granite area have minor production.
Appendix 3

2.25.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>unknown</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.25.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>0</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0</td>
</tr>
</tbody>
</table>

2.25.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.26. Rhymney

2.26.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 661 521 E, 5 877 729 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.7</td>
<td>0°</td>
<td>1.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.26.2. Description

The Rhymney ore field (named after its largest producing mine) contains two mines (VicMine; Bradford, 1894; Cayley and Taylor, 2001; Cayley and Taylor, undated; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated; Ferguson, 1899; Flett, 1979a; Flett, 1979b; Krause, 1875a; Krause, 1875b; Taylor, 1878). The mines lie within the outcrop of the Silurian Moornambool Metamorphic complex. One report (Bardford, 1894) mentions primary gold about “half a mile to the east” of the Rhymney mine. This was not noted in modern mapping. If it is correct, then the Rhymney ore field should be considered part of the Armstrong ore field.

Rhymney ore field
### 2.26.3. Production and endowment

#### Historic production

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>106</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>15</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>4251</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>0</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

#### Estimated total endowment

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.26.4. Recorded mines (VicMine)

The Rhymney mine (VicMine ID 431688) produced 61 kg gold at a grade of 23 g/t. The Victoria produced 49 kg gold at 28 g/t.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>2</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Rhymney</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>2</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>106</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>90 m (Rhymney)</td>
</tr>
</tbody>
</table>

### 2.26.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>0.6 m wide reef (Rhymney)</td>
</tr>
<tr>
<td>Orientation</td>
<td>Dip 80°, dip direction 330° (Rhymney) – dip reported elsewhere as 30° W</td>
</tr>
</tbody>
</table>

### 2.26.6. Host rocks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Greenstone</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>Regional (±actinolite±cordierite±andalusite)</td>
</tr>
</tbody>
</table>
2.27. Slaty Creek

2.27.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 710 283 E, 5 947 950 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>5.9</td>
<td>330°</td>
<td>11.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.27.2. Description

The Slaty Creek ore field contains 56 mapped reefs and two mines (all west of the St Arnaud fault, Geological Survey of Victoria, undated Parish of St Arnaud; Krokowski de Vickerod, 1997), all lying within the outcrop of the Cambrian St Arnaud Group.

![Slaty Creek ore field](image)

2.27.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 2 |
| Recovered grade, g/t                  | 15 |
| Processed ore, t                      | 131 |
| Recent gold production (1983-2007)     | none |
| Current resource / reserve (12/2007)   | none |
Appendix 3

Estimated total endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

*The following production is reported in VicMine:*

- Little Boulder mine (363465) – 38 oz gold from 104.65 t ore (Department of Mines, Victoria, Undated).
- Red, White and Blue mine (363652) – 26 oz from 26.42 t ore (Dunn, 1912; Department of Mines, Victoria, Undated).

2.27.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>2</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Little Boulder</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>2</td>
</tr>
<tr>
<td>Mining method</td>
<td>unknown</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.27.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Average reef length 180 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Typically 330°</td>
</tr>
</tbody>
</table>

2.27.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>Deep marine turbidites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.28. St Arnaud

2.28.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 702 012 E, 5 944 641 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>105.5</td>
<td>9</td>
<td>0°</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

