4D EVOLUTION OF THE OROGENIC GOLD DISTRICT OF

SIGUIRI, GUINEA (WEST AFRICA)

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À maman et Jean-Luc.
Ça y est, c'est enfin l'heure des mamans !
ABSTRACT

The West African Craton hosts some of the biggest gold deposits in the world such as Obuasi, Sadiola, Morila or Siguiri. However, the Craton is still largely unexplored and its formation, evolution and how and when the gold deposits it hosts developed during the Eburnean orogeny remain unclear. The Siguiri district is one of West Africa’s largest Paleoproterozoic sedimentary basins and sits in the northern part of the Siguiri Basin. The district and its hosting Basin have received limited attention from the scientific community to date. This thesis makes use of a multi-scale and multi-disciplinary approach in order to constrain the evolution of the Siguiri district and Siguiri Basin architecture and hydrothermal activity through time. The objective is to provide the backbone of future exploration strategies for orogenic gold deposits in the Siguiri Basin and, potentially, in the rest of the West African Craton.

Fieldwork was undertaken in eleven deposits of the Siguiri district. Particular attention was given to the Sintroko PB1, Kosise, Kami, Bidini and Sanu Tinti deposits due to their structural complexity, lithostratigraphic position, outcropping conditions and accessibility. Work was focused on structural mapping, lithofacies recognition, core logging, geochemical sampling, GIS and 3D modelling. In addition to the data collected in the Siguiri district, regional fieldwork was also carried out in the rest of the Siguiri Basin for geochronological sampling and regional mapping.

Regional and district scale geochronological sampling and lithofacies observations indicate that the central Siguiri Basin is of Lower Tarkwa Group age (ca. 2015 Ma) and deposited late during the Eburnean orogeny. Lithostratigraphic observations from the Siguiri district indicate that the district is hosted in three distinct sedimentary Formations (the Balato, Fatoya and Kintinian Formations). Stacks of polymict conglomerate in the Kintinian Formation, interpreted to be olistostrome deposits, marks a change in the tectonic setting of the Siguiri Basin that may correspond to the onset of a period of orogenic compression during the
Eburnean Orogeny and highlight the early architecture and fundamental structures controlling the morphology of the Siguiri Basin. These fundamental structures are viewed as the first order structures controlling the location of the world-class Siguiri district in the eponym Basin.

District to deposit scale structural work indicates that the Siguiri district underwent four deformation events: a N-S compression (D\textsubscript{1S}), an E-W compression (D\textsubscript{2S}) progressively evolving into a transpression and later on into a transtension (early- and late-D\textsubscript{3S} respectively), and a NW-SE compression (D\textsubscript{4S}). While D\textsubscript{1S} deformation is cryptic and commonly expressed as F\textsubscript{1S} recumbent folds with E-W to NW-SE and NE-SW striking axial traces, D\textsubscript{2S} is typically characterised by F\textsubscript{2S} upright folds with NNE-SSW to NNW-SSE striking axial planes that refolds F\textsubscript{1S} folds and are responsible for the bulk of the deformation and structural grain observed in the Siguiri district and Siguiri Basin. The F\textsubscript{2S} folds are overprinted by four main orientations of structures that develop (or are reactivated) during the early stages of D\textsubscript{3S} deformation and are consistent with a transpressional deformation: N-S thrusts, E-W normal faults, NE-SW dextral shear zones and WNW-ESE sinistral shear zones. In field exposures and in drill core, these structures are typically discreet and only expressed as sub-vertical damage zones ten to fifteen meters wide and characterised by an increase in vein density or by disseminated pyrite. The veins that developed along these structures are commonly found to be conjugate and their orientation is consistent with a transtensional deformation. These late-D\textsubscript{3S} veins are overprinted by the sub-vertical NE-SW striking S\textsubscript{4S} cleavage that characterises the D\textsubscript{4S} deformation event. Based on finite strain analysis of D\textsubscript{2S} structural elements and paleo stress-field reconstruction from early-D\textsubscript{3S} faults and late-D\textsubscript{3S} conjugate veins, two stress-switches were identified in the Siguiri district. These stress-switches are also documented at a regional scale and highlight the homogenisation of the stress-tensor prior to gold mineralisation. This process is postulated to occur in numerous orogenic gold deposits around the world and may be a pre-requisite for orogenic gold mineralisation.

Deposit to microscopic scale work indicate that hydrothermal activity in the Siguiri district was polyphase and that gold mineralisation developed over three distinct periods. Gold
was first found to be associated with early ankerite-pyrite veins, developed late during $D_{3S}$ deformation. In these veins, LA-ICP-MS data shows that gold is locked in the pyrite crystal lattice. The second and main episode of mineralisation also occurs late during $D_{3S}$ deformation and is associated with the later quartz-ankerite-arsenopyrite-(pyrite) veins, which crosscut the early ankerite-pyrite veins and are coeval with pyrite dissemination in conglomerate layers. Gold is either found native in the veins or invisible and locked in the vein-hosted arsenopyrite crystal lattice. The last gold event is associated with the $D_{4S}$ deformation, which fractures previously developed sulphides and precipitate free gold in their fractures. The geochemical footprint of gold mineralisation in the Siguiri district was recognised to be associated with a wide halo of at least fifteen meters, enriched in: Ag, Au, As, Bi, Co, LOI, Mo, Sb, Se, $SO_3$, Te and W, typical of orogenic gold mineralisation. Comparison of the characteristics and timing of gold mineralisation in the Siguiri district with other gold deposits from the West African Craton indicates that gold mineralisation in Siguiri is coeval with mineralisation in other gold deposits. However, other orogenic gold deposits in the West African Craton are associated with later gold events that may have formed economic concentrations in the rest of the Siguiri Basin.

The conclusions from this multi-scale multi-disciplinary work have implications for exploration targeting in and around the Siguiri Basin. This thesis highlights the importance of the early architecture as a first order control on orogenic gold systems. The expression of the second and third order structures controlling the mineralisation are thought to develop in response to regional stress-switches that can be recognised in the field. Finally, at a deposit scale, high grade zones can be targeted by geochemistry. This thesis hence shows the power of multiscale and multi-disciplinary studies to unravel the complexity of mineral systems and provide a critical understanding that can be used as a foundation for new exploration strategies.
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Figure 37: Photographs of the main structural elements from the Bidini and Sanu Tinti deposits. A) Overview of the Bidini deposit. In the foreground, 5 to 20 m-deep holes dug by local villagers are used to reach V_{3b} veins in one of the NE-SW trending high grade zones along which the deposit sits. A second high grade zone is visible on the right (just below the (SE) symbol). B) Conjugate relationships between V_{3b} veins. C) Folded V_{3b} vein and axial planar S_{4s} cleavage. D) Pyrite developed along the S_{4s} cleavage. E) Close-up photograph of the polymict conglomerate from the Kintinian Formation found below the Bidini deposit and in the Sanu Tinti deposit. F) Structural contact (fault) between the Kintinian and Fatoya formations in the Sanu Tinti deposit.

Figure 38: Microphotographs of A) siderite grains being pseudomorphosed by V_{3b} pyrite; B) Fractured arsenopyrite in a V_{3b} vein showing gold-chalcopyrite-(galeana) infills; C) Disseminated V_{3b} pyrite fractured and showing gold-chalcopyrite infills; D) Sanu Tinti style V_{3b} pyrite overprinted by chalcopyrite veinlets; E) V_{3b} arsenopyrite showing quartz strain fringes associated with the development of the S_{4s} penetrative cleavage. This cleavage is also responsible for the preferential orientation of the sericite and the strain shadows developing around the siderite grains; F) Textural similarities between V_{3a} pyrite and arsenopyrite suggesting their coeval development; G) Backscattered electron image of V_{3a} pyrite displaying As-rich and As-poor growth rings and being crosscut by gold infilled fractures; H) Hematite inclusions in V_{3a} pyrite associated with gold. Hematite laths seem to follow the pyrite crystal lattice whereas gold displays triangular textures typical of open space infill (Taylor, 2010). Aspy: arsenopyrite, Au: gold, Ccp: chalcopyrite, Gna: galeana, Hem: hematite, Py: pyrite, Qtz: quartz, Ser: sericite, Sid: siderite.

Figure 39: Photographs of the main structural elements found in the Sintroko PB1 deposit. A) Overview of the deposit. The main ore shoot found in this deposit follows the black shale layer (left) and cuts across the F_{2s} sub-vertical fold found on the eastern side of the deposit (right). B) Photograph of an ore shoot, expressed as a sub-vertical damage zone (area between blue dashed lines) associated with dense V_{3s} veining. C) Another example of a damage zone (area between blue dashed lines) associated with high gold grades and of the large scale conjugate geometry displayed by the V_{3b} veins. D) Refraction of V_{3b} vein orientations between beds of greywacke and shale. E) Strain shadows around arsenopyrite crystals developed around a V_{3b} vein (crumbled down on the right) by the S_{4s} cleavage. F) Conjugate relationship of the V_{3b} veins at the outcrop scale.

Figure 40 (previous page): Log of hole SKRCD0040 (location map on Figure 35). This log highlights the strong link between brittle deformation, veining, sulphidation and carbonate alteration with gold. The alteration intensity section displays carbonate alteration in light brown and overprinting chloritisation in green. Way-up indicators (Y) in red are based on graded bedding ripple marks and rip-up clasts. Position of the collected samples reported as coloured disks (shale samples in blue, greywacke in orange). Deformation intensity scaled arbitrarily from 0 (no deformation) to 1 (moderate deformation) and 2 (intense deformation).

Figure 41: Photographs of the main structural elements found in the Kosise deposit. A) Overview of the deposit. The northern part of the deposit (centre) hosts a bedding parallel thrust fault that develop intense V_{3s} veining (B). B) Veining developed in the northern part of the deposit. The V_{3b} veins are stratigraphically controlled and mainly hosted in the greywacke and sandstone beds. C) Close-up photograph of one of the rare discrete structures controlling gold grades in the Siguri district, a dextral NE-SW shear zone. Gold grades across this shear zone are over 100 g/t Au. D) Siderite grains developed around the ore shoots. The sub-vertical S_{4s} cleavage overprints these grains.

Figure 42: Cumulative frequency diagrams for As, Au, Bi, SiO_2, SO_3 and W. The datasets are separated by hosting formation (Kintinian in red, Fatoya in blue and Balato in green). The first inflexion in each


FIGURE 45: PARAGENETIC SEQUENCE FOR THE SIGUIRI DISTRICT.

FIGURE 46: REGIONAL GEOLOGICAL MAP OF THE WEST AFRICAN CRATON AND LOCATIONS OF SOME MAJOR GOLD DEPOSITS. LEGEND AS IN FIGURE 32 AND LIGHT BLUE COLOUR REPRESENTS TARKWA GROUP SEDIMENTARY ROCKS. MODIFIED AFTER LEBRUN ET AL. (2015); CHAPTER 2.

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CHAPTER 1: INTRODUCTION

4D EVOLUTION OF THE OROGENIC GOLD DISTRICT OF

SIGUIRI, GUINEA (WEST AFRICA)

PREAMBLE AND KNOWLEDGE GAPS

The West African Craton (WAC) is also known as the Leo-Man Shield. It is made of two distinct terranes: the Archean Kénéma-Man domain to the south-west, and the Paleoproterozoic Baoulé-Mossi domain (Figure 1A). The Archean domain is dominated by gneiss dated between ca. 3540 and 2750 Ma (Kouamelan et al., 1997; Thiéblemont et al., 2001) while the Paleoproterozoic domain displays an assemblage of volcano-sedimentary belts and felsic intrusives, ranging in age from ca. 2250 to 2040 Ma (Davis et al., 2015; Parra-Avila, 2015; Tshibubudze et al., 2013). A large part of the Baoulé-Mossi domain is overlain unconformably by the Neoproterozoic sediments of the Taoudeni Basin (Begg et al., 2009; Lawrence et al., 2013a; Villeneuve and Cornée, 1994). The Baoulé-Mossi domain was accreted against the Kénéma-Man domain during the Eburnean orogeny (ca. 2210-2040 Ma; Abouchami et al., 1990; Egal et al. 2002; Thiéblemont et al., 2004; Lahondère et al., 2002; Parra-Avila, 2015; Davis et al., 2015). This orogeny is associated with the development of numerous world-class gold deposits across the West African Craton. These deposits formed at different times during the Eburnean orogeny and display a wide range of mineralization styles ranging from: intrusion related gold (e.g. Morila; McFarlane et al., 2011), orogenic gold (e.g. Obuasi, Sadiola and Loulo; Fougerouse et al., in press; Masurel et al., in press 2015; Lawrence et al., 2013a; Lawrence et al., 2013b), atypical orogenic gold (e.g. Masawa deposit; Treloar et al., 2015),
residuum gold (e.g. Yatela; Hanssen et al., 2004) and placer type deposits (e.g. Tarkwa; Sestini, 1973; Pigois et al., 2003). Amongst this breadth of gold mineral systems, the Siguiri gold district in north-eastern Guinea is the only large gold deposit (> 50 t Au; AngloGold Ashanti Ltd., 2013) hosted in the Siguiri Basin (Figure 1B) and one of the largest gold mineral systems in the West African Craton.

Figure 1: Geological map of A) the West African Craton and its gold deposits (red disks), and; B) the Siguiri Basin. Modified from Milési et al. (1989) and Miller et al. (2013).

The Siguiri Basin is located in the Baoulé-Mossi domain, directly north of the Archean Kénéma-Man domain (Figure 1A). The Basin spreads over more than 40,000 km², mostly in north-eastern Guinea but also in southern Mali, and is one of the largest sedimentary basins of
the West African Craton. The Siguiri Basin rocks were described has Lower Birimian sediments by Milési et al. (1989) and Egal et al. (1999). These sediments are metamorphosed to sub-greenschist facies and were interpreted to derive from Paleoproterozoic volcanic rocks and felsic intrusions that were emplaced during the early stages of the Eburnean orogeny (Milési et al., 1989; Begg et al., 2009; Feybesse and Milési, 1994). The Niandan ultramafics and the Kéniéro Range mafics and felsic volcanic rocks border the Siguiri Basin to the west and southwest (Figure 1B). The felsic volcanic rocks were dated at ca. 2095 Ma (Feybesse et al., 1999). Bordering the Basin to the east, the Yanfolila Belt displays an assemblage of sedimentary and mafic to intermediate volcanic rocks intruded by felsic magmas. In the west of the Yanfolila Belt, intermediate to felsic calc-alkaline volcanic rocks from the Niani suite were dated at ca. 2210 Ma and interpreted to be arc-related and derived from subduction of a young and hot oceanic plate (Lahondère et al., 2002). To the south, the Siguiri Basin is bordered by a series of late Eburnean intrusives (ca. 2090-2070 Ma) and by the Sassandra fault separating the Basin sediments from the Archean Kénéma-Man gneiss (Egal et al., 2002). The Archean banded iron formations of the Simandou also outcrop south of the Siguiri Basin (Egal et al., 1999). Finally, to the north, the Siguiri Basin is unconformably overlain by the Neoproterozoic sediments of the Taoudeni Basin. The Siguiri Basin sediments are intruded by a number of late Eburnean monzogranite and biotite granite intrusions dated at ca. 2090-2070 Ma such as the Malea monzogranite, outcropping in the northernmost part of the Basin, 50 km north of the Siguiri district (Egal et al., 2002; Parra-Avila, 2015). On the basis of this regional framework the age of the Siguiri Basin is loosely constrained between ca. 2210 and 2093 Ma (Egal et al., 1999; Lahondère et al., 2002). In addition, a series of Mesozoic dolerite sills, ENE-striking dolerite dykes and basaltic lava flows, all related to the South Atlantic Ocean opening, intrude and overlie the Basin sedimentary rocks (Abouchami et al. 1990; Paranhos, 2008; Egal et al., 1999; Egal et al., 2002). This large age bracket for the age of the Siguiri Basin sedimentary rocks highlights an important knowledge gap in the understanding of the lithostratigraphic position and tectonic significance of the Siguiri Basin within the Eburnean orogeny.
The Siguiri Basin, has been known for its gold endowment since the 12th century and potentially as early as the 3rd century, and is associated with a prolonged and ongoing artisanal mining history (Watts, 2010). Over the last 84 years, gold in the Basin has been produced at an industrial scale by various international mining companies including by a French company starting the production in 1931, a Russian company from 1960 to 1963, and North American and British companies in the 1980s. In 2002, the world-class Siguiri gold district was bought by AngloGold Ashanti Ltd. (Watts, 2010). Gold mineralisation in the Siguiri district have been discussed by a MSc student (Steyn, 2012) and contractors (e.g. Paranhos, Holcombe, Watts), but descriptions and interpretations differ greatly. For instance, typology of gold mineralisation in the district has been ascribed to a variety of styles ranging from epithermal lode (Paranhos, 2008), orogenic (Holcombe, 2007) to paleoplacers overprinted by mineralised veins (Watts, 2010). Even though all these studies propose that gold mineralisation in Siguiri is dominantly controlled by veins, no consensus was reached by the authors on what controls the location of the Siguiri gold district at the scale of the Siguiri Basin or what controls the extent of the ore shoots at the district and deposit scales.