2.28.2. Description

The St Arnaud ore field, almost identical in extent to the historic St Arnaud Goldfield (Weston, 1991; Krokowski de Vickerod et al., 1997), contains 115 recorded mines (including 102 named) and 369 mapped reefs (VicMine; Anon, 1861; Anon, 1912; Anon, 1915; Anon, undated. New Bendigo workings; Anon, undated, Parish of St Arnaud; Anon, undated, St Arnaud North Gold Mine; Bannear, D., 1994; Baragwanath, 1921; Baragwanath, 1924; Baragwanath, 1925; Bradford, 1903a; Canavan, 1988; Couchman, 1885; Cundy, 1904; Cundy et al., undated; Department of Mines, Victoria, 1889; Department of Mines, Victoria, 1891; Department of Mines, Victoria Annual reports; Department of Mines, Victoria Goldfields of Victoria Monthly Returns; Department of Mines, Victoria Goldfields of Victoria: Reports of the Mining Registrars; Department of Mines, Victoria Reports and Statistics of the Mining Department; Dunn, 1909b; English, 1859; Geological Survey of Victoria, undated, St Arnaud Goldfield; Hunter, 1894; Hunter, 1895; Hunter, 1915; Hunter, undated; Krokowski de Vickerod et al., 1997; Lenard, 1988; Mining Department Victoria, 1861; Minnet Australia Pty Ltd., 1996; Moon, 1897; Planet Gold Ltd., 1967; Stirling, 1888; Stirling, 1889; Taylor, 1888; Ulrich, 1864; Whitelaw, 1898b; Whitelaw, 1908; Whitelaw, 1909a; Whitelaw, 1909b; Whitelaw, 1909c; Whitelaw and Couchman, undated). Some reefs and mines may have been recorded at slightly different locations by different authors and those may have been duplicated. The reefs and mines all occur within the outcrop of the Cambrian St Arnaud Group.
2.28.3. Production and endowment

**Historic production**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>10500</td>
</tr>
<tr>
<td>Historic silver production (1854-1940), kg</td>
<td>3500</td>
</tr>
<tr>
<td>Recovered gold grade, g/t</td>
<td>12</td>
</tr>
<tr>
<td>Recovered silver grade, g/t</td>
<td>4</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>886,000</td>
</tr>
<tr>
<td>Recent gold production (1955-1996)</td>
<td>310 kg (included in total production)</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

**Estimated pre-mining endowment**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>12500</td>
</tr>
<tr>
<td>Contained silver, kg</td>
<td>4800</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>806,000</td>
</tr>
<tr>
<td>In situ grade gold, g/t</td>
<td>15.5</td>
</tr>
<tr>
<td>In situ silver grade, g/t</td>
<td>&gt;6</td>
</tr>
</tbody>
</table>

**Notes on production records**

The bulk of the total gold production from the St Arnaud ore field was from the Lord Nelson mine. Total officially recorded production from the mine to the end of 1916 was 10305 kg of gold bullion from 658,754 t of processed ore (Department of Mines, Victoria, 1917). Numerous sources appear to use the compilation of production records.
by Baragwanath (1921) who estimated total gold production from the mine as 10059 kg
gold bullion from 633,467 t of ore (Baragwanath, 1946; Bowen, 1974). However, this
was an estimate of production to the end of 1913, while the mine was working until 1916.

Krokowski de Vickerod et al. (1997) estimated total gold production from the
Lord Nelson to be 8832 kg. A probable reason for lower estimates of gold production
by Krokowski de Vickerod et al. (1997) (and currently recorded in VicMine) is that
their estimates were apparently based only on individual (quarterly or annual) official
production records of Mining Registrars. However, these individual production records
are incomplete. For example, no official production records are available between 1892
and 1897 – while at least 1.5 t of gold was produced from the Lord Nelson mine during
that period (Baragwanath, 1921).

Krokowski de Vickerod et al. (1997) estimated total recorded primary gold bullion
production from the St Arnaud Goldfield to be 11970 kg. This included 174 kg of gold
produced in 1993-1995. VicProd records indicate that total recent production in 1993-
1996 amounted to 280 kg. If the total estimate of Krokowski de Vickerod et al. (1997)
for the ore field includes only 8832 kg gold bullion production from the Lord Nelson
mine, the total production estimate for the ore field needs to be increased to 13549 kg – to
account for the apparent underestimation of production from the Lord Nelson mine and
recent mining activities.

VicProd indicates up to 12.3 t of recorded primary gold bullion production which
could be attributed to the St Arnaud ore field with a high degree of confidence. However,
there are no production records for the period between October 1891 and December 1897
(when at least 1.5 t of gold bullion was produced from the Lord Nelson mine alone) or
before 1864, and production records for the rest of 1860’s were incomplete.