To further the understanding of the characteristics, geometry and genesis of gold mineralisation in the Siguiri district, a multi-scale and multidisciplinary approach was employed. This approach addresses the various scales at which geological processes work in gold mineral systems. Modern gold exploration strategies in other provinces increasingly rely on such an approach, involving integration of fieldwork, geophysics, and geochemistry among other techniques, used at different scales (McCuaig and Hronsky, 2014; McCuaig et al., 2010; Robert et al., 2005; Miller et al., 2010; Williams and Currie, 1993; McIntyre and Martyn, 2005; Blewett et al., 2010; Goldfarb et al., 2005; Groves et al., 2003; Groves et al., 2000; Neumayr et al., 2008; Eilu and Groves, 2001; Eilu et al., 1999). At a province scale, numerous studies highlight the role of early architecture as a primary control on gold mineralisation (Robert et al., 2005; Miller et al., 2010; McIntyre and Martyn, 2005; Chapter two). Down one scale at the district level, secondary structures control and/or host gold mineralisation (Blewett et al.,
Province- and district-scale controlling structures are typically delineated using geophysical datasets (Blewett et al., 2010; Chapter two) but can also be exposed by exploration geochemistry, especially at smaller scale (e.g. deposit scale; Eilu and Groves, 2001; Eilu et al., 1999; Chapter four).

The present work thus focuses on the detailed description of the geology and regional framework of gold mineralisation in the world-class Siguiri gold district through a multi-scale and multi-disciplinary approach. The results of this study presents the 4D (space-time) evolution of the Siguiri district lithostratigraphic record, structural architecture, and mineral alteration. Collectively, the data recorded during the course of this study provides an insight into the tectonic context, genetic processes and the geochemical footprint of gold mineralisation in the Siguiri district. All these elements define the knowledge base to improve exploration strategies in and around the Siguiri Basin as well as in the broader West African Craton.

AIMS OF THESIS

Based on background information and knowledge gaps identified in the Siguiri Basin and Siguiri district, the principal objectives of this study are to:

1) Characterise the lithostratigraphy and tectonic significance of the Siguiri district and Siguiri Basin sediments in the context of the Eburnean orogeny;  
2) Use this newly developed understanding to highlight the early architecture of the Siguiri Basin and the large scale structures which may have played a fundamental role in the location of the Siguiri district;  
3) Characterise the structural evolution of the district, attributing relative timing to the major structures and deformation events in the context of previous structural work conducted in West Africa;
4) Develop an integrated model for the control on the geometry and mineralisation processes within the Siguiri district at the ore shoot, ore body and district scales;

5) Characterise the mineral assemblage, its evolution and the geochemical footprint left by the gold mineralisation in the metasediments of the Siguiri district;

GENERAL METHODOLOGY

This section briefly details the different methods and techniques used to meet the defined objectives of this study.

Fieldwork and sampling

In order to achieve the objectives identified in the previous section, fieldwork was conducted in and around the Siguiri district. A total of 22 weeks were spent in the field over the course of this study. Fieldwork was focused on geological and structural mapping, core logging and sampling in the different deposits of the district but was also conducted around the district and outside of the Siguiri Basin.

Thirteen deposits from the Siguiri district were accessible over the course of this study. From south to north: Sintroko PB1, Sintroko PB2C, Sintroko PB3A, Sintroko North, Kosise, Kami, Kozan, Kalamagna PB1, Tubani, Bidini, Sanu Tinti, Eureka North and Seguelen (Figure 2). These deposits are spread along an average WNW-ESE trend across the three different sedimentary Formations hosting the district: the Kintinian, Fatoya and Balato Formations (Figure 2; Watts, 2010). Fieldwork was undertaken in all these deposits but the greater part of the work was focused on Sintroko PB1, Kosise, Kami, Bidini and Sanu Tinti. This choice was based on the:

1) importance of the gold mineralisation in the deposit;

2) hosting Formation;

3) proximity to contact with another Formation;

4) outcropping quality of the deposit, and;
5) density of drill holes in the deposit.

![Geology map of the Siguiri district and its deposits. After Chapter 3.](image)

**Figure 2: Geology map of the Siguiri district and its deposits. After Chapter 3.**

Sampling was focused in these five key deposits and organised to cover the main lithotypes (greywacke, shale and conglomerate) inside and outside of the ore zones. Sampling for whole-rock multi-element geochemistry was focused in the Kosise deposit. For more details on sampling, see the methodology sections of Chapters two and four.

Regional fieldwork was first conducted in the first hundred kilometres around the Siguiri district. Two main regions were targeted for structural and lithostratigraphic observations and sampling: the Maléa monzogranite region, ~30 km north of the district, and the Saraya greenfield project ~50 km to the west of the district. The Maléa site was chosen
because this monzogranite represents the closest and largest mapped pluton intruding the sediments of the Siguiri Basin. Dating of this intrusive hence gives a minimum age for the Siguiri Basin sediments. Additionally, structural observations from this site would get an absolute timing constraint that could later be used to relate the overall deformation history in Siguiri to that of the overall West African Craton during the Eburnean orogeny. The second site, Saraya, was chosen for its lithostratigraphy, displaying volcanic rocks not encountered in the district. This site was also selected for dating, lithostratigraphic and structural observations. In addition to these two regional localities, a N-S transect from Siguiri to the Archean Kénéma-Man Craton was completed. This transect focused on the lithostratigraphic and structural characterisation of the Siguiri Basin sediments, extrusives and intrusives rocks as well as the igneous and gneissic rocks located along and beyond the Sassandra fault. For more details on how structural readings were taken during fieldwork, see the methodology section of Chapter three.

**Analytical techniques**

**PETROGRAPHY AND IMAGING**

Petrographic observations of polished thin-sections were undertaken at the Centre for Exploration Targeting (CET) in Perth, Western Australia. These observations were complemented by Secondary Electron Microscope (SEM) imaging on a Tescan Vega 3 at the Centre for Microscopy, Characterisation and Analysis (CMCA) at the University of Western Australia (UWA). For more details on the SEM imaging, see the methodology section of Chapter four.

**U-PB SHRIMP GEOCHRONOLOGY**

U-Pb SHRIMP II geochronology on detrital and igneous zircons was carried out at the John de Laeter Centre for Isotope Research (JdL) at Curtin University in Perth, Western Australia. The use of an ion microprobe was essential for the high precision and small beam
size required, as well as for logistical reasons. This technique spatial resolution (20 μm ablation diameter versus 30-60 μm for LA-ICP-MS) allows for the very small detrital zircons and highly damaged igneous zircons collected to be analysed while avoiding cracked, damaged or metamict areas. This technique was the most appropriate for this study. For more details on this technique and sample preparation, see the methodology section of Chapter two.

**WHOLE-ROCK MULTI-ELEMENT GEOCHEMISTRY**

Samples for whole-rock geochemistry were analysed for major and minor elements at the Intertek Genalysis laboratory in Perth, Western Australia. Major elements were obtained by X-Ray fluorescence spectrometry (XRF) and trace elements by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The loss on ignition (LOI) was determined by gravimetry. For more details on the geochemistry techniques used, see the methodology section of Chapter four.

**GIS AND 3D MODELLING**

Data integration, spatial analysis and 3D modelling were carried out in ArcGIS and LeapFrog Mining 3D computer programs.

**ORGANISATION OF THIS THESIS**

This thesis is presented as a series of three refereed journal publications tied together by an introduction and a conclusion chapter, following the University of Western Australia regulations outlined in the Postgraduate Research and Scholarships Handbook. Regulation 30.(1)(b) states that: "A typescript may be structured in any of a range of ways, including, but not limited to: a monograph; a paper or series of papers suitable for publication in scholarly journals; or a combination of published and unpublished work ". This thesis includes:
1) an introduction (Chapter one) that presents the current state of knowledge, the gaps this thesis aims to address and details the approach used to address these knowledge gaps;

2) one paper submitted and accepted in a special issue on West Africa of the journal Precambrian Research (Chapter two). This paper presents the lithostratigraphy and geochronology of the central Siguiri Basin rocks. It revises the lithostratigraphic and tectonic position of the Siguiri Basin in the evolution of the Eburnean orogeny. It also discusses the early architecture of the Basin, thus highlighting the first order structural controls at play in the Siguiri district and in the rest of the Basin;

3) one paper submitted and accepted in a special issue on West Africa of the journal Economic Geology (Chapter three). This paper presents the structural evolution of the Siguiri district and the second and third order structures hosting the mineralisation. It also discusses the mode of emplacement and stress-field variations associated with the veins hosting the bulk of the mineralisation in Siguiri;

4) one paper submitted to Mineralium Deposita (Chapter four). This paper presents the petrographic and geochemical characteristics of the mineral assemblages observed in the Siguiri district. It also discusses the use of laser ablation to constrain the timing of mineralisation and the polyphase nature of hydrothermal activity and gold mineralisation in the Siguiri district and in the rest of the West African Craton;

5) a conclusion (Chapter five) that summarizes the main findings of this thesis and introduces the remaining questions to answer and possible future work.

The three papers form the separate parts of a coherent study on the Siguiri district litho-structural and hydrothermal evolution and that of its host basin in the context of the
West African craton and the Eburnean orogeny. The overall scope of this study zooms in from a regional scale in Chapter two, to a district scale in Chapter three, to a deposit scale in Chapter four, emphasizing the multi-scale approach of this work. Each chapter is linked to the previous by a brief introductive paragraph explaining how the overall study evolves and benefits from the following work.

**JUSTIFICATION OF THESIS FORMAT AND AUTHORSHIP**

This PhD project combines the resources and personnel at the Centre for Exploration Targeting at UWA, at the John de Laeter centre at Curtin University, and at AngloGold Ashanti Limited. As a result, a number of collaborators from these institutions contributed to the studies presented in this thesis. Collaborative work has been properly acknowledged and all co-authors gave their permission for me to include the results of our collaboration in this thesis. According to UWA regulations 29.(1) and 29.(3), I declare that all the material presented in this thesis has not been presented in part or full for a degree at any other university. In accordance with regulation 30.(2)(a) stating that: "the work done by the student must be clearly indicated and certified as such by the co-authors", the contribution of the candidate and all co-authors for the papers presented in Chapter two, three and four is listed below.

The manuscript presented in Chapter two is first authored by the candidate and co-authored by Nicolas Thébaud, John Miller, Stanislav Ulrich, Julien Bourget, and Ockert Terblanche. The candidate undertook all sampling, sample preparation, geochronological analyses and writing of the manuscript. Drs Nicolas Thébaud, John Miller, Stanislav Ulrich all went on the field with the candidate on numerous occasions and contributed to the gathering of geological observations presented in the manuscript. Dr Nicolas Thébaud also helped with SHRIMP data processing. Dr Nicolas Thébaud and Dr John Miller assisted in the development of the overall idea of the paper and provided many fruitful discussions. Dr John Miller also
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The manuscript presented in Chapter three is first authored by the candidate and co-authored by John Miller, Nicolas Thébaud, Stanislav Ulrich, and Campbell T. McCuaig. The candidate developed the idea behind the paper and is responsible for the entire writing of the manuscript. Drs Stanislav Ulrich, John Miller, Nicolas Thébaud, and Campbell T. McCuaig all contributed to structural data collection on the field. Dr Stanislav Ulrich spent the most time with the candidate on the field and contributed to the overall interpretation of the structural evolution of the Siguiri district. Dr John Miller also contributed to this interpretation and provided numerous fruitful discussions regarding stress-switches in orogenic gold deposits. Drs Nicolas Thébaud, and Campbell T. McCuaig also largely contributed in the revisions done to the manuscript and by providing insightful discussions.

The manuscript presented in Chapter four is first authored by the candidate and co-authored by Nicolas Thébaud, John Miller, Malcolm Roberts and Noreen Evans. The candidate undertook all sampling, sample preparation, optical microscopy, whole-rock geochemical analyses and writing of the manuscript. Drs Nicolas Thébaud and John Miller provided numerous tips to help sampling and numerous editorial comments. Dr Malcolm Roberts assisted with the Electron Probe Micro-Analyzer (EPMA) data collection on sulphides, data processing and numerous fruitful discussions. Dr Noreen Evans assisted with the Laser Ablation
Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) data collection and first-pass data processing.

**SUPPORTING REFERENCES**

In addition to the three journal publications submitted forming the main chapters of this thesis, the PhD candidate Lebrun wrote another submitted publication and six abstracts and extended abstracts for a number of international conferences:

**Publications**


**Peer reviewed extended abstracts**


**Short communications**


REFERENCES


West Africa: A Look at Gold Mining in Ghana, Mali and Burkina Faso, 2014, Available from: 
CHAPTER 2: PAPER ONE

GEOCHRONOLOGY AND LITHOSTRATIGRAPHY OF THE

SIGUIRI DISTRICT: IMPLICATIONS FOR GOLD

MINERALISATION IN THE SIGUIRI BASIN (GUINEA, WEST AFRICA)

The Siguiri district sits alone in the central Siguiri Basin, one of the biggest sedimentary basins of the West African Craton. The following paper presents the lithostratigraphy and geochronology of the central part of the Siguiri Basin. The study is based on field observations and geophysical datasets from the whole Siguiri Basin. This work constitutes the first integrated study of the Siguiri Basin lithostratigraphy and geochronology. A total of six new U-Pb ages were determined from three sedimentary Formations (five ages) and one igneous rock.

The Siguiri Basin sediments were deposited around ca. 2015 Ma, making the Siguiri Basin relatively young compared to most West African sedimentary basins. A major change in the lithostratigraphy observed across the entire Siguiri Basin in geophysical datasets and ground-truthed in the field, is interpreted to represent olistostrome deposits that mark a change in the Basin opening and tectonic dynamics and may mark the onset of a period of orogenic compression during the Eburnean Orogeny. The morphology of this olistostrome is controlled by faults interpreted as fundamental structures associated with the early architecture of the Siguiri Basin and viewed as the first order controls on the location of the
Siguiri district. These conclusions make the Siguiri Basin and the Siguiri district key locations for the understanding of the Eburnean orogeny and gold mineralisation in this part of the West African Craton.

This chapter was submitted to Precambrian Research and is hence formatted in this style. It was revised a number of times by all co-authors and by two reviewers from the Precambrian Research journal before resubmission.
Geochronology and lithostratigraphy of the Siguiri district: implications for gold mineralisation in the Siguiri Basin (Guinea, West Africa)

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Abstract:

Geochronology and lithostratigraphic characterisation of the Siguiri district in the Paleoproterozoic Birimian terrane of West Africa has provided a reappraisal of the Siguiri Basin stratigraphy. This new insight into the evolution of the central part of the basin further highlights first order controls on the location of the world class Siguiri orogenic gold district. Three metasedimentary formations occur in the Siguiri district: the Balato, Fatoya and Kintinian formations. These formations consist of fine-grained organic-rich shales, mudstone and siltstone/greywacke/limestone interbeds, decimetre- to metre-thick graded greywacke beds and debris flow deposits. The Balato Formation displays low-energy, hemipelagic marine
or lake sediments, whereas the Fatoya Formation consists of distal turbidite deposits (thin-bedded turbidites and channel-fill deposits). Altogether they form a basal regressive sequence. The overlying Kintinian Formation is shale-rich, and contains a stack of polymict conglomeratic interbeds (up to 100 metres in thickness) around the base of the Formation in the Siguiri district. This conglomerate unit transects the whole Siguiri Basin and is interpreted to be the product of repeated subaqueous debris flow deposits and represent olistostromes (or mélange of sedimentary origin) with various autochthonous and allochthonous clasts. The youngest detrital zircon age population for each of the Balato, Fatoya and Kintinian formations yields ages of 2113 ± 10 Ma, 2113 ± 5 Ma and 2124 ± 7 Ma respectively, thus constraining the maximum age of deposition for each of these formations. The minimum age of deposition of these sedimentary rocks is constrained by an unconformably overlying volcanic breccia and dated at 2092 ± 5 Ma, and by the Maléa monzogranite intrusion dated at 2089 ± 12 Ma.

Comparison of the sedimentary facies and geochronology of the Siguiri sedimentary rocks with other sedimentary basins in the West African Craton, suggests that the Kintinian Formation is part of the Lower Tarkwa Group, best described as “late orogenic basin” sediments. The Kintinian olistostromes are inferred to highlight the possible onset of renewed tectonic activity associated with the Eburnean Orogeny in the Siguiri Basin at ca. 2115 Ma. The peculiar morphology of these olistostromes compared to the bulk of the Siguiri Basin sedimentary rocks, illustrates a major change in lithofacies. This change is interpreted to have developed along fundamental basement structures, controlling the early architecture of the Siguiri Basin as well as the location of world-class gold mineralisation in the Siguiri district. These fundamental structures are thought to have acted as first order fluid pathways during the E-W progressive compressional event responsible for orogenic gold mineralisation in the Siguiri district.

Keywords: West Africa, Siguiri Basin, geochronology, lithostratigraphy, early architecture, gold
Introduction

A comprehensive understanding of the lithostratigraphy is a fundamental part of defining the regional structural framework of any mineralized province. Lithostratigraphic syntheses of Precambrian terranes have highlighted how the early architecture and fundamental structures controlling the lithostratigraphic record can be delineated (e.g. Williams and Currie, 1993; McIntyre and Martyn, 2005; Robert et al., 2005; Blewett et al., 2010). These early structures are often proposed to apply a multi-scale control on mineralisation, as highlighted by the mineral system concept (McCuaig and Hronsksy, 2014). This early architecture is often cryptic and consists of incipient unexposed structures (Lebrun et al., in press 2016; Chapter 3; "vertical accretive growth" structures of McCuaig and Hronsksy, 2014). Later reactivation of these structures to the regional stress-field by overpressured fluids (Sibson et al., 1988; Sibson and Scott, 1998), develops veining in, around, and above these structures, often following lithostratigraphic interfaces (Robert et al., 2005; Miller et al., 2010).

Numerous orogenic gold deposits hosted in sedimentary basins around the world are interpreted to be controlled by early structures highlighted by lithofacies variations. For example, the Kirkland Lake deposit in Canada is hosted along the Kirkland-Lake Cadillac fault, highlighted by the unconformity between the Timiskaming sedimentary rocks and the Abitibi Supergroup (Hyde, 1980). Similarly, in the Western Australian Yilgarn Craton, gold deposits such as Ant Hill, Bullant, Porphyry and Wattlebird are hosted along the Ballard-Zuleika Shear Zone and highlighted by the Kurrawang Group sedimentary rocks (Weinberg et al., n.d.; Mueller et al., 1996; Robert et al., 2005). In the West African Craton, the giant Obuasi deposit in Ghana is hosted along the Ashanti fault separating the Birimian sedimentary rocks from the "late orogenic" Tarkwaian sedimentary rocks of the Ashanti Belt (Sestini, 1973; Perrouty et al., 2012).

Also located in the West African Craton, the world-class orogenic gold district of Siguiiri is hosted in the northern part of the Siguiiri Basin (Guinea), about 200 km south-west of Bamako in Mali and 150 km north of Kankan (Steyn, 2012; Lebrun et al., in press 2016; Chapter
The district measured resources were 21.08 t Au indicated resources from ore averaging 2.35 g/t as of the 31st of December 2013 (inclusive non-attributable resources only) and produced an estimated cumulative total of 240 t Au (AngloGold Ashanti Ltd., n.d.).

Due to limited exposure, the lithostratigraphy of the Siguiri Basin has received little attention, and existing studies have mostly focused on the importance of magmatism during the Eburnean Orogeny (Egal et al., 2002). Early regional mapping from the French Geological Survey (BRGM) described the Siguiri Basin as a homogeneous package of undifferentiated fine sedimentary rocks and few geochronological constraints on the timing of deposition of the sedimentary units exist in the study area and in the broader Siguiri Basin area (Egal et al., 1999; Feybesse et al., 1999; Egal et al., 2002).

This paper presents a multi-disciplinary study combining sedimentological, geochronological, and geophysical analyses from the Siguiri district that allows for further discrimination of the Siguiri Basin sedimentary record. Used collectively, the datasets characterise the lithostratigraphic succession of the central Siguiri Basin and permit the drafting of a new geological map for this critical region. The results of this study enhance our understanding of the fundamental lithofacies and architecture of the Siguiri Basin and its tectonic position in the West African Craton evolution and demonstrate that the location of the world-class orogenic gold Siguiri district is controlled by the early architecture of the basin.

Geological context

Regional Geology

The Siguiri Basin is located in the north-western part of the Paleoproterozoic Baoulé-Mossi domain, which covers western Guinea, southern Mali, most of Burkina Faso, western Niger, south-east Liberia, Ivory Coast and western Ghana. In addition, the Kédougou-Kéniéba inlier, in eastern Sénégal, represents the western-most expression of the Baoulé-Mossi domain (ca. 2050–2200 Ma; Figure 3A). The Paleoproterozoic Baoulé-Mossi domain was accreted to the Archean Kénéma-Man domain, in the south-west of the West African Craton, during the
Eburnean Orogeny (ca. 2100–2000 Ma; Abouchami et al., 1990; Egal et al. 2002; Thiéblemont et al. 2004). The Neoproterozoic sedimentary rocks of the Taoudeni Basin overlie both these domains unconformably.

Figure 3: A) Geological map of the West African Craton. Orogenic gold deposits are displayed as small red discs. B) Geological map of the Siguiri Basin. Location of the Siguiri district map in red. Location of the Saraya geochronological sample, Si326, in white. Modified from Milési et al. (1989) and Miller et al. (2013).
The Siguiri Basin is bordered to the west and south by the 2093 ± 2 Ma mafic to felsic volcanic rocks of the Kéniéro Range (Feybesse et al., 1999), the Niandan komatiite suite, and by a large volume of ca. 2090–2070 Ma granodiorite (Egal et al., 2002; Figure 3B). To the south, the Sassandra fault separates the Siguiri Basin from the Archean Kénéma-Man domain (Egal et al., 2002), host to the Simandou banded iron formations. To the east, the Siguiri Basin is bordered by the intermediate to felsic calc-alkaline 2212 ± 6 Ma Niani suite and by the Yanfolila greenstone belt, composed of an intercalation of volcanoclastic sedimentary rocks and dominantly mafic to intermediate volcanic rocks. To the north, the Siguiri Basin is overlain unconformably by the flat-lying sandstones of the Neoproterozoic Taoudeni Basin. Mesozoic sills, volcanic flows and ENE-WSW dykes related to the south Atlantic opening also cut across or overlie the Siguiri Basin (Abouchami et al. 1990; Egal et al., 1999; Egal et al., 2002; Paranhos, 2008). Localised Archean banded iron formations also outcrop to the north-west and south of the Siguiri Basin.

The lithostratigraphy of the West Africa Craton has received little attention since its early description and craton-scale correlations by Milési et al. (1989), Milési et al. (1992) and Feybesse and Milési (1994), and the later reassessment of the Ghanaian geochronology by Hirdes et al. (1992), Taylor et al. (1992), Hirdes and Davis (1998) and Loh and Hirdes (1999). The most recent regional reconstructions have systematically used geochronological and geophysical constraints when delineating lithological distributions across a study area (Baratoux et al., 2011; Perrouty et al., 2012; Perrouty et al., 2014; Davis et al., 2015; Parra-Avila et al., 2015).

The Siguiri Basin was mapped by the BRGM and other authors as a homogeneous package of undifferentiated fine sedimentary rocks derived from erosion of Paleoproterozoic granitoids that were emplaced during the earliest stages of the Eburnean Orogeny (Goloubinow, 1936; Milési et al. 1989; Villeneuve, 1992; Egal et al., 1999). The Siguiri Basin sedimentary rocks are interpreted to have been deposited contemporaneously with volcanic rocks during the Lower Birimian and later intruded by monzogranites and biotite granites at ca.
2075 Ma (Milési et al. 1989; Feybesse and Milési 1994; Egal et al., 1999; Feybesse et al., 1999; Egal et al., 2002).

**Structural framework**

A protracted deformation history for the Siguiri Basin has been recently compiled on the basis of a Siguiri district study (Steyn, 2012; Lebrun et al., in press 2016; Chapter 3). This deformation history is characterized by three folding episodes associated with: a N-S compression, $D_{1S}$, followed by an E-W compression, $D_{2S}$ (that progressively evolved into a transpressional and then a transtensional event during $D_{3S}$), and a late NW-SE compression, $D_{4S}$ (Figure 4).

![Figure 4: Structural scheme of the deformation history observed in the Siguiri district. The E-W compression $D_{2S}$ evolves progressively to a transtension responsible for gold mineralisation in Siguri, $D_{3S}$. After the work from Lebrun et al. (in press 2016); Chapter 3.](image)

While $D_{1S}$ is characterized by discreet E-W folds, $D_{2S}$ is associated with the bulk of the deformation observed in the Siguiri district and is responsible for the N-S structural grain of the Siguiri Basin. Finite strain analysis of the ductile and brittle structural elements associated with $D_{2S}$ and $D_{3S}$ (e.g. folds, faults, veins) indicates multiple stress-switches. The early-$D_{2S}$ E-W compression is interpreted to have evolved into an early-$D_{3S}$ E-W transpression before the stress-field switched to a late-$D_{3S}$ NNW-SSE transtensional deformation responsible for the development of gold mineralisation. Ore shoots are controlled by four orientations of structures formed during the waning stages of $D_{2S}$ (N-S reverse faults and E-W normal faults) and in the early stages of $D_{3S}$ (NE-SW to ENE-WSW dextral shear zones and WNW-ESE sinistral shear zones), but were all reactivated late-$D_{3S}$. An increase in gold-bearing vein density characterises these structures are characterised in outcrop. These veins are composed of
quartz-carbonate-arsenopyrite, are consistently NE-SW-trending across the entire Siguiri district and are typically steeply dipping to the SE. Overprinting all earlier structures, \( D_{45} \) is represented by a penetrative steep cleavage, \( S_{45} \), that is parallel to the supra-solidus magmatic fabric found in the Maléa monzogranite that intrudes the Siguiri Basin sedimentary rocks a few kilometres north of the Siguiri district (Figure 3B).

**Methodology**

*Fieldwork and sample selection*

Twenty-two weeks of fieldwork in the Siguiri Basin were conducted over 2 years starting in April 2011. Fieldwork campaigns, of about a month length each, were mainly focused on the Siguiri district tenement (Figure 5), with 2 weeks of regional field transects undertaken. Observations and description of the stratigraphy, lithofacies associations and geochronological sampling were conducted directly on outcrop and in drill core. These observations, integrated with geophysical data, were compiled on a geology map of the district (Figure 5). Seven diamond drill holes were logged to create a synthetic lithostratigraphic column (Figure 5). The lithostratigraphic succession proposed in this column was constrained by sedimentary descriptions and interpretations (Figures 6 to 8), as well as structural observations (e.g., fold vergence). The stratigraphic column (Figure 9) was constructed by detailed logging of bedsets in the selected cores and stacking each log according to field observations of geopetal indicators or structural relationships.

*Geophysical data*

The Siguiri gold district is characterised by a <200 m thick lateritic profile. To see through this thick cover in order to make district-scale and regional-scale interpretations regarding the Siguiri Basin lithostratigraphy, multiple geophysical datasets were used. The airborne electromagnetic (AEM) response for each individual lithostratigraphic formation and the contrast between them were used in the making of the district-scale geological map.
(Figure 5) whereas regional correlations were constrained by using a similar method on the magnetics datasets.
The AEM system employed is the fixed-wing SPECTREM platform that simultaneously measures electromagnetic, total field magnetic and radiometric response. Both the electromagnetic and magnetic sensors are towed (as “birds”) behind the aircraft in the slingram configuration, while the radiometric crystals are installed inside the cabin. The SPECTREM system has a 100% duty cycle with a base frequency of 75 Hz, a 400 000 A.m\(^2\) RMS dipole moment, the X & Z components are measured and the AEM data is binned into 8 channels or windows. The survey was completed in 2007 using 200 m line-spacing at 45° and a nominal aircraft altitude of 90 m.

The mineral exploration community has historically applied AEM as a “bump detector” for bedrock conductors. Another application of AEM is the ability to discriminate between or use as a remote predictive mapping technique to identify individual lithologies or lithostratigraphic packages within a sedimentary basin. Due to the lithofacies variations of the Balato, Fatoya and Kintinian formations (as described in §4.1); the Kintinian Formation is generally more conductive, whereas, the Fatoya Formation is more resistive (Figure 5). Because of the deep weathering profile, both mid-time and late-time Tau-Z products have been employed to ensure bedrock variations are being highlighted. The use of the Tau products also minimises severe terrain-clearance effects that are evident on the Z-channel grids within isolated areas.

The study used airborne magnetic data, with the analytical signal (Roest et al., 1992) being one of the key data sets. This is a function related to magnetic fields by a combination of derivatives. While the analytical signal is not a measurable parameter it is useful for interpretation purposes as it is completely independent of the Earth’s magnetic field. This
means that all geological bodies displaying a similar geometry, exhibit the same analytical signal. As the peaks of analytic signal functions are symmetrical and occur directly above the edges of wide geological entities, interpretation of analytical signal maps and images can provide simple indications of magnetic source geometry. It is a useful dataset to delineate various geological entities, lithologies or lithostratigraphic packages. In particular, faults tend to be highlighted by low or high magnetic responses linked to oxidation or hydrothermal alteration, respectively.

**Geochronology**

Six rock samples were collected in the Siguiri Basin. Five representative detrital samples were selected for each interpreted major lithostratigraphic lithofacies encountered in the Siguiri district. One sample of greywacke was collected from each of the Balato, Fatoya and Kintinian formations, one sample of conglomerate was also collected from the Kintinian Formation and one sample of greywacke was collected from the Marble Hill (Figure 5). An additional sample from an unconformably overlying volcanic breccia was also sampled to the west of the district (Figure 3). Samples were collected from pit exposures, outcrop or drill core. Three to 5 kg of material were collected for most samples, except for coarse-grained conglomerate and brecciated samples where 10 kg of material was sampled to compensate for their larger grain-size. While most samples came from ore zone vicinities, care was taken to choose samples exhibiting minimal hydrothermal alteration and weathering. All samples had their weathered area trimmed off prior to being crushed.

The samples were crushed and the zircons separated using standard crushing techniques and heavy liquid and magnetic techniques by GeoTrack International laboratories in Melbourne (Australia). Mineral concentrates were then sent to MinSep Laboratories in Denmark (Australia), where zircons were hand-picked, mounted and polished for SHRIMP analysis. Mount imaging was conducted on a Nikon Eclipse LV100 POL at the Centre for Exploration Targeting (CET) in Perth (Australia). Scanning Electron Microscopy imaging by
backscatter electron (BSE) and cathodoluminescence (CL) was conducted on a TESCAN VEGA3 at the Centre for Microscopy, Characterization and Analysis (CMCA) at the University of Western Australia, also in Perth. Each mount, containing 2 to 3 samples, was cleaned according to the standard protocol described by Wingate and Kirkland (2014), then dried in an oven for 1 hour at 60°C before being coated with a 40 nm thick gold layer at the John de Laeter Centre for Isotope Research of Curtin University, in Perth.