Total historic gold bullion production from the St Arnaud ore field is accepted to be
approximately 14 t. This is only marginally higher than the available previous estimates
of total recorded production to (partially) account for missing production records. This
estimate of total gold bullion production includes a significant proportion of silver alloyed
with gold.

Based on reported gold bullion prices (Department of Mines, Victoria, 1870-1915;
Baragwanath, 1946), gold bullion produced at St Arnaud usually contained between 10%
and 30% silver, with an estimated average of approximately 25%. For individual reefs,
silver content of produced bullion varied widely between 5% and >80%. The original silver
content of auriferous ores at St Arnaud was substantially higher than that indicated by the
gold bullion composition alone. During the 1860’s, dedicated silver mining was a major focus at St Arnaud, with more than 0.5 t of officially recorded silver production, mostly from near-surface gossans and likely secondary enrichment zones (Mines Department, Victoria, 1864-1869). However, after the early 1870’s, the metallurgical processes were not optimised for a substantial silver recovery (Department of Mines, Victoria, 1873). Also, significant amounts of sulphide-rich tailings were exported to Germany for further processing and extraction of silver and gold, with no available records of additional silver production (Department of Mines, Victoria, 1874).

Average recovered grade for the St Arnaud ore field is estimated to be approximately 16 g/t of combined gold and silver, including 12 g/t gold.

**2.28.4. Recorded mines (VicMine)**

- Lord Nelson (VicMine IDs 363473 and 363474) produced 8832 kg gold bullion from 567400 t of ore.
- New Bendigo (VicMine ID 363583) produced 688 kg gold from 37110 t of ore.
- Brownings Luck (VicMine ID 363366) produced 175 kg gold from 11270 t of ore.
- Glenburn Manor (VicMine ID 363427), which reworked several historic mines produced 174 kg gold from 152301 t of ore.
- Lady Nelson (VicMine ID 605363) produced 124 kg gold from 12230 t of ore.
- Ballarat Reef (VicMine ID 363347) produced 108 kg gold from 4970 t of ore.
- Bell Rock (VicMine ID 363351) produced 91 kg gold from 4248 t of ore.
- Blink Bonny (VicMine ID 363351363) produced 69 kg gold from 1050 t of ore.
- New Chum (VicMine ID 363589) produced 45 kg gold from 2687 t of ore.
- Silver Mines (VicMine ID 363678) produced 35 kg gold from 2445 t of ore.
- Comstock (VicMine ID 363383) produced 35 kg gold from 1480 t of ore.
- Hopeful (VicMine ID 363445) produced 33 kg gold from 525 t of ore.
- Jerejaw (VicMine ID 363451) produced 26 kg gold from 1639 t of ore.

The other mines with production records include the Gap Reef, Rotten, Bonanza, Welcome Nelson, Garibaldi, Economic, Prince of Wales, Lord Nelson North, Armenian, Queen Semiramis, Sebastapol Reef, Chance Reef, Clarkes Reef, Queen Mary, East Newk, Lord Nelson Extended, Easter Monday, New Bendigo South and Warwickshire mines, as well as a number of mines with reported production of under 100 oz and many mines, both named and unnamed, with no recorded production.
2.28.5. Ore bodies and systems

| Character of ore bodies | Free and refractory gold in laminated quartz veins. Typical sharp reduction of reported recovered gold grades below the water table suggests that a considerable proportion of gold was refractory. Ore contained up to 5% of sulphides (mostly pyrite and chalcopyrite) and typically had high silver contents (Ag: Au on average 1:3, often > 1 and sometimes > 5). |
| Dimensions | Length of individual veins often exceed 200 m, thickness - from <0.5 m to >6 m, depth – up to 700 m, but at most reefs mining stopped at a depth of less than 100 m from the surface. |
| Orientation | Most reefs strike north-west (320°-340°) – similar to bedding and cleavage, and dip steeply (70-80°) to the west. Some reefs have gentler dips of 45-50° and cut the bedding of sedimentary rocks at a high angle (Morning Star and Garibaldi reefs). |