All mounts were analysed by Sensitivity High Resolution Ion Microprobe (SHRIMP II) at the John de Laeter Centre for Isotope Research of Curtin University, in Perth (Australia). Analytical conditions and operational procedures are standard and include a primary beam current of 2.0–2.6 nA, a 15–20 μm beam size and 5 scans of 15 min each per analysis (Compston et al., 1984; Claoue-Long, 1995; Wingate and Kirkland, 2013). For each sample, an average of fifteen analyses of the standard BR266 (559 Ma, 903 ppm U; Stern, 2001) or M257 (561 Ma, 840 ppm U; Nasdala et al., 2008) were carried out over the SHRIMP session. Raw data reduction was completed following Wingate and Kirkland, (2013) using SQUID (Ludwig, 2000). Corrections for common Pb were based on measured $^{204}\text{Pb}$, assuming an average crustal composition fitting the age of the mineral (Stacey and Kramers, 1975). Calibration uncertainties and error of mean were used for the error calculation of the $^{238}\text{U}/^{206}\text{Pb}$ ratios. This in turn provided the way to merge multiple raw data files from different SHRIMP sessions of the same rock sample, increasing the statistical validity of the reduction. Merging was conducted for samples: 1) KMRCDD113 224.5 (two mounts); and 2) Si241 (three mounts). Limit values for the analyses of unknowns were as follow: 1) common Pb < 1.0%; and 2) -2 % ≤ discordance ≤ 5%. Analyses on zircons with high crack density or strong metamict damage were discarded.
Results

The Sigui district lithostratigraphy

The Sigui district lithostratigraphy consists of a thick (≥800 m) sedimentary sequence metamorphosed to sub-greenschist facies. Overall, the metasedimentary rocks mostly consist of normally graded to massive, dm- to m-thick greywacke beds interbedded with claystone-siltstone, and shale (Figures 6, 7, 8, 9). In detail, the lithostratigraphy of the Sigui district was divided into three distinct sedimentary formations (Figure 9; Watts, 2010). These formations are, from oldest to youngest: the Balato, Fatoya and Kintinian formations. A schematic log representing the lithostratigraphic column of the Sigui gold district is presented in Figure 9.
Figure 6 (previous page): Core photographs from: the Balato Formation (A), showing massive, dark grey shales; the Fatoya Formation (B, C, D) showing thin-bedded, fining-upward turbidites with massive to cross-laminated greywacke bases grading to siltstone and mudstone (Tc-e of the Bouma sequence); the Kintinian Formation, showing (E) the basal polymict conglomerates observed in the Sanu Tinti deposit and (F) the upper massive dark-green shales with cm-thick, limestone interbeds. c: clast; l: limestone interbeds; m: matrix; qv: quartz vein.

The Balato Formation is dominated by dark grey to light grey massive siltstone beds grading upwards to shale, alternating with cm-thick shale-siltstone and rare fine greywacke interbeds (Figure 6A). The Formation is moderately incompetent, intensely deformed, and displays isoclinal folding. Only the apparent top of this Formation is sampled by the existing drill core and the thickness of the Balato Formation is difficult to evaluate. The contact between the Balato and overlying Fatoya Formation was neither observed in drill core nor in the field.

Figure 7: Field photographs of (A) ripple marks in the Kami deposit, Fatoya Formation; (B) rip-up clasts of shale at the base of a turbidite (greywacke) bed in the Fatoya Formation; (C) cm to dm-thick bedded greywacke turbidites in the Fatoya Formation associated with basal erosional (scour) surfaces (white arrows); (D) basal conglomerate of the
The Fatoya Formation is composed dominantly of normally-graded (fining-upward), dm- to m-thick beds of medium to coarse-grained greywacke grading upwards to siltstone and mudstone (Figures 5C, 5D and 6B). Beds are delineated by sharp scoured basal surfaces (Figures 6D and 7C). Sub-angular to sub-rounded rip-up clasts of siltstone, mudstone and shale are rarely observed (Figure 7B), suggesting that the fining-upward greywacke beds were the product of erosional flows. Fatoya Formation sediments display numerous sedimentary features that can be used as way-up indicators, such as: cross-bedding, rip-up clasts and ripple marks (Figure 7). High- to low-angle cross-lamination is commonly observed demonstrating that the deposition of current ripples was under lower flow regime conditions (Figures 6B and 6D). Asymmetric ripple marks are also observed in the field (Figure 7A). Pyrite is abundant in the upper, fine-grained layers of the beds (Figure 6B). Although difficult to evaluate because of the poor correlation between each logged drill-core, the minimum thickness of the Fatoya Formation is estimated to be ~400m (Figure 9). Field observation of the contact between the Fatoya and Kintinian formations demonstrates that the latter stratigraphically overlies the former. In the Seguelen deposit further to the north, the contact between the two formations is sharp and disconformable (Figure 8C).
Figure 8: Photographs of A) the Saraya volcanic breccia; B) marbles from the Marble Hill location; and C) the contact between the Fatoya and the Kintinian Formation in the Seguelen deposit.

The Kintinian Formation is a >400 m thick sequence dominated by massive dark-green shale with cm-thick, boudinaged limestone interbeds (Figure 6F), and less common thin beds of siltstone or fine graded greywacke. The most striking feature of the Kintinian Formation is the presence of a thick sequence (~100 m) of at least two stacked conglomeratic layers observed interbedded within the Formation (Figures 6E and 7D). This conglomerate unit is dominantly clast-supported with 5 to 30 vol% of a fine-grained (mudstone to fine greywacke) matrix (Figure 6E). The clasts are angular to sub-rounded and poorly sorted, ranging in size from a few millimetres up to a meter but on average are 2–3 cm (Figure 7D). Based on lithological and petrographical observations, clast lithologies in the Siguiri district include:
- shale. These commonly massive clasts sometimes show fine laminations or are interbedded with siltstone and greywacke. They are dark grey to light brown when not altered, and represent about 85 vol% of the clasts observed;

- limestone. These clasts are commonly white to light cream in colour and show a massive to laminated texture. They represent an average of about 10 vol% of the clasts observed but can locally be found to be the dominant clasts observed, such as in drill core SIDD002;

- felsic volcanic rocks. They typically show a massive texture and are thought to represent less than 1 vol% of the clasts observed;

- felsic intrusives. These clasts are difficult to recognize since carbonate alteration spotting and albite alteration can sometimes be confused with their granular texture. Clasts mineralogy comprises quartz, plagioclase and biotite. They may represent about 1 vol% of the clasts observed and were mostly found in darker intersects of conglomerate;

- banded iron formation (BIF). These black clasts are only rarely observed in thin-section (below 1 vol%), where they show discrete banding and a mineralogy made of hematite, quartz, plagioclase and biotite;

- possible mafic volcanic rocks. These black massive clasts are typically more rounded and show an aphanitic texture in cores. They may represent up to 4 vol% of the observed clasts.

The thickness of individual conglomerate beds and their stacking patterns is difficult to determine from drill core, as larger clasts might be mistaken for major breaks in the sedimentation. However, available drill core logging data show that the Kintinian conglomerate occur as thick (~10–15 m) deposits overlain by thin (<50 cm) shale to mudstone intervals. The conglomerate unit was observed at the contact with Fatoya greywackes, above a reverse fault in the Sanu Tinti deposit, and reworking meta-limestone/marble in drill cores from the Silakoro area. Based on the current logging data, the conglomerate unit that sit near
the base of the Kintinian Formation, is overlain by mudstone and boudinaged limestone interbeds representing the bulk of the Kintinian Formation (Figure 6F), and its thickness varies across the map and in cores.

In order to integrate the observations from the Siguiri district in the broader Siguiri Basin framework, two additional localities were investigated: the Marble Hill and the Saraya areas (Figures 3B and 5A). Located between the Kintinian and the Fatoya formations (area around sample Si241 on Figure 5A), the Marble Hill is composed of conglomerate and greywacke that overly strongly foliated limestone beds (Figure 6D). This is the only place in the Siguiri district where in situ beds of limestone were observed. The conglomerate found in the Marble Hill area is similar to the conglomerate unit hosted in the Kintinian Formation and observed in the Sanu Tinti deposit. However, in the conglomerate from the Marble Hill area, limestone clasts increase in proportion (drill-hole SIDD002; Figure 5A). The Marble Hill conglomerate is viewed as a locally sourced lateral variation of the Kintinian conglomerate found in the Sanu Tinti deposit. The meta-limestone beds are, therefore, considered to represent the overturned stratigraphic top of the Fatoya Formation or base of the Kintinian Formation (Figure 9). Even though the meta-limestone unit did not yield enough zircon for detrital geochronology, meta-greywacke from the top of the Marble Hill were sampled for geochronological analysis (sample Si241; Figure 5A).

The Saraya area is located ~50 km west of the Siguiri district (area around sample Si327 on Figure 3B). The lithostratigraphy in the Saraya area is similar to that of the district, displaying fine-grained micaceous greywacke, siltstone and shale beds alike of those of the Balato, Fatoya and Kintinian formations. The Saraya area shows a low AEM response, similar to that of the Fatoya Formation. The Saraya sedimentary rocks are overlain unconformably by volcaniclastic rocks of andesitic composition that contain cm- to dm-sized subangular felsic clasts (Figure 6A) alternating with black chert lenses and meter-thick layers of tuff (Cayn, 2011). These volcaniclastic units are estimated to be over 400 m thick and were sampled for geochronology (sample Si327; Figure 3B).
Figure 9: Lithostratigraphic column of the Siguiri district. This synthetic log was constructed using six different drill holes spread across the district. True thickness of each sedimentary formation is unknown.
Geological map and regional stratigraphic integration

The field and drill core observations were integrated with the geophysical datasets available over the Siguiri district. Both airborne electromagnetic and magnetic datasets were used to constrain the extent and boundaries of the district lithostratigraphy. Both methods are detailed below.

Airborne electromagnetic dataset (AEM):

The variation in the amount of conductive material (e.g. shale) in the different units has resulted in some important contrasts in the AEM response of the three major sedimentary formations observed in the district. The Kintinian Formation, dominated by shale is the most conductive in AEM, whereas, the greywacke-dominated Fatoya Formation is the least conductive. The Balato Formation AEM response returns an intermediate signal between that of the Fatoya and Kintinian Formation. Using these conductivity contrasts as a proxy for lithological boundaries and after field validation when possible, a revised map of the Siguiri district was constructed (Figure 5A). The highly conductive Kintinian Formation makes up the western part of the map. The medium AEM response of the Balato Formation makes up most of the eastern part, slightly rotating in strike around a N-S orientation (Figure 5B). A thin, elongated section of the low response Fatoya Formation makes up the central and northern parts of the map and separates the two other formations. The Maléa monzogranite, is non-conductive (resistive) and is delineated to the north.

Isolated windows of the Fatoya Formation can also be found in the Kintinian Formation. Most notably, the region of Silakoro (core SIDD002 on Figure 5A) displays numerous marble and conglomeratic drill core intersects which appear to be at the contact between domains where the AEM response is analogous to that of the Fatoya and Kintinian formations. Multiple fold successions were also identified using the AEM response between these two formations in the central-lower part of the district, as well as faults and dykes (Figure 5A).
Magnetic dataset:

The magnetic datasets, were used to delineate regional features but were of no use, at the scale of the Siguiri district, to distinguish between the three sedimentary formations. At a regional scale however, the magnetic datasets were used to highlight dykes, structures and to follow the conglomeratic base of the Kintinian Formation throughout the entire Siguiri Basin (Figure 10).

![Figure 10: Geological map of the Siguiri Basin overlain by the magnetics analytical signal and showing the spatial continuity of the magnetic conglomerate throughout the basin (global trend highlighted in red). The WSW-striking and WNW-striking magnetic highs, respectively found in the northern and southern parts of the basin are dykes (Figure 2).](image)

This unit shows a stronger magnetic response than the rest of the Siguiri Basin sedimentary rocks and forms a distinctive “Z”-shape from the Siguiri district to the south of the city of Kankan (Figure 10). Ground-truthing of this geophysical observation indicates a strong
magnetite-rich hydrothermal alteration of the conglomerate in the southern part of the Siguiri Basin consistent with the observed magnetic anomaly. In outcrop, lateral compositional variation consistent with the local geology were also observed across the Basin. For instance, numerous limestone clasts were observed in the conglomerate from the Marble Hill location (Figure 5), north-west of the Siguiri district, whereas the nature of the clasts observed in the district conglomerate is dominated by shale and greywacke from the Fatoya and Balato formations.

U-Pb zircon geochronology

Below is the detailed description of the detrital and igneous samples collected in the Siguiri Basin. Macroscopic and petrographic observations for each sample are given as well as detailed on the dated zircons are given. Analytical data for each sample can be found in Table 1 (in Electronic Appendices).

Sample SKRCDD040 236.5, meta-greywacke (WGS84, UTM 29N, 462781E, 1271072N, Elev.: 364 m)

This sample is a fine-grained, massive, equigranular, dark grey greywacke (~60 vol% matrix) that is metamorphosed to sub-greenschist facies and belongs to the Balato Formation (Sintroko PB1 deposit). Modal composition for quartz, albite and white micas equals 20, 25 and 20 vol%, respectively. Carbonate and chamosite make up the remaining volume. Rock fragments in this greywacke are rare. The zircons sampled from this sample are colourless to pale brown. Crystals are usually heavily fractured but remain subhedral with a prismatic habit and present typical crystal size of 80x100 μm. Cathodoluminescence imaging shows that grains exhibit oscillatory zoning (Figure 11E).
Figure 11: Cathodoluminescence images of the representative zircons for each age population for each sample. These images were taken at an acceleration voltage of 10 kV and working distance around 14.5 to 15 mm. Weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ dates for each population in red.

Fifty-three analyses were obtained from 53 zircons (error of mean: 0.14% (1σ error)). Ten analyses that yielded results that were >5% discordant and four analyses that were >2% reversely discordant were not included in the U-Pb concordant age calculation. Six additional analyses were rejected from the age calculation because morphological defects (e.g. cavities, fractures) over the spots analysed. The remaining 33 concordant to slightly discordant analyses yield two prominent detrital populations with a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of (Figures 12A and 12B): $2113 \pm 10$ Ma (MSWD = 0.83; n = 8; average U content: 138 ppm) and $2143 \pm 6$
Ma (MSWD = 1.03; n = 23; average U content: 172 ppm), plus individual zircons of: 2221 ± 11 Ma (U content: 199 ppm) and 2334 ± 15 Ma (U content: 109 ppm). The eight analyses of the youngest population yielded a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of 2113 ± 10 Ma (2σ, MSWD = 0.83) which is interpreted to represent the maximum age of deposition of the Balato Formation.

Figure 12: Concordia plots and distribution histograms for analysed samples SKRCDD40 237 (A and B), KMRCDD113 224.5 (C and D) and Si241 (E and F). Data in black or color are within -2 and +5% discordance. Each colour represents a different detrital age population. Distribution histogram for concordant and semi-concordant data only.
Sample KMRCDD113 224.5, meta-greywacke (WGS84, UTM 29N, 461552E, 1277874N, Elev.: 400 m)

This sample is a massive, coarse-grained dark grey feldspathic greywacke (~50 vol% matrix) at sub-greenschist facies from the Fatoya Formation (Kami deposit). The modal composition of this sample is 20 vol% quartz, 25 vol% albite, 20 vol% white micas and trace amounts of pyrite. Carbonate and chamosite make up the remaining volume. Only rare rock fragments were observed in this greywacke. The zircon yield was abundant and the average crystal size was 60x80 μm. The zircons are mostly colourless or pale brown, subhedral and heavily fractured. Cathodoluminescence imaging shows that grains exhibit oscillatory zoning (Figure 11F).

The respective errors of mean (1σ error) of the sample, mounted and dated on two separate mounts, was: 0.18 and 0.17%. A total of 108 analyses were obtained from 105 zircons. Forty-two analyses >5% discordant and one analysis >2% reverse discordant were rejected in the age calculation. Two additional analyses were rejected from the age calculation because of morphological defects over the spots analysed. The remaining 63 analyses yielded four detrital populations with a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of (Figures 12C and 12D): 2113 ± 5 Ma (MSWD = 1.00; n = 43; average U content: 102 ppm), 2167 ± 9 Ma (MSWD = 0.88; n = 16; average U content: 89 ppm), 2239 ± 16 Ma (MSWD = 0.88; n = 3; average U content: 127 ppm) and a single zircon dated at 2713 ± 13 Ma (U content: 68 ppm). Forty-three analyses of the youngest population yielded a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of 2113 ± 5 Ma (2σ, MSWD = 1.00) which is interpreted to represent the maximum age of deposition of the Fatoya Formation.
Sample Si241, meta-greywacke (WGS84, UTM 29N, 449911E, 1285773N, Elev.: 574 m)

This sample is a strongly foliated, very coarse-grained, dark green feldspathic greywacke at sub-greenschist facies displaying ~30% of matrix. It comes from the Marble Hill location, a hill made of limestone, conglomerate and greywacke sedimentary rocks. The modal composition of this sample is 20 vol% quartz, 25 vol% albite and 20 vol% white micas. Carbonate and chamosite make up the remaining volume. The proportion of rock fragments is, however, higher than in the other greywacke samples. Zircons are medium to dark brown, display an average crystal size of 50x70 μm, are fractured and mostly subhedral to anhedral. The vast majority of grains exhibit oscillatory zoning in cathodoluminescence imaging (Figure 11B).

The sample was mounted and dated on three separate mounts. The respective errors of mean for each mount was (1σ error): 0.23, 0.20 and 0.38%. A total of 158 analyses were conducted on 145 zircons. Forty-two analyses that are >5% discordant and 8 analyses that are >2% reverse discordant were rejected for the age calculation. Two extra analyses were also rejected due to fractures at the spot of the analyses. The remaining 106 concordant to slightly discordant analyses yielded three detrital-zircon age populations with a weighted mean $^{207}\text{Pb}^{*}/^{206}\text{Pb}^{*}$ date of (Figures 12E and 12F): 2111 ± 4 Ma (MSWD = 1.00; n = 60; average U content: 99 ppm), 2162 ± 5 Ma (MSWD = 1.00; n = 41; average U content: 75 ppm) and 2222 ± 28 Ma (MSWD = 0.03; n = 5; average U content: 56 ppm).

The sixty analyses of the youngest population yielded a weighted mean $^{207}\text{Pb}^{*}/^{206}\text{Pb}^{*}$ date of 2111 ± 4 Ma (2σ, MSWD = 1.00) which is interpreted to represent the maximum age of deposition of the Marble Hill greywacke.
**Sample ST1, conglomerate (WGS84, UTM 29N, 460252E, 1280352N, Elev.: 400 m)**

This sample is a clast-supported polymictic conglomerate from the Sanu Tinti deposit, at the base of the Kintinian Formation. Clasts are angular and their source rock is dominated by carbonates, but clasts of mafic volcanic, felsic intrusive and even banded iron formation (BIF) could also be found. This conglomerate can be extremely porous as attested by large amounts of disseminated pyrite and the strong hydrothermal alteration in some other samples. Similar conglomerate was found across the Siguiri Basin. The matrix is dominated by quartz, plagioclase and white micas as per the previous detrital samples. The zircons display an average crystal size of 40x60 μm, are mostly colourless or light-brown, heavily fractured but remains subhedral with a prismatic habit and a strong oscillatory zoning visible by cathodoluminescence imaging (Figure 11C).

Fourty-eight analyses were collected from 48 zircons (error of mean: 0.26% (1σ error)). Eighteen analyses >5% discordant and 2 analyses >2% reverse discordant were rejected for the age calculation. One extra analysis was also rejected due to fractures at the spot of the analyses. The remaining 27 analyses display three detrital-zircon age populations with a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}^*$ date of (Figures 13A and 13B): 2124 ± 7 Ma (MSWD = 0.63; n = 14; average U content: 155 ppm), 2154 ± 8 Ma (MSWD = 0.36; n = 9; average U content: 175 ppm) and 2205 ± 15 Ma (MSWD = 0.42; n = 4; average U content: 102 ppm). The fourteen analyses of the youngest population yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}^*$ date of 2124 ± 7 Ma (2σ, MSWD = 0.63) which is interpreted to represent the maximum age of deposition of the Kintinian conglomerate.
Figure 13: Concordia plots and distribution histograms for analysed samples ST1 (A and B), BDRCDD009 402 (C and D) and Si327 (E and F). Data in black or color are within -2 and +5% discordance. Each colour represents a different detrital age population. Distribution histogram for concordant and semi-concordant data only.
Sample BDRCDD009 402, meta-greywacke (WGS84, UTM 29N, 460946E, 1280579N, Elev.: 352 m)

This sample comes from the base of the Kintinian Formation, below the Bidini deposit. It is a medium-grained, equigranular, massive, feldspathic greywacke (~50 vol% matrix) metamorphosed to sub-greenschist-facies. Petrographic observations indicate that its modal composition is around: 20 vol% quartz, 25 vol% albite, 20 vol% white micas. Zircon yield was low and the average crystal size is 60x80 μm. The zircons are mostly colourless and fractured but remain subhedral to euhedral with a prismatic habit. Cathodoluminescence imaging shows that grain exhibit oscillatory zoning (Figure 11D).

Thirty-eight analyses from 37 zircons were obtained from sample BDRCDD009 402 (error of mean: 0.23% (1σ error)). Six analyses >5% discordant and 3 analyses >2% reverse discordant were omitted. Five additional analyses were rejected from the age calculation because of morphological defects at the spots analysed. The remaining 24 analyses yielded four detrital populations with a weighted mean \(^{207}\text{Pb}^*/^{206}\text{Pb}^*\) date of (Figures 13C and 13D): 2120 ± 5 Ma (MSWD = 0.93; n = 11; average U content: 194 ppm), 2152 ± 6 Ma (MSWD = 0.68; n = 11; average U content: 141 ppm), as well as two monozircon detrital ages: 2193 ± 10 Ma (U content: 119 ppm) and 2265 ± 10 Ma (U content: 98 ppm). The eleven analyses forming the youngest population yielded a weighted mean \(^{207}\text{Pb}^*/^{206}\text{Pb}^*\) date of 2120 ± 5 Ma (2σ, MSWD = 0.93) which is interpreted to represent the maximum age of deposition age of the Kintinian Formation, and minimum age of deposition of the underlying Fatoya Formation.

Sample Si327, volcanic breccia (WGS84, UTM 29N, 415178E, 1290080N, Elev.: 371 m)

This sample, from the Saraya region (west of the Sigui district), is a strongly foliated silica-rich volcanic breccia displaying numerous dark grey and brown sedimentary clasts of quartzitic nature (chert) and of carbonates. Centimeter to decimeter subangular clasts of light-pink pumice or tuff can also be found in the cream-pink groundmass. All minerals are interlocked (no or little porosity) and the groundmass displays a granular texture. The
mineralogy of the groundmass is characteristic of an intermediate to felsic composition (Cayn, 2011). Zircon yield was low (20+) and a large amount of pyrite was also found in the heavy mineral concentrate. Zircon grains are pale brown with an average crystal size of 80x100 μm. Crystals are subhedral, fractured, with a prismatic habit and display oscillatory zoning visible by cathodoluminescence imaging (Figure 11A).

Thirty-six analyses were obtained from 32 zircons (error of mean: 0.22% (1σ error). Fourteen analyses >5% discordant and one analysis >2% reverse discordant were rejected from the age calculation. Four additional analyses were also rejected due to the presence of inclusions and fractures at the spot of the analyses. The remaining 17 analyses display one population with a weighted mean $^{207}\text{Pb}^{*}/^{206}\text{Pb}^{*}$ date of 2092 ± 5 Ma (MSWD = 1.2; n = 17; average U content: 110 ppm; Figures 13E and 13F). The weighted mean $^{207}\text{Pb}^{*}/^{206}\text{Pb}^{*}$ date of 2092 ± 5 Ma (2σ; MSWD = 1.2) is interpreted to represent the age of crystallisation for the Saraya volcanic breccia.

All five detrital samples display a polymodal detrital zircon age distribution. The magmatic sample from Saraya does not show any inheritance (one age population). Mean U content remains relatively constant and around 100–150 ppm for all samples, except for the sedimentary rocks from Marble Hill, where values are slightly lower. All maximum ages of deposition and the magmatic age are compiled in Figure 14.
Figure 14: Summary diagram of the maximum deposition ages of each detrital sample and the crystalisation age of sample Si326. All detrital sample ages plot around ca. 2105-2130 Ma while sample Si326 is consistent with other late Eburnean magmatic ages (Egal et al., 1999).
Discussion

Depositional environments of the Siguiri district

The very fine grain size of the Balato Formation deposits suggests deposition in a low energy, marine or lake setting. The dominantly dark colour of the Balato shales suggests high content of organic material and deposition in reduced water oxygenation and circulation, characteristic of a relatively quiescent phase of sedimentation.

The sedimentary rocks of the Fatoya Formation are interpreted to be the product of submarine, sediment-laden gravity flows waning through time (Mulder and Alexander, 2001). The normally-graded greywacke to mudstone beds are interpreted as the Ta/b (coarser-grained, massive greywacke with basal rip-up clasts), Tc/d (current ripples) and Td/Te (siltstone and mudstone) terms of the Bouma sequence (Bouma, 1962). The Fatoya Formation is therefore interpreted as a marine or deep lake sequence formed by turbidity current deposits. The relatively fine-grained, thin-bedded turbidites suggest a rather distal depositional setting, such as the outer part of a channel-levee system (Piper and Deptuck, 1997) and/or a distal turbidite lobe setting (e.g. Gervais et al., 2006; Bourget et al., 2010). In contrast, the presence of thick beds (up to ~5 m-thick) of massive medium to fine-grained greywacke in drill cores suggest deposition in a low-relief, channelized depositional environment such as lobe distributaries (Gervais et al., 2006; Bourget et al., 2010). The meta-limestone/marbles, reworked by the Kintinian conglomerate, are interpreted to lay at the top of the Fatoya Formation or base of the Kintinian Formation.

The Kintinian Formation strongly contrasts lithologically with the other sedimentary formations recognized in the Siguiri district. The stacked conglomerate sitting near its base is interpreted as the product of subaqueous, cohesive debris flows (Mulder and Alexander, 2001). It incorporated relatively locally sourced clasts, as highlighted by the clast angularity, sorting, and lateral mineralogical and clast variation. This is exemplified by the shale-dominated clasts eroded along the marine (or lake) slope from the older Balato and Fatoya formations in the Siguiri district while limestone clasts dominate the conglomerate observed
closer to the Marble Hill location. The rest of the Kintinian Formation is interpreted to reflect a return to a low energy marine or lake depositional setting with fluctuating water geochemistry and conditions at the origin of the organic-rich shales and limestone interbeds (Figure 6F).

Overall, the Siguiiri district sedimentary rocks are interpreted as marine or lake sedimentary deposits. They initially form a regressive (coarsening-upward) sequence showing the following transition (Figure 9):

1) low-energy marine (or lake) organic-rich shales (lower Balato Formation);

2) onset of gravity-flow deposits and distal turbidite deposition possibly representing turbidite lobe complex such as distributary channel fills, and;

3) onset of high-energy debris flow deposition (basal Kintinian conglomerate unit). The sequence then fines up to the upper Kintinian Formation, which is associated with a return to lower energy marine (or lake) deposits as a result of either a shutdown of the coarse-grained siliciclastic input in the basin and/or a relative increase in water depth (e.g. transgression).

This interpretation is relatively consistent with the observations of “a succession of mudstones and siltstones formations” made by Egal et al. (1999) and their interpretation of the Siguiiri Basin sedimentary rocks as “fine marine sediments”.

The stacked Kintinian conglomerate (which were also previously described by Egal et al., (1999) and Feybesse et al. (1999)) can be considered as olistostrome deposits with various autochthonous and allochthonous clasts (Flores, 1955; Neuendorf et al., 2005). Olistostromes (or mélanges of sedimentary origin) are interpreted as the product of submarine debris flow triggered by slope failure (Prothero and Schwab, 2004; Dalrymple and James, 2010), possibly associated with earthquake-induced faulting events (Moore et al., 1976; Chang et al., 2001; Wendorff, 2005; Cieszkowski et al., 2009). The basal Kintinian olistostrome is laterally continuous throughout the entire Siguiiri Basin (Figure 10). This basal conglomerate strongly contrasts lithologically with the rest of the Siguiiri Basin “fine sediments” described by Egal et
al., (1999) and Feybesse et al. (1999), and marks an abrupt change in depositional energy and tectonic context.

The presence of olistostromes near the base of the Kintinian Formation is therefore regarded as a major change in lithofacies (Figure 3B), marking a change in the dynamics of the Siguiri Basin opening and tectonic activity. This change reflects the transition from a relatively quiescent marine or deep lake sequence formed in a distal depositional setting (Balato and Fatoya formations) to a period accompanied by enhanced faulting and mass-wasting events along the paleo-marine slope, resulting in over-steepening, erosion, and deposition of a stack of conglomerate from repeated debris-flow events (Kintinian Formation).

**The Siguiri district geochronology in the West African context**

Geochronological constraints on the timing of deposition of the sedimentary rocks from the Siguiri district are typically limited by the mechanisms that generate them, including erosion, transport and deposition. The prismatic habit and strong oscillatory zoning displayed by the vast majority of zircons analysed in this study is suggestive of a magmatic origin for these minerals. The ages considered in this study are therefore interpreted as crystallisation ages of eroded igneous rocks and thus represent maximum depositional ages. The fact that all five detrital samples display a polymodal distribution of detrital zircon ages reflects the existence of multiple lithological sources.

The maximum ages of deposition for the Siguiri district sedimentary formations are all within error of each other and average at ca. 2117 Ma (Figure 14). Currently, the only constraint on the minimum age of deposition is provided by the crystallisation age of the Saraya volcanic breccia (2092 ± 5 Ma), sitting on top of the siliciclastic sedimentary rocks of the Siguiri district. This volcanic unit is coeval with the intrusion of the Maléa monzogranite, whose crystallisation age was dated to be 2089 ± 12 Ma (Parra-Avila et al., 2015).
Based on a recent regional synthesis, Davis et al. (2015) proposes that the lithostratigraphic succession of the Baoulé-Mossi domain exhibits three distinct sedimentary units including from bottom to top:

- Ca. 2300–2150 Ma Lower Birimian basins that are composed of pyroclastics, volcanoclastics and associated with extensive volcanism;
- Ca. 2150–2115 Ma Upper Birimian basins that unconformably overly the Lower Birimian volcanosedimentary rocks and are composed of greywacke, argilite and some volcanoclastics, and;
- Ca. 2115–2095 Ma Tarkwa Group basins that are composed of sandstone, greywacke and conglomerate. These basins are less common compared to the other two.

When put into the regional context of the West African Craton, the maximum sedimentation ages observed in the Siguiri district appear younger than the Lower Birimian rocks (Figure 15). For example, the Sefwi Formation in Ghana (Perrottet et al., 2012), which is dominated by pyroclastics and volcanoclastics, has an age of crystallisation of 2162 ± 6 Ma (Loh et al., 1999) and is associated with widespread basaltic and andesitic volcanism dated from ca. 2200 up to ca. 2140 Ma (Taylor et al., 1992; Davis et al., 1994; Hirdes and Davis, 1998; Adadey et al., 2009; Davis et al., 2015). The Sefwi Formation displays similar facies and age of deposition as the Fetekoro sedimentary rocks and its equivalents in the Boromo, Houndé and Banfora belts in Burkina Faso (Baratoux et al., 2011; Davis et al., 2015). The Boromo, Houndé and Banfora sedimentary rocks have been described as tuffs, epiclastic volcano-sedimentary rocks, volcaniclastics, argilites and wackes with occasional intercalations of andesite flows (Baratoux et al., 2011). The Komana sedimentary rocks in the Yanfolila Belt of Mali, are another example interpreted by Davis et al. (2015) to be a lateral equivalent of the Sefwi Formation (Figure 15).
Figure 15: Simplified lithostratigraphic and geochronological chart of some key areas of the West African Craton. Ages from the Siguiri district and Saraya are reported in the left column. Modified from: Baratoux et al. (2011), Davis et al. (2015), Lahondère et al. (2002), Lebrun et al. (in press 2016), Parra-Avila et al. (2015), Perrouxi et al. (2012); Chapter 3.
In contrast, the depositional ages of the Siguiri Basin sediments compare to those of
the Upper Birimian and Tarkwa Group rocks such as the Kumasi Formation (Ghana), Batie
Formation and Bambela Basin sedimentary rocks in Burkina Faso, and Fingouana, Kabaya and
Her’kono formations in Mali. Each of these stratigraphic packages are dominated by flysch-like
metasediments (e.g. greywacke, argillite) deposited after ca. 2150 Ma (Figure 15; Davis et al.,
2015). The Siguiri district sedimentary rocks are therefore interpreted to have deposited at the
same time than that of the Lower Tarkwa Group deposited between 2115 and ca. 2095 Ma, or
to represent the last expression of Upper Birimian sedimentation dated as 2150–2115 Ma
(Davis et al., 2015).