2.28.6. Host rocks

| Stratigraphy | St Arnaud group |
| Host rock types | Turbidites |
| Metamorphism | greenschist facies |
| Structural history | unknown |
2.29. Stawell

2.29.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 658 250 E, 5 898 598 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.4</td>
<td>6</td>
<td>320°</td>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>

2.29.2. Description

The Stawell ore field contains one hundred and eighty four mines (all named; VicMine). Almost all the mines lie within the outcrop of the Cambrian St Arnaud Group metasediments and igneous rocks.
2.29.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 65500 |
| Recovered grade, g/t | 20.7 |
| Processed ore, t | 3,000,000 |
| Recent gold production (1983-2007) | 59,000 |
| Recent recovered grade, g/t | 4.5 |
| Current resource / reserve (12/2008) | 10500 kg Au @ 4.6 g/t |
| Current measured and indicated resource (12/2008) | 7200 kg Au @ 2.4 g/t |

**Estimated pre-mining endowment**

| Contained gold, kg | 145,000 |
| In situ ore tonnage, t | 17,000,000 |
| In situ grade, g/t | 8.5 |

**Notes on production records**

Estimated pre-mining endowment of the Stawell ore field includes current ore reserves and measured and indicated resources, but excludes inferred resources (2.5 t Au) and endowment of the Wonga deposit (~10 t Au), which was previously classified as possibly intrusion-related.

Historic gold production has been accepted after Inan (1990) and Cayley and Taylor (2001) for total gold bullion production (65.3 t) and Ramsay and Willman (1988) and Bush et al. (1995) – for recovered grade (20.7 g/t – including ~12% of recovered silver). Modern gold production until 2008 has been accepted after Fredericksen and Miller (2008).

2.29.4. Recorded mines (VicMine)

Some of the largest producers include:

- Magdala Decline (VicMine ID 877586) produced 28510 kg gold from an unrecorded tonnage of ore.
- Pleasant Creek Cross Reef (VicMine ID 31755) produced 9177 kg gold from 270,758 t of ore.
- Wimmera (VicMine ID 431776) produced 6013 kg gold from 380,905 t of ore.
- Moonlight (VicMine ID 431754) produced 5919 kg gold from 329,780 t of ore.
- Wonga Decline (VicMine ID 432147) produced 4649 kg gold from 1,659,000 t of ore.
### Appendix 3

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>184</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>100</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Magdala Decline</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>25</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>88708</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut, adit</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>735 m (Magdala Decline)</td>
</tr>
</tbody>
</table>

#### 2.29.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>Quartz reefs; quartz-rich shear zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length 5,000 m, depth 1700 m, width 1200 m (Magdala Basalt dome, Northgate Minerals Corporation, 2008).</td>
</tr>
<tr>
<td>Orientation</td>
<td>Dip to W, strike 340°</td>
</tr>
</tbody>
</table>

#### 2.29.6. Host rocks

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>The stratigraphy at Stawell is divided into three principal units: Magdala Basalt; Albion Formation; Leviathan Formation, Intruded into this sequence are the Stawell Granite and a number of felsic and mafic intrusions. This rock unit, previously termed the Magdala Volcanogenics, is an alteration facies that locally occurs adjacent to the basalt (Northgate Minerals Corporation, 2008).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Subaqueous low-K tholeiitic lavas, turbidites, intruded by quartz ± feldspar - phyric felsic intrusions (Northgate Minerals Corporation, 2008).</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>Peak metamorphism at Stawell reached mid-greenschist grades (Northgate Minerals Corporation, 2008).</td>
</tr>
<tr>
<td>Structural history</td>
<td>At least seven deformation events have been recognised at Stawell. These deformation events can be broadly split into two categories; early, ductile deformation (D1 to D4), and late brittle deformation (D4 and later) (Northgate Minerals Corporation, 2008).</td>
</tr>
</tbody>
</table>
2.30. Stuart Mill

2.30.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 703 159 E, 5 925 640 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.7</td>
<td>7.7</td>
<td>330°</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

2.30.2. Description

The Stuart Mill ore field coincides with the Stuart Mill historic goldfield. It contains 19 recorded mines (including 18 named) and 27 mapped reefs (VicMine; Krokowski de Vickerod, 1997b; Krokowski de Vickerod, 1997c; Bannear, 1994; Walker, 1894a; Department of Mines, Victoria, Undated. Goldfields of Victoria Monthly Returns. Series published monthly between September 1898 and July 1902 volumes 4 to 50; Bradford, 1903a; Department of Mines, Victoria, Undated. Annual report. Series published since 1874; Department of Mines, Victoria, 1891; Anon, undated. Parish of St Arnaud 1858/M/9; Stirling, 1895; Blair, 1869; Krokowski de Vickerod et al., 1997). The reefs and mines all occur within the outcrop of the Cambrian-Ordovician St Arnaud Group.
Appendix 3

2.30.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Historic gold production (1854-1940), kg</th>
<th>850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered grade, g/t</td>
<td>15.1</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>56,000</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated pre-mining endowment

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>51,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Notes on production records

From official production records (Mines Department, Victoria, 1864-1869; Department of Mines, Victoria, 1870-1915; VicProd), the total gold production from the Stuart Mill ore field was at least 804 kg, at an estimated average recovered grade of 15.1 g/t Au. To account for unrecorded production before 1864 and incomplete production records for the rest of 1860’s, total production is accepted to be 850 kg. This estimate includes approximately 10% of silver – subtracted from the estimates of pre-mining gold endowment.

2.30.4. Recorded mines (VicMine)

- According to VicMine, Greenock mine (VicMine ID 363435) produced 574 kg gold from 36248 t of ore. However, an analysis of production records indicated that this erroneously over-states actual recorded production by 280 kg Au.
- Oxonian mine (VicMine ID 363601) produced 311 kg gold from 21082 t of ore.
- Lancashire mine (VicMine ID 363461) produced 47 kg gold from 9298 t of ore.

The other mines with production records include the Star of the East, Isis, Devonshire, Stuart Mill, Rose and Thistle reef and Batchelor reef mines. There are a further nine named and one unnamed mines, for which there are no production records in this ore field.
2.30.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Character of ore bodies</th>
<th>unknown</th>
</tr>
</thead>
</table>

2.30.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.31. Warrenmang

2.31.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 710 380 E, 5 898 692 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.8</td>
<td>11.2</td>
<td>90°</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

2.31.2. Description

The Warrenmang ore field contains 42 reefs (some of which are reported more than once, depending on the source). None of these reefs are reported to have yielded gold, however the high number of quartz reefs mapped in a well defined area indicates that this is an area where mineralising processes similar to those in other ore fields have been active (Cayley, 1995; Krokowski de Vickerod, 1997b; Whitelaw et al., 1903). These reefs all lie within the outcrop of the Cambrian St Arnaud Group.

![Warrenmang ore field](image-url)
2.31.3. Production and endowment

Historic production

| Historic gold production (1854-1940), kg | unknown |
| Recovered grade, g/t | unknown |
| Processed ore, t | unknown |
| Recent gold production (1983-2007) | none |
| Current resource / reserve (12/2007) | none |

Notes on production records

No mines have been recorded within this ore field.