The Kintinian Formation – a Tarkwa Group sequence?

Even with detrital geochronology analyses, it remains difficult to determine whether
the Siguiri district sedimentary rocks belong to the Upper Birimian or Tarkwa Group. The
Tarkwa Group (Davis et al., 2015), previously referred to as "Tarkwa-like" by Baratoux et al.
(2011), was defined based on its lithotype characterisation over 40 years ago: the Tarkwaian
sedimentary rocks in Ghana (Sestini, 1973). The Tarkwaian consists of intercalations of
conglomerate, sandstone and phyllite. The conglomeratic layers display Birimian quartz
pebbles and volcanic clasts and were interpreted to represent piedmont-type deposits (short
transport in an environment of active continental erosion; Bossière et al., 1996; Mueller et al.,
1996), similar to that found on the southern foot of the Alps and the Himalayas (Sestini, 1973;
Hirdes and Nunoo, 1994). Since this early work, sedimentary rocks from the Tarkwa Group
have been described in other parts of the West African Craton. Tarkwa Group rocks were
deposited late during the Eburnean Orogeny lithostratigraphic evolution.

The Tarkwa Group rocks are therefore considered “late orogenic basin”-type
sedimentary rocks. Such rocks were found to have deposited at different times from the
Archean to the present day, in various cratons and locations around the globe. These rocks
typically deposit late during the lithostratigraphic evolution of an orogeny, but early when
compared with the timing of orogenic contraction (Robert et al., 2005). The Timiskaming sedimentary rocks and the rest of the Duparquet Basin in Canada, as well as the Kurrawang Group in the Eastern Goldfields of Western Australia, are Archean examples (Mueller et al., 1996; Krapež et al., 2000). The Hanmer Basin, a foreland sedimentary basin in New Zealand, is a modern example of a “late orogenic basin” (Wood et al., 1994). These sediments may be associated with early phases of orogenic contraction (Ledru et al., 1994; Robert et al., 2005), as pull-apart basins developed in transpressive environments (e.g. Krapež and Pickard, 2010), or alternatively, as extensional basins developed during regional extension (e.g. Blewett et al., 2010).

The sedimentary facies of the Kintinian Formation strongly contrasts with that of the Balato and Fatoya formations. The Kintinian Formation conglomerate, that contains banded iron formation clasts interpreted to be sourced from the Archean Simandou, compares well with Tarkwa Group sediments. Together, the age overlap and peculiar facies of the Kintinian Formation suggests that this Formation may belong to the Lower Tarkwa Group (Figure 15), as defined by Davis et al. (2015). We suggest that the Kintinian Formation formed late during the Eburnean Orogeny lithostratigraphic evolution as distal turbiditic lobes in deep water and olistostromes characteristic of the early stages of “late basin” sedimentation. Based on these premises and the relative timing between the deposition of Tarkwa Group sediments at ca. 2115-2095 Ma and the juxtaposition during the Eburnean Orogeny of the Baoulé-Mossi Domain with the Kénéma-Man Archean Craton by ca. 2115 Ma (Davis et al., 2015), we propose that the Kintinian Formation "late basin" sedimentation marks a change in the tectonic setting of the Siguiri Basin that may correspond to a stage of Eburnean convergence.

*Early architecture of the Siguiri Basin and orogenic gold systems*

Regardless of the timing of mineralisation, it has been demonstrated in several terranes of varying age that the structural framework associated with mineralisation is intimately controlled by the early architecture (Dörling et al., 1996; Love et al., 2004; Garwin et
Early architecture is crucial for exploration targeting and major stratigraphic boundaries are commonly targeted by orogenic gold exploration (Robert et al., 2005). These boundaries and variations within a basin are typically controlled by, and therefore highlight, fundamental structures that were active at the time of the basin formation (Hajná et al., 2011; Gindre et al., 2012; Ersoy et al., 2014; Collins et al., in press). These fundamental structures are commonly reactivated multiple times and will act as important fluid pathways, focusing fluids produced from deep-seated sources (e.g. magmatic, mantle derived, metamorphic). The early architecture and associated structures are often cryptic and difficult to recognize on the field. These structures may be visible in large-scale geophysical datasets, and highlighted in the field by lithological variations (e.g. Miller et al., 2010).

The basal Kintinian olistostrome is located at the faulted interface between the Fatoya and Kintinian formations, marks a change in the Siguiri Basin opening dynamics, and can be traced in regional magnetic datasets and by field mapping as a narrow N-S layer of linear geometry in map view across the Siguiri Basin (Figure 10). Bends in the Kintinian olistostrome and in the rest of the lithostratigraphy defined in the Siguiri district can be observed both at the scale of the district (Figure 5) and at the regional scale where the olistostrome forms a peculiar “Z”-shaped unit recognized across the entire Siguiri Basin (Figures 3B and 10). From observations in the Siguiri district where the Kintinian olistostrome is bound by WNW-ESE, N-S and NE-SW structures, we infer that structures with similar orientations may also bound the rest of the olistostrome unit across the entire Siguiri Basin. In the Siguiri Basin, we also note that WNW-ESE, N-S and NE-SW structures sometimes seat on along-strike changes in the thickness of a particular lithology, such as the olistostrome unit, or the volcanic rocks of the Keniero region (Figures 3B, 5 and 10).

The location of the Siguiri district, previously described as being hosted amidst an undifferentiated package of sedimentary rocks, falls at the intersection between early WNW-ESE and N-S faults highlighted by the Kintinian olistostrome and also recognized in magnetic
and gravity datasets by Markov et al. (2015). These structures also intersect with the locations of other smaller deposits hosted in and around the Siguiri Basin (e.g. Léro, Jean et Gobelé, Kalana). In addition, the olistostrome is affected by magnetite alteration and intruded by numerous magmatic plugs (Figure 3B).

Robert et al. (2005) highlights the common association of major stratigraphic boundaries with early architecture and fundamental structures, active at the time of sedimentation, that controlled the morphology of such stratigraphic breaks. Whereas further work would be required to understand the original timing of formation of these structures, together, these elements suggest that the WNW-ESE, N-S and NE-SW structures that bound the Kintinian olistostrome across the Siguiri Basin, could represent fundamental deep basement structures that controlled the thickness and morphology of this unit at the time of its deposition and applied a first-order structural control on fluid flow and magmatism. This first-order structural control enabled fluid migration and led to the apparent preferential emplacement of magmatic intrusions along the basin early architecture (Figure 3B), the development of a regional magnetite alteration within the Kintinian conglomerate (Figure 10), and the development of gold mineralization in the basin.

In the West African Craton, such association between "late orogenic basins" and gold mineralisation is also exemplified by the Tarkwa Basin in Ghana where numerous deposits, including the giant Obuasi deposit, are hosted along structures controlling the morphology of the Tarkwa Basin (Figure 3B). Delineation of the Tarkwa Group sedimentary rocks is therefore viewed as an important tool for orogenic gold targeting in the West African Craton.
Conclusion

The lithostratigraphy and geochronology of the Siguiri Basin, and of the Siguiri district in particular indicates that:

1) The Siguiri Basin is not a uniform package of undifferentiated fine-grained sedimentary rocks, but has a complex lithostratigraphy. This lithostratigraphy includes (from top to bottom) the Kintinian, Fatoya and Balato sedimentary formations;

2) In the context of the West African Craton, the central Siguiri Basin and sedimentary rocks from the Siguiri district are interpreted as spanning the transition from Upper Birimian to Lower Tarkwa Group sedimentation. The Tarkwa Group sediments are “late basin”-type sediments associated with margin convergence and the central Siguiri Basin sedimentary rocks mark a change in the tectonic setting and may signal the onset of a period of orogenic compression during the Eburnean Orogeny.

3) The polymict conglomerate of the Kintinian Formation are interpreted as an olistostrome with various autochthonous and allochthonous clasts. It marks a major change in lithofacies in the Siguiri district and was deposited as a linear belt crossing the entire Siguiri Basin;

4) The morphology of the Kintinian-Fatoya stratigraphic boundary may highlight the early architecture of the Siguiri Basin and fundamental WNW-ESE, N-S and NE-SW structures that controlled the deposition of the Kintinian Formation at the time of the basin opening and the location of the Siguiri gold district and of its ore shoots;

5) Delineation of similar Tarkwa Group sedimentary rocks is viewed as a key targeting tool for orogenic gold in the rest of the West African Craton.

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CHAPTER 3: PAPER TWO

STRUCTURAL CONTROLS ON THE WORLD-CLASS SIGUIRI

GOLD DISTRICT, SIGUIRI BASIN, GUINEA, WEST AFRICA

The following paper presents the structural framework associated with the Siguiiri gold district and its evolution through the Eburnean orogeny. The study is based on field observations, geophysical datasets, drill core logging and petrographic observations. This work focuses on district and deposit-scale observations of the second and third order structures controlling gold mineralisation. It describes the different structural features encountered in the Siguiiri district and the link they have with gold mineralisation. This paper discusses the deformation history of the Siguiiri district, the development of gold mineralisation in the district and the stress-field variations associated with this mineralisation. Based on this work, four deformation events were recognized to affect the Siguiiri district sediments: a N-S compression ($D_{1s}$), an E-W compression ($D_{2s}$) interpreted to progressively evolve into transpression and then transtension ($D_{3s}$), and a NW-SE compression ($D_{4s}$). Gold mineralisation was interpreted to occur late during $D_{3s}$ around ca. 2100 Ma and be associated with stress-field variations happening at a regional scale. This deformation scheme matches that of the deformation history previously described for the West African Craton.

Not only is this work crucial for the understanding of the deformation events that affected the Siguiiri district, but is also critical to highlight the role stress-field variations have as a process leading to orogenic gold mineralisation.
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Structural controls on an orogenic gold system: The world-class Siguiri gold district, Siguiri Basin, Guinea, West Africa

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Abstract:

Ore bodies in the Siguiri district, a world-class Paleoproterozoic orogenic gold camp located in the Birimian of northeastern Guinea, are typically represented by cryptic sub-vertical damage zones that host a high density of mineralized veins. Although no large regional fault system was recognized, observations from five representative deposits of the Siguiri district (Sanu Tinti, Bidini, Kami, Kosise, and Sintroko PB1) show that these ore bodies are locally controlled by incipient structures and spread across three distinct structural and lithostratigraphic domains. Two shale-dominated peripheral domains adjoin a central domain whose lithostratigraphy is dominated by medium- to coarse-grained greywacke and this domain hosts the bulk of the gold endowment of the district. The three domains exhibit similar structural elements that can be described within a four-stage deformation scheme. The first deformation event (D₁₅) is poorly constrained and interpreted to have been a N-S compressional event. It included development of minor folds with W to WNW gently plunging fold axes without a clear axial planar cleavage. The main and second deformation event (D₂₅) is interpreted to have been associated with E-W to ENE-WSW directed compression. The D₂₅ event was responsible for forming the dominant N-trending structural grain of the district and
creating interference patterns between F_{1s} and F_{2s} folds. The third event (D_{3S}) developed progressively from D_{2S} compression into an early-D_{3S} E-W to ENE-WSW directed transpression and a late-D_{3S} NNW-SSE directed transtension responsible for most of the gold mineralization in the Siguirir district. The fourth and last event (D_{4S}) was a NW-SE oriented compressional event responsible for the localized overprinting of veining by a steep to shallowly dipping NNE-SSW ductile cleavage.

Late-D_{3S} gold-bearing mineral occurrences formed along sub-vertical N-S reverse faults, NE-trending dextral shear zones, WNW-trending sinistral faults, and E-trending normal relay faults developed or reactivated early-D_{3S}. Mineralization is expressed as mineralized shear zones or sub-vertical damage zones, characterized by a 10-15 m wide zone of dense quartz-carbonate-sulfide veining or disseminated gold-bearing sulfides. The mineralized veins consistently strike ENE-WSW, are steeply dipping, and commonly have a conjugate geometry at the meso-scale. Finite strain analysis of deformation, including analysis of folds, faults, and conjugate mineralized vein sets, is consistent with a stress switch from a compressional (D_{2S}) to transpressional deformation (termed early-D_{3S}). Results of paleostress analysis on conjugate mineralized vein sets which formed late during D_{3S} indicate that the stress-field ranged from extensional to strike-slip, sometimes within the same vein locality. The late-D_{3S} deformation is interpreted to have been a transtensional event. The first change in the orientation of the principal stress axes is related to a switch from a far field-dominated to a body force-dominated stress field reducing the deviatoric component on the stress tensor. The second change in the orientation of the principal stress axes, from early-D_{3S} transpression to late-D_{3S} transtension, suggests that \sigma_1 and \sigma_2 were similar in magnitude, which facilitated localized stress switches. In the Siguirir district, the early-D_{3S} and late-D_{3S} stress switches, which occurred at both a local and regional scale, enhanced the fracture permeability and were critical for the establishment of active fluid pathways leading to the formation of a world-class gold system.

Keywords: West Africa; Siguirir; orogenic gold; tectonics; stress-switch
Introduction

Orogenic gold deposits are common across the Paleoproterozoic Birimian rocks of the West African Craton (e.g., Milési et al., 1989, 1992; Lawrence et al., 2013a). The location of orogenic gold deposits is typically controlled by complex regional-scale fault networks (Groves et al., 2000; Goldfarb et al., 2001). In West Africa, the Ashanti fault system in Ghana, is one example of such a network, and its many faults host some of the biggest vein-hosted and fault-vein-hosted orogenic gold deposits (e.g., Obuasi: Allibone et al., 2002; Fougerouse et al., 2015). The Siguiri district (240 tonnes [t] Au; AngloGold Ashanti Ltd., 2013; AngloGold Ashanti Ltd., n.d.) is unusual in West Africa because it is not located on a recognized large regional scale fault system. Instead it is located in the center of a large sedimentary basin in the Paleoproterozoic Baoulé-Mossi domain of the West African Craton. The Siguiri gold district currently consists of eleven accessible deposits, and is the only gold district with > 50 t Au hosted in the weakly metamorphosed rocks of the Siguiri Basin (Egal et al., 1999).

Previous work in the district has recognized grade trends, but has struggled to put the geology together and highlight the incipient structures that control gold mineralization at a deposit-, district-, and regional-scale. Most notably, a study on the structural controls of auriferous quartz veining in eight of the deposits of the district was conducted by Steyn (2012). Steyn (2012) concluded that mineralization is hosted by veins, mainly controlled by competent lithologies, and associated with N-S to NW-SE fold hinges and N-S to NE-SW shear zones developed during ENE-WSW transpression. Transpression is the result of coeval compression and strike-slip movements along a fault-bounded zone of deformation and is attributed to what is termed wrench/transcurrent tectonics (Sanderson and Marchini, 1984). This paper builds on the observations made by Steyn (2012) and describes the different brittle, ductile, and brittle-ductile structures observed in the district, including the different vein generations from five representative deposits including Sanu Tinti, Bidini, Kami, Kosise, and Sintroko PB1.

Based on this dataset this paper documents the local deformation history and characterizes the structural controls on gold mineralization. The world-class Siguiri orogenic
gold district displays a series of structural features that are used to constrain the paleo-orientation of the stress-field before, during, and after the main phase of gold mineralization. In turn, these paleo-orientations are used to assess the role stress switches have had on mineralization. This paper is the first study to put the geology of the Siguiri district together. It highlights the structures that control gold mineralization at a deposit- and district-scale and that may represent local expressions of more regional structures controlling the location of the Siguiri district within the Siguiri Basin.