2.31.4. Recorded mines (VicMine)

| Total number of mines | 0 |
| Number of mines with recorded production | 0 |
| Biggest producer | none |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | 0 |
| Mining method | none |
| Depth of mining | none |

2.31.5. Ore bodies and systems

| Dimensions | Typical reef length about 200 m |
| Orientation | Typical reef strike appears to be 330° |

2.31.6. Host rocks

| Host rock types | unknown |
| Metamorphism | unknown |
| Structural history | unknown |
2.32. Waterloo

2.32.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 714 916 E, 5 863 845 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>3.4</td>
<td>0°</td>
<td>4.5</td>
<td>2</td>
</tr>
</tbody>
</table>

2.32.2. Description

The Waterloo ore field contains three mines (two named) and twelve reefs, of which eleven are reported as having been worked. There are also twenty six shafts which are associated with some of the reefs – these are probably early workings associated with the reef outcrops or ancillary works to the main shafts (VicMine; Cayley and McDonald, 1995; Cayley, 1995; Nott, 1985; Department of Mines, Victoria, 1891; Lidgey, 1897 Geological Survey of Victoria, 1984; Swensson, 1988) all lying within the outcrop of the Cambrian St Arnaud Group.
2.32.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 26.8 |
| Recovered grade, g/t | 8 |
| Processed ore, t | 3187 |
| Recent gold production (1983-2007) | none |
| Current resource / reserve (12/2007) | none |

**Estimated total endowment**

| Contained gold, kg | unknown |
| In situ ore tonnage, t | unknown |
| In situ grade, g/t | unknown |

2.32.4. Recorded mines (VicMine)

| Total number of mines | 3, although mapped reefs also appear to have been worked |
| Number of mines with recorded production | 2 |
| Biggest producer | Richmond/Best Bower |
| Major mines (over 25 kg gold) | 0 |
| Total recorded gold production, kg | 26.8 |
| Mining method | shaft s and open cut |
| Depth of mining | 60+ m |

Richmond/Best Bower reef (VicMine ID 432568; Cayley and McDonald, 1995; Nott, 1985; Department of Mines, Victoria, 1891) are the largest reef workings known from the Beaufort Goldfield. Some 300 m length of reef have been worked to shallow depths, with deeper workings restricted to a section of the reef. Recorded production is 15.2 kg gold from 1091 t ore, at a grade of 13.9 g/t Au.

Sheet Anchor/Bushmans reef (VicMine ID 432569; Nott, 1985; Lidgey, 1897; Department of Mines, Victoria, 1891). Crushing commenced in early 1864. These workings are parallel to and about 100 m to the west of Richmond reef. Recorded production is 10.2 kg gold from 1911 t ore, for a grade of 5.4 g/t.
2.32.5. Ore bodies and systems

| Dimensions                  | Worked length: About 300 m (Richmond/Best Bower reef) |
|                            | Thickness: 0.3 m (Richmond/Best Bower reef)          |
| Orientation                | dip 80° to 065° (Richmond/Best Bower reef)           |

2.32.6. Host rocks

<table>
<thead>
<tr>
<th>Host rock types</th>
<th>sandstone, slate, siltstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.33. Welcome Reef

2.33.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 729 529 E, 5 926 019 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>3</td>
<td>350°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.33.2. Description

The Welcome Reef ore field contains one mine and four reefs (VicMine; Barber, 1987), all lying within the outcrop of the Cambrian St Arnaud Group.

![Welcome Reef ore field](image)

2.33.3. Production and endowment

**Historic production**

| Historic gold production (1854-1940), kg | 98.7 |
| Recovered grade, g/t | 29 |
| Processed ore, t | 3385 |
| Recent gold production (1983-2007) | none |
| Current resource / reserve (12/2007) | none |
**Estimated total endowment**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**2.33.4. Recorded mines (VicMine)**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Welcome Reef</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>1</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>98.7</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Welcome Reef (VicMine ID 362837; Bannear, 1993; Department of Mines, Victoria, 1891; Department of Mines, Victoria, Undated. Goldfields of Victoria; Department of Mines, Victoria, Undated. Reports and Statistics of the Mining Department) was the only mine recorded in this ore zone.

**2.33.5. Ore bodies and systems**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**2.33.6. Host rocks**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Deep marine turbidites</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
2.34. Wildwood

2.34.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 647 694 E, 5 920 740 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.5</td>
<td>48.5</td>
<td>325°</td>
<td>14.5</td>
<td>3</td>
</tr>
</tbody>
</table>

2.34.2. Description

The Wildwood ore field deposit is covered by Tertiary Murray Basin sediments over 40 m thick (Dugdale et al., 2006, Perseverance Corporation Ltd, 2006, Perseverance Corporation Ltd, 2007). The ore field is hosted by the Cambrian Albion Formation and the Leviathan Formation and the Wildwood Basalt and felsic dykes. The dimensions of this ore field are speculative.
### 2.34.3. Production and endowment

**Historic production**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>0</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>0</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>0</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007), kg</td>
<td>1002</td>
</tr>
</tbody>
</table>

**Estimated total endowment**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>322 (indicated resource), 680 (inferred resource)</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>140,000</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>2.3</td>
</tr>
</tbody>
</table>

**Notes on production record**

There has been no production from this ore field.

### 2.34.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>0</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>0</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0</td>
</tr>
</tbody>
</table>

### 2.34.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>unknown</td>
</tr>
<tr>
<td>Orientation</td>
<td>unknown</td>
</tr>
</tbody>
</table>

### 2.34.6. Host rocks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>Mudstone, sandstone, basalt</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>Hydrothermal alteration - stilpnomelanesiderite-Fe-rich-chlorite and silica</td>
</tr>
</tbody>
</table>
2.35. Wimmera

2.35.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 687 821 E, 5 899 295 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>1.9</td>
<td>0°</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.35.2. Description

The Wimmera ore field contains four mines and two mapped reefs and is named after its most important mine (VicMine; Department of Mines, Victoria, 1891; Caldwell, 1928; Nott, 1985; Beilby, 1996). The reefs and mines lie within the outcrop of the Cambrian St Arnaud Group.

![Wimmera ore field](image)

2.35.3. Production and endowment

Historic production

| Historic gold production (1854-1940), kg | Less than 150 g |
| Recovered grade, g/t | 47° |
| Processed ore, t | 3 |
| Recent gold production (1983-2007) | none |
| Current resource / reserve (12/2007) | none |

° Wimmera mine


**Estimated total endowment**

<table>
<thead>
<tr>
<th>Contained gold, kg</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Notes on production records**

The only mine with recorded production in VicMine is the Wimmera (VicMine ID 432552). The other named mines are the Perrys, Appelts and Trevallyn mines. It is likely that the production from this ore field is under-reported.

**2.35.4. Recorded mines (VicMine)**

Wimmera (VicMine ID 432552), with a total recorded production of about 140 g Au.

<table>
<thead>
<tr>
<th>Total number of mines</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mines with recorded production</td>
<td>1</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>Wimmera</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>0</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>Under 150 g</td>
</tr>
<tr>
<td>Mining method</td>
<td>Shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>30 m (Wimmera)</td>
</tr>
</tbody>
</table>

**2.35.5. Ore bodies and systems**

Dimensions | 800 m long (Appelts Reef) |

**2.35.6. Host rocks**

| Host rock types | Schist, diorite |
2.36. Winjallok

2.36.1. Location and dimensions

<table>
<thead>
<tr>
<th>Ore field centroid</th>
<th>MGA Zone 54: 694 946 E, 5 917 086 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore field data quality</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total area (km²)</th>
<th>Area of cover (km²)</th>
<th>Long Axis Direction</th>
<th>Long Axis Length (km)</th>
<th>Short Axis Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.8</td>
<td>5.4</td>
<td>340°</td>
<td>11</td>
<td>3</td>
</tr>
</tbody>
</table>

2.36.2. Description

The Winjallok ore field contains one unnamed mine and sixty nine reefs (VicMine; Krokowski de Vickerod, 1997c). There are small, shallow workings associated with some of the reefs which indicates that at least some of the reefs were gold-bearing, but probably uneconomic (A. Radojkovic, pers. comm.). The reefs and mines all occur within the outcrop of the Cambrian St Arnaud Group.