**Geological context and exploration history**

The Siguiri district is located in the northwestern part of the Paleoproterozoic Baoulé-Mossi domain, which covers the majority of the Man-Leo shield in West Africa. The Birimian terranes (ca. 2210-2040 Ma: Davis et al., 2015; Figure 16) of the Paleoproterozoic Baoulé-Mossi domain were accreted to the Archean Kénéma-Man domain, in the southwestern part of the West African Craton, during the Eburnean orogeny (ca. 2210-2040 Ma: Abouchami et al., 1990; Egal et al. 2002; Lahondère et al., 2002; Thiéblemont et al. 2004; Davis et al., 2015). Both domains are unconformably overlain by rocks of the Neoproterozoic Taoudeni Basin, which covers a large part of the craton (Villeneuve and Cornée, 1994; Begg et al., 2009; Lawrence et al., 2013a).
Figure 16: A) Simplified geological map of the southern West African Craton. Red box highlights the Siguiri Basin shown in B. The Sassandra fault, bordering the Archean domain and the Siguiri Basin is shown as a thick black line; B) Geology map of the Siguiri Basin. Red box highlights the Siguiri district shown in Figure 17. Red lines indicate the segments of the regional composite cross-section (Figure 16C). Dashed black lines represent the interpreted regional extension of the N-S and WNW-ESE faults controlling mineralization in the Siguiri district. Modified from Milési et al. (1989) and Miller et al. (2013). C) Simplified composite E-W cross-sections of the Siguiri Basin and its eastern border. The folds were interpreted from the structural elements observed in the Siguiri district. Interpreted conformable contacts are shown by full black lines, unconformable and unknown contacts by dashed lines.
The Siguiri Basin covers about 40,000 km² in Guinea and adjacent Mali. It consists of upper Birimian sedimentary, volcanioclastic, and volcanic rocks and intrusive rocks. The upper Birimian sediments were derived from Paleoproterozoic volcanic rocks and felsic intrusions that were emplaced during the early stages of the Eburnean orogeny (Milési et al. 1989; Feybesse and Milési 1994; Begg et al. 2009). The Siguiri Basin is bordered to the southwest by the Niandan komatiite suite and the mafic to felsic volcanic rocks of the Kéniéro Range (not shown on map), dated at ca. 2095 Ma by Feybesse et al. (1999). To the south, the Sassandra fault puts rocks of the Kénéma-Man Archean domain in contact with those of the Siguiri Basin (Figure 16A, Egal et al., 2002). To the east, the Siguiri Basin is bordered by the Yanfolila granite-greenstone belt, which consists of volcanioclastic sedimentary and mafic to intermediate volcanic rocks. Finally, to the north, the flat-lying sandstones of the Neoproterozoic Taoudeni Basin unconformably overlie rocks of the Siguiri Basin. Paleoproterozoic intrusive rocks emplaced into the Siguiri Basin sediments, such as the Maléa monzogranite (Parra-Avila et al., in press; Parra-Avila, 2015), outcrop north of the Siguiri district (Figure 16B). Mesozoic sills, lava flows, and ENE-striking dikes, which are related to the opening of the South Atlantic Ocean, also cut or overlie rocks of the basin (Abouchami et al. 1990; Egal et al., 1999; Egal et al., 2002; Paranhos 2008, unpublished).

The deposits of the Siguiri district are hosted in fine-grained organic-rich shale, siltstone, greywacke interbeds, graded greywacke beds, and rare conglomerate. The Balato, Fatoya and Kintinian Formations were defined based on aeromagnetic, magnetic, and gravimetric data, as well as on drill core and field observations (Figure 17; Lebrun et al., 2015; Chapter 2). The Balato Formation is dominated by dark grey siltstone beds grading upwards to shale. The contact between rocks of the Balato and those of the overlying Fatoya Formation was not observed. The Fatoya Formation is dominated by meter-thick beds of medium- to coarse-grained greywacke fining upwards to siltstone and shale. Rocks of the Kintinian Formation, overlying those of the Fatoya Formation, are dominated by massive dark-green shale with centimeter-thick interbeds of limestone. The Kintinian Formation is also
characterized towards its interpreted base by a stack of polymict clast-supported conglomerate beds. In the Sanu Tinti deposit, detailed further below, a reverse fault marks the contact between rocks of the Fatoya and the overturned Kintinian formations.

Figure 17: A) Form line map, and; B) structural map of the Siguiri gold district and its different deposits constrained by aeromagnetic, magnetic, gravity, drill core, and field data. The three structural domains follow the lithostratigraphy. Red lines indicate individual segments of the district-scale composite cross-section shown in C. C) Simplified composite E-W cross-sections of the Siguiri district (deposit cross-sections in Figure 18). Interpreted conformable contacts are shown by full black lines, unconformable and unknown contacts by dashed lines.

Only one publicly available research study, conducted by Steyn (2012), has been conducted in the Siguiri district. This study detailed the different structures and described the structural controls on auriferous quartz veining in eight of the deposits of the district. Based on
bedding-fabric-vein-fault relationships, Steyn (2012) identified three deformation events in the Siguiri district as D1, D2, and D3. One gold event was recognized in the district and is associated with steeply dipping syn-D2 quartz-carbonate-sulfide veins striking to the N-S to NE-SW and commonly displaying conjugate relationships. These veins are accompanied by carbonate alteration in the form of millimeter-sized nodules overgrowing the quartz-albite-sericite host rock mineralogy. Based on bedding-fabric-vein-fault relationships, Steyn (2012) concluded that auriferous veining in the Siguiri district is controlled by competent lithologies, N-S to NW-SE F2 fold hinges, and N-S to NE-SW shear zones developed during D2 in an ENE-WSW dextral transpressive environment.

The Siguiri region has been long recognized for its endowment and has been producing gold for centuries. In the 3rd century, the Sarakolle Kingdom was already familiar with its widespread gold endowment from Senegal to the Niger River. Production of gold from this region is thought to have continued through the 12th and 13th centuries in areas controlled by the Mindingo Kingdom, whose capital Niani is near the present eastern border between Guinea and Mali, less than 100 km from Siguiri. Continued gold production was used as tribute by the Mali Empire during the 17th century. In the late 19th and early 20th century, minor extraction and prospecting in the Siguiri area was started by the French. Modern-day mining of gold from the Siguiri district started in 1931, with nearly 75 t Au produced between 1931 and 1951 (AngloGold Ashanti Ltd., 2013). Between 1960 and 1963, a Russian state company was actively mining in the region, focusing their operations on placer deposits. In the 1980s, North American and British companies conducted reconnaissance mapping, traversing, and sampling. In the early 1990s, Société Aurifère de Guinée followed up this work and reported a production of 1.1 t Au. In 1995, Golden Shamrock started a pre-feasibility study of the Siguiri district, before merging with Ashanti Goldfields (now AngloGold Ashanti Ltd) in 1996. Since 2004, the Siguiri mine has been owned 85% by AngloGold Ashanti Ltd and 15% by the Guinean government. The district’s estimated resources included 21.08 t Au indicated resources from ore averaging 2.35 g/t and inferred resources of 59.09 t Au from ore averaging 0.8 g/t as of the
end of 2013 (AngloGold Ashanti Ltd., 2013). Since AngloGold Ashanti took over the operations, production in the Siguiiri district has been approximately 10 t Au/year for an estimated cumulative production of 105.5 t Au through 2014 (Table 2; AngloGold Ashanti Ltd., n.d.). Therefore, the cumulative production from the Siguiiri district is approx. 180 t Au, with resources of approx. 80 t Au, making the district world-class according to the classification of Schodde and Hronsky (2006). AngloGold Ashanti has been focusing its mining and exploration activity in the Siguiiri district on the oxidized upper part of the deposits. Minor free gold concentrations are still being extracted by local miners from localized Phanerozoic paleo-placers and from hydromorphic reconcentration in and below the mottled zone of the lateritic profile. Individual gold nuggets of as much as several kilograms in weight have been found near the regolith surface (Watts, 2010).

**Methodology**

For the purpose of this paper, each of the 11 open pits is considered a deposit and they are collectively termed the Siguiiri district. A few deposits of the district were not accessible at the time the fieldwork was conducted, and as a result few data could be collected from them (e.g., Sokunu; Figure 17). Out of the 11 accessible deposits that were visited and mapped, five deposits were defined as being of key importance for the understanding of the overall district architecture and mineralization style. These deposits highlight critical components of character of the host rocks, host rock controls on mineralization, and key structural features with different relative timing. The five deposits selected for detailed analysis were, from north to south, Sanu Tinti, Bidini, Kami, Kosise, and Sintroko PB1. The Sanu Tinti, Bidini, and Kosise deposits are all located near or at the contact between two of the sedimentary rock formations hosting gold deposits in the district, whereas the Kami and Sintroko PB1 deposits are located in the middle of the Fatoya Formation.

Seven months of fieldwork in the Siguiiri district were conducted over two years, starting in April 2011. Mapping, structural data collection, and sampling in the district were
accomplished in the open pits and, where field exposure was limited, augmented by logging of selected drill cores. All readings are given in true north coordinates. Planar features are given in dip direction/dip format (e.g., 180/45 for an E-W plane dipping at 45° to the south). Each structural element or event is suffixed by “XS” or ”XY” subscripts, with “X” representing a digit related to the relative timing of the deformation event mapped, “Y” representing a particular group of structural elements, and “S” standing for Siguiri. In addition, terminology includes $D_{YS}$ for deformation events; $S_{YS}$ for fabrics, with $S_0$ being bedding; $F_{YS}$ for folds; and $V_{YS}$ or $V_{XY}$ for veins. For example, $V_{2S}$ and $S_{2S}$ are part of the $D_{2S}$ event.

Optical microscopy was used to constrain the relative timing and kinematics of various structural elements (e.g., cleavages, veins). Petrographic work on polished thin-sections was conducted at the Centre for Exploration Targeting (CET), University of Western Australia, Perth, using a Nikon Eclipse LV100 POL. Further petrographic work was conducted by SEM at the Centre for Microscopy Characterisation and Analysis of the University of Western Australia.

**Key deposits of the Siguiri district**

The following section reviews the main geological characteristics of five key deposits from the Siguiri district: Bidini, Sanu Tinti, Kosise, Kami, and Sintroko PB1 (Figure 17). For each deposit, the lithostratigraphy, structures, mineralization styles, and alteration assemblages are presented.

**Bidini**

The Bidini deposit is located in the northern part of the district (Figure 17). Bidini is hosted in the greywacke-dominated Fatoya Formation, and is adjacent to the Sanu Tinti deposit (Figure 18A). In the Bidini deposit, the Fatoya Formation can also present minor alternations of siltstone and shale beds.
Discrete folds occur in the southwestern part of the Bidini deposit (Figure 19A). These gently inclined to recumbent folds are open to tight, and have a wavelength of about 15 m and fold axes that plunge moderately to the WSW. These folds are associated with an axial planar cleavage that trends NW-SE to N-S and dips shallowly to moderately to the WSW (Figure 18A). This moderate-dipping cleavage is the oldest mappable fabric in the deposit, and the folds are therefore termed $F_{1S}$. The discreet $F_{1S}$ folds are refolded by a second generation of folds, termed $F_{2S}$. The $F_{2S}$ folds in Bidini (Figure 19B) are not associated with any mappable axial planar foliation. The Bidini deposit itself is located along the hinge of a larger scale $F_{2S}$ fold. This
larger scale $F_{2s}$ fold is a tight upright anticline with an estimated wavelength of 500 m (Figure 18A). The axial surface of this anticline trends NNE-SSW, and its fold axis plunges shallowly to the north and south. An asymmetric N-S trending $F_{2s}$ syncline with a western long limb, eastern short limb, and an axial surface dipping to the east, occurs between the Bidini and Sanu Tinti deposits, giving an overall west vergence to the folding (Figure 18A).
Bedding parallel veins can be observed along bedding and $F_{25}$ folds in Bidini (Figure 19C). These veins, whose orientation varies across the deposit, are typically only a few millimeters to 5 cm thick. Multiple sub-vertical damage zones, oriented NE-SW and N-S, crosscut the $F_{25}$ folds and overprint the bedding parallel veins (Figure 18A). These sub-vertical structures are not defined by a discrete shear zones or fault planes, but instead are represented by 10 to 15 m wide zones of higher vein density compared to the surrounding rocks (Figure 19D). The veins developed in these incipient NE-SW and N-S damage zones are oriented NE-SW and commonly displays antitaxial textures and sheet-like geometries (Figure 19E). These veins are commonly conjugate with a bimodal vein distribution of approximately 141/89 and 150/66 (Figure 19F). Field observations and crosscutting relationship from drill core indicate that both these vein generations postdate the development of the bedding parallel veins.

Mineralization in the Bidini deposit follows the NE-SW and N-S damage zones, and is contained in both the second and third vein generations. The first bedding-parallel vein generation, dominated by quartz and minor ankerite and albite, is barren. The second vein generation is composed of ankerite and pyrite and the third vein generation is composed of
quartz-ankerite-arsenopyrite+/-pyrite (Figure 19E, 19G, 19H and 19I). Native gold in the quartz-ankerite-arsenopyrite veins is present within the quartz or between the quartz and the ankerite rims (Figure 19E). Alteration surrounding the ore shoots is characterized by albitization of the host rock. Carbonate alteration is often characterized by the bleaching of the host rock up to 1 m surrounding individual veins (Figure 19G). A late penetrative planar fabric, termed S_{45}, strikes to the NE and dips moderately to the SE (Figure 18A). This late-stage S_{45} fabric overprints all earlier structures (Figure 19H). Thin section analyses indicate this fabric is defined by sericite and it is preferentially developed in shale beds. It is also visible in greywacke beds where it is highlighted by quartz-carbonate-sericite-(pyrite) strain shadows and strain fringes surrounding the arsenopyrite crystals associated with the steep NE-SW veins (Figure 19I).

**Sanu Tinti**

The Sanu Tinti deposit is one of the northernmost deposits (Figure 17). It is located at the faulted contact between the greywacke-dominated Fatoya Formation to the east, and the overturned and younger rocks of the Kintinian Formation to the west (Figure 18A and 20A). The Kintinian Formation in the Sanu Tinti deposit is characterized by a basal sequence of polymict, clast-supported conglomerate. The remainder of the Kintinian Formation that is exposed in the deposit is composed of shale and fine siltstone beds. The deposit is on the western long limb of a large-scale F_{25} N-S trending open-to-closed syncline within the Fatoya Formation (Figure 18A). This N-S syncline has an E-dipping axial plane that shows a fold vergence to the west (Figure 20B), has a wavelength of about 500 m, and extends into the Bidini deposit (Figure 18A and 19B). No planar fabric parallel to the axial surface was observed.
Figure 20: Structural elements from the Sanu Tinti deposit. A) Faulted contact between the greywacke-rich Fatoya Formation to the SE, and the Kintinian Formation to the NW. In the stereogram, bedding is represented by black poles or full black Great Circles, constructed fold axial planes are represented by dashed black great circles and constructed $F_{2S}$ fold axes are in yellow. B) Photograph of an upright open $F_{2S}$ syncline. C) Conjugate $V_{38}$ vein sets. D) Spaced brittle $S_{45}$ cleavage in the conglomerate layer. E) Disseminated pyrite in the conglomerate layer. F) Microphotograph of a disseminated pyrite. Free gold is associated with chalcopyrite and displays triangular textures characteristic of infill crystallization (Taylor, 2010).

In rocks of the Kintinian Formation, there are a few veins (~1 vol%) striking to the NE and dipping steeply to the SE that crosscut the conglomerate beds. These veins are thin, averaging 2-3 cm in width, but can extend for a few meters in length. In the Sanu Tinti deposit,
the faulted contact between rocks of the Kintinian and the Fatoya Formations (Figure 18A and 20A) is marked by brecciated textures developed in the first few meters surrounding the fault. The fault is oriented N-S to NNE-SSW, dips moderately to the SE, and has been delineated in core to a depth of more than 300 m (Figure 18A). Slickensides indicate that this contact is a reverse fault. In rocks of the Fatoya Formation, a poorly defined and spaced planar fabric trends to the NNE and dips moderately to the WNW (Figure 18A). This fabric is overprinted by bedding parallel veins following the western long limb of the large scale F_{2S} N-S trending syncline developed in rocks of the Fatoya Formation.