Winjallok ore field
2.36.3. Production and endowment

Historic production

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic gold production (1854-1940), kg</td>
<td>unknown</td>
</tr>
<tr>
<td>Recovered grade, g/t</td>
<td>unknown</td>
</tr>
<tr>
<td>Processed ore, t</td>
<td>unknown</td>
</tr>
<tr>
<td>Recent gold production (1983-2007)</td>
<td>none</td>
</tr>
<tr>
<td>Current resource / reserve (12/2007)</td>
<td>none</td>
</tr>
</tbody>
</table>

Estimated total endowment

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained gold, kg</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ ore tonnage, t</td>
<td>unknown</td>
</tr>
<tr>
<td>In situ grade, g/t</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Notes on production records

The only mine (unnamed) recorded in this ore field is registered as VicMine ID 363550.

2.36.4. Recorded mines (VicMine)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of mines</td>
<td>1</td>
</tr>
<tr>
<td>Number of mines with recorded production</td>
<td>0</td>
</tr>
<tr>
<td>Biggest producer</td>
<td>unknown</td>
</tr>
<tr>
<td>Major mines (over 25 kg gold)</td>
<td>unknown</td>
</tr>
<tr>
<td>Total recorded gold production, kg</td>
<td>0</td>
</tr>
<tr>
<td>Mining method</td>
<td>shaft, open cut</td>
</tr>
<tr>
<td>Depth of mining</td>
<td>unknown</td>
</tr>
</tbody>
</table>

2.36.5. Ore bodies and systems

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Typical reef lengths between 150 and 200 m</td>
</tr>
<tr>
<td>Orientation</td>
<td>Typical strike 340°</td>
</tr>
</tbody>
</table>

2.36.6. Host rocks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock types</td>
<td>unknown</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>unknown</td>
</tr>
<tr>
<td>Structural history</td>
<td>unknown</td>
</tr>
</tbody>
</table>
3. Summary and Conclusions

The Stawell Zone produced more than 140 t of gold from primary mesozonal orogenic gold deposits, distributed over 37 primary ore fields and 692 individual mines and reefs. There were an additional 94 isolated mines (of which 18 had production records) which had production under 25 kg gold per mine. The latter group had an aggregate production of 115 kg gold from 6519 tonnes ore (less than 1% of the production of the defined ore fields) with this production included in the aggregate totals above.

The aggregate area of the ore fields is about 970 km², of which 317 km², about 33%, was under alluvial cover. The total area of the Stawell Zone is 47310 km², so the area of gold ore fields represents 2% of the total area of the Stawell Zone.

Most ore fields showed considerable anisotropy in shape, with the ratios of the long to short axes from 1.0 to 5.8, with an average of 2.5. The orientations of the long axes trend 390° (±10°) in about half of the ore fields. Although the orientations of individual ore fields often correspond to the orientations of the individual mineralised structures within them, occasionally there will be a discrepancy, especially where there are multiple lines of mineralisation.

The deepest mines were in the Stawell ore field (up to 1300 m) and the average depth of the deepest mines for each of the ore fields in the Stawell Zone was about 200 m.

There was a total of 71 mines in the Stawell Zone which produced over 25 kg of gold each, with most lying within the Stawell ore field. Of the 37 ore fields, only 10 had more than one mine which produced more than 25 kg gold. For 21 of the 37 ore fields, more than half of the recorded mines had no production records at all, with only about half of mines having any recorded production for the Stawell Zone as a whole. Where production records were available, they often covered only part of the period of during which an individual mine may have operated. Even if we assume that the mines with no production records tended to be small, this would still imply that the aggregate totals quoted above significantly understate production.

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Anon., undated. New Bendigo workings, parish of St Arnaud 1858/L/1. Plan No 1858.

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Appendix 3

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