Sub-vertical ENE-trending veins cut the large-scale F_{2S} syncline. These veins often display a conjugate geometry and are a few centimeters to 15 cm thick, but can extend for tens of meters in length (Figure 20C). In the Sanu Tinti deposit, these conjugate veins are typically oriented as two main sets at 335/82 and 196/84. Either of these sets can have a conjugate geometry with additional secondary veins of similar orientation to the other vein set. In the northern part of the Sanu Tinti deposit, from core logging and 3D modeling, the density of these veins increases to as much as 20-30 vol% over 10 m along an inferred NE-SW damage zone (Figure 18A). An increase in vein density was also observed along the F_{2S} syncline hinge in the same area of the deposit. A second planar fabric, defined as S_{4S}, overprints all previously described structures. It is penetrative, oriented NE-SW in the Sanu Tinti deposit, and dips gently to the SE (Figure 18A). In the Kintinian conglomerate, this S_{4S} penetrative planar fabric maintains a similar orientation but is manifested as a spaced brittle fabric (Figure 20D).

Mineralization in the Sanu Tinti deposit displays two styles. The first style is spatially associated with the footwall of the reverse fault (Figure 18A) and consists of pyrite disseminated in the Kintinian Formation conglomerate (Figure 20E). The pyrite is often anhedral. Gold is free within fractures in the pyrite or is present as inclusions displaying triangular textures (Figure 20F), and is associated with chalcopyrite, hematite, and galena. Minor tourmaline can be associated with the pyrite. The second style consists of the sub-vertical ENE-trending veins cutting F_{2S} folds (Figure 20C). Similarly to the Bidini deposit, these
veins consist of quartz, ankerite, arsenopyrite, and minor pyrite. Native gold occurs within the quartz or along the margins of the quartz and ankerite.

*Kami and Kosise*

The Kami and Kosise deposits are both hosted in the Fatoya Formation, which is dominated by meter-thick greywacke-sandstone beds fining up into, or alternating with, minor centimeter-thick beds of siltstone and shale (Figure 17). The Kami deposit is located in the center of the formation, whereas Kosise occurs further to the east.

The Kami deposit has a structural style characterized by open F$_{15}$ upright folds, with fold axes gently plunging to the NE or the SW, and by open F$_{25}$ upright folds, with fold axes gently plunging to the north or south (Figure 18B). The intersection of these folds forms a broad domal structure that hosts the Kami deposit (Figure 21A). The Kosise deposit is adjacent to Kami and is hosted on the hinge and short limb of an open N-S F$_{25}$ syncline that has a sub-horizontal fold axis (Figure 18C, 21B and 21C). The axial surface of this N-S syncline is moderately inclined (between 60° and 30°; Fleuty, 1964) and indicates a fold vergence to the west for this fold (Figure 18C). A series of N-S faults parallels the short limb of the Kosise syncline to the east (Figure 18C and 21C). These incipient faults dip steeply to the east and are sub-parallel to the contact between rocks of the Fatoya and the Balato Formations (Figure 18B and 18C). An early cryptic sub-horizontal spaced brittle planar fabric was observed in both deposits, however its timing and significance are poorly constrained. This fabric is overprinted by a quartz-dominated vein set that is parallel to bedding or has an en-echelon geometry along the contact between different units (Figure 21D). The bedding-parallel veins are commonly ~5 cm thick, and can extend for several tens of meters. The en-echelon veins are typically thinner and rarely exceed 4 cm in thickness. The en-echelon vein arrays can extend for 2-3 m, but individual veins typically extend for no more than 50 cm. This oldest vein set is not mineralized and crosscut the already albiteised and sericitised host rock.
Figure 21: Structural elements from the Kami and Kosise deposits. A) Domal structures in the Kami deposit. The $V_{38}$ veins, mined by local villagers, can be seen focused in the dome and following competent beds. Each bench is about 7 m high. B) and C) photograph and structural cross-section of the Kosise syncline. A N-S incipient shear zone and a NE-SW dextral shear zone are highlighted in black. Intersections between NE-SW dextral shear zones and N-S reverse faults are typically highly mineralized (Figure 19C). Minor faults represented by dashed lines. Stereograms: $S_0$ in black, calculated $F_{25}$ fold axes in yellow, equal angle (Wulff) projection. D) En-echelon barren quartz $V_{25}$ veins. The projected poles from the entire Kosise deposit of bedding, $V_{25}$ bedding-parallel and $V_{25}$ en-echelon veins, highlight
that orientations and sigmoidal character of $V_{2S}$ veins are consistent with their formation by flexural slip along bedding during $F_{2S}$ folding. In the equal area stereonet/Schmidt projection stereogram, bedding is represented by black poles, the constructed fold axial plane is represented by a dashed black great circle and the constructed fold axis by a large yellow disk. Bedding-parallel veins are represented by orange poles, en-echelon are in purple. One sigma Gaussian density contours.

E) Photograph of the NE-SW dextral shear zone highlighted in B) and C).

The barren veins, the open folds in the Kami deposit, and the $F_{2S}$ syncline in the Kosise deposit are crosscut by sub-vertical discrete shear zones, or by what have been defined as incipient structures (Figure 18C). Examples of the discrete shear zones include a 1 m wide discrete NE-SW fault zone displaying dextral kinematics that is a major structural feature observed in the Kosise deposit (Figure 21B, 21C and 21E), as well as minor discrete E-W trending fault zones in the Kami deposit that indicate normal movements. However, incipient structures are more common in the Kosise and Kami deposits, and similarly to the Bidini deposit, are expressed by an abundance of veins along a 10 to 15 m wide damage zone of sheet-like geometry with no visible discrete zone of faulting or shearing along which weathering is more intense (Figure 22A). Similar N-S, E-W, WNW-ESE, and NE-SW damage zones extending along strike for a few hundred meters to more than 1 km were recognized in the field (Figure 17, 18B and 18C). The only N-S damage zone recognized in the Kosise deposit is sub-parallel to the stratigraphy, transects the deposit in its center (Figure 18C) and extends to the Kozan deposit, which displays similar structural features (Figure 17 and 22B). No kinematic indicators could be observed in the WNW-ESE damage zones in the Kami or Kosise deposits.

Gold ore zones in the Kami and Kosise deposits are associated with veins that crosscut the oldest barren quartz-dominated vein sets, which developed adjacent to discrete fault zones, and also with veins within damage zones related to incipient structures (Figure 18B and 18C). The vein arrays occurring adjacent to the discrete fault zones and within the damage zones can be separated into two generations. The first generation of these veins consists of ankerite-pyrite and rare albite, and was only observed in drill core and extends outward for a
few meters from the damage zone linked to the discrete fault zones (Figure 22C and 22D). The orientation of these veins could only be constrained from drill core observation and is not consistent (Figure 22C). The veins are a few millimeters to 15 cm thick and commonly display brecciated textures (Figure 22C). Their lateral extent is not known. Gold is present in fractures in pyrite. The veins are associated with the bulk of the carbonate alteration observed in the Kami and Kosise deposits, with millimeter-thick siderite surrounding the vein for as far as 1 m. The veins cross-cut the moderately albitized host rock but are also locally associated with further albitization, which typically is developed within 10 cm of a vein.

Figure 22: Structural elements from the Kami, Kosise and Kozan deposits. A) Incipient shear zones highlighted by increased weathering. B) Kozan F_{2S} open upright syncline, thought to be structurally adjacent to the Kosise F_{2S} syncline. C) Gold-rich, ankerite- and pyrite-bearing V_{3A} veins developed as a brecciated vein. In the equal area stereonet/Schmidt projection stereogram, V_{3A} poles are in yellow and a great circle was constructed in blue from their average orientations. One sigma Gaussian density contours. D) Shallow V_{3B} vein cutting ankerite-pyrite V_{3A}
The ankerite-pyrite vein generation is crosscut by the youngest and dominant vein generation, which forms the majority of the veins associated with the damage zones in both deposits (Figure 22D). These youngest veins consist of quartz, ankerite, arsenopyrite, and rare pyrite, are 0.5 to 10 cm thick, and extend for tens of meters. The veins commonly show antitaxial textures and display a bimodal orientation at mainly 150/40 and 145/70. In the field, veins from one set can be found conjugate with veins from the other, or with other secondary veins with a slightly differently orientation (Figure 22E and 22F). Within 10-15 m of these damage zones, the conjugate vein sets can also be found in domal structures along particularly competent greywacke beds (Figure 21A). Most of the gold in the Kami and Kosise deposits is associated with the quartz-ankerite-arsenopyrite veins. Free gold grains occur in the quartz and along the rims of the ankerite. Similarly to other deposits, free gold can also be present in the arsenopyrite and along fractures in the veins with chalcopyrite, galena, and lesser sphalerite. Gold grades across some of the discrete fault zones can locally be >100 g/t (Figure 21E). The gold-bearing veins have carbonate alteration haloes that are a few tens of centimeters wide and mainly defined by siderite nodules.

The gold-rich vein generation is refolded and overprinted by a late sub-vertical fabric oriented NNE-SSW and termed S45. This penetrative fabric also overprints all previous structural elements (Figure 22G). Strain shadows associated with the S45 fabric commonly develop surrounding disseminated sulfides in the alteration zones of the quartz-ankerite-arsenopyrite veins. These strain shadows are dominated by quartz, ankerite, chalcopyrite, and rare pyrite. Sericite is also present in these microstructures and typically is related to the late S45 penetrative fabric. Late chloritization is observed along minor sub-vertical N-S brecciation zones that are a few meters in length.
**Sintroko PB1**

Sintroko PB1 is one of the southernmost deposits of the Siguiri district (Figure 17). It is hosted in rocks of the Balato Formation, which are dominated by alternating centimeter- to meter-scale shale and siltstone beds. Beds of fine- to medium-grain greywacke are also exposed in Sintroko PB1 and the central area of the deposit is dominated by black shale (Figure 18D).

The deposit is located along two open anticlines separated by an area of sheared sub-vertical NNW-SSE trending bedding in the center of the deposit (Figure 18D and 23A). The eastern side of the deposit displays an upright open F₂₅ anticline, with a sub-vertical fold axis. The western side shows a reclined F₂₅ open anticline with a sub-vertical fold axis (Figure 23A). The wavelength of the two anticlines is estimated to be about 500 m. Locally isoclinal F₂₅ folds have an amplitude of a few meters (Figure 23B), although vertical fold axes are also common in the deposit. Bedding-parallel veins oriented at about 310/80, and typically as thick as 1 cm and extending for a few meters, occur across the entire deposit. These veins and the F₂₅ folds at the Sintroko PB1 deposit are crosscut by a major NNE-SSW shear zone in the central part of the deposit that border the central black shale area (Figure 18D). A sub-horizontal lineation was observed along the shear zone, but no kinematic indicators were identified. A series of sub-vertical incipient structures oriented N-S, NE-SW, and E-W also crosscuts the F₂₅ folds (Figure 18D). Similar to the Kami and Kosise deposits, these cross-cutting incipient structures are not characterized by any distinctive fault plane. They are, however, expressed as a planar damage zone with a 10-15 m thickness of dense veining (Figure 23C, 23D and 23E). Veining associated with the damage zones is also preferentially developed in competent beds (Figure 23A, 23C and 23D). The veins associated with the damage zones, and with the central NNE-SSW shear zones, display various orientations that can be mainly grouped into two distinct conjugate sets with orientations of 172/26 and 150/70 (Figure 23D, 23E and 23F). The veins are as thick as 10 cm and locally extend along strike for more than 10 m (Figure 23E). The two
vein sets display crack-seal and antitaxial textures (Figure 23G), and commonly display conjugate relationships between themselves and within a same set (Figure 23E and 23F). All previously described structural elements are overprinted by a sub-vertical NNE-striking penetrative fabric termed S_{4s} (Figure 18D). Kinematic indicators, such as pressure fringes, C'-type shear bands, asymmetric folding, and overprinted quartz veins, suggest that sinistral shearing was associated with this cleavage (Figure 23H).
Figure 23 (previous page): Structural elements from the Sintroko PB1 deposit. A) Upright open $F_{25}$ fold with steeply plunging fold axis from Sintroko PB1. Note the consistent orientation of the veins mined by local villagers (vertical cavities in wall) and the rheological control on mineralization (seal cap of shales, in dark grey, with strong veining restricted to underlying sandstones). B) Isoclinal fold from the border between the Sintroko PB1 and PB3A deposits. C) and D) Incipient structure in Sintroko PB1 marked by an increase in quartz vein ($V_{3B}$) vein density. The mineralized veins (dotted lines in B), mined by local villagers, keep a consistent orientation and cut across the $F_{25}$ fold. Mineralization develops around the incipient structure, and is also controlled by the rheology of the sedimentary units. E) Minor damage zone in Sintroko PB1 displaying mutually crosscutting $V_{3B}$ steep and shallow conjugate vein sets. F) Conjugate $V_{3B}$ veins. G) Steep quartz-ankerite $V_{3B}$ mineralized veins with arsenopyrite halo. The arsenopyrite typically crystallizes along the edges of the vein or in the adjacent host rock, but rarely in the vein itself. The vein to the left displays a unitaxial geometry, characteristic of the crack-seal growth mechanism (Passchier and Trouw, 2005). Both veins are represented as red great circles in the equal angle stereonet/Wulff projection stereogram. H) Microphotograph of sinistral pressure fringes developed around a $V_{3B}$ arsenopyrite crystal and dark seams developed around a siderite nodule by the $S_{4S}$ cleavage.

The ore zones in the Sintroko PB1 deposit are associated with the veining developed in the different damage zones and also surrounding the central NNE-SSW shear zone (Figure 18D). Conjugate gold-bearing veins consist of quartz, ankerite, arsenopyrite, and rare pyrite, and are restricted to greywacke beds. The arsenopyrite is more abundant in veins hosted by the shale units of the Balato Formation (Figure 23G). The host rocks for the Sintroko PB1 deposit are albitized and intensely carbonate altered. The carbonate alteration is expressed by millimeter-sized siderite nodules and bleaching of the greywacke (Figure 23G). Late chloritization can also be observed along highly fractured zones for lengths of a few meters.

Discussion

**Structural event history**

The field relationships documented in the Siguiri district suggest a polyphase deformation history. All structural elements documented in the Siguiri district can be grouped into four sequential deformation events that have been termed $D_{25}$, $D_{25}$, $D_{3S}$, and $D_{4S}$. Within these events, three distinct folding episodes and three distinct veining episodes (Figure 24)
allow determination of the relative timing and geometric controls on mineralization within the overall structural evolution of the district.

<table>
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Figure 24: Summary table of the deformation events and timing of the structural events recognized at Siguiri in this study and by Milési et al. (1989, 1992), Miller et al. (2013), and Steyn (2012).

Strain partitioning between the three stratigraphic formations in the Siguiri district resulted in a heterogeneous strain distribution. In the shale-dominated Balato and Kintinian Formations, the strain is intense and folds tend to be tight to isoclinal. By contrast, the Fatoya Formation is dominated by a greywacke-sandstone association, which displays a lower strain intensity characterized by open folds (Figure 17). As a result of this competency contrast, bedding orientations can be found to be locally quite variable (Figure 17, 25A, 25B, 25C and 25D).
Figure 25: Stereograms of the structural data collected over the Siguiri district divided into four mine areas, from north to south (black deposit outlines on maps at left). Bedding poles in black. Measured $F_{1s}$ fold axes in blue, measured $F_{2s}$ fold axes in red and constructed fold axes (pole of a great circle fitting the bedding poles of an observed fold) in yellow. Measured fold axial planes represented as black great circles. Cleavages are colored according to their interpreted generation: $S_{1s}$ in blue, late $S_{4s}$ in green. Mineralized $V_{3b}$ vein sets represented as red poles. Unless specified, all stereograms use equal angle (Wulff) projection.
Cryptic $D_{1S}$: The first deformation event, $D_{1S}$, is a ductile event characterized by cryptic $F_{1S}$ folds that are rarely observed in the district, whose axial trace strikes E-W to NW-SE and NE-SW (Figure 17 and 26). Remnants of these folds have been observed in the northern part of the district (e.g., Bidini deposit, Figure 19A). The $F_{1S}$ folds are commonly tight with recumbent orientation, and fold axes gently plunge to the E and WNW (Figure 25A, 25B and 25C). In the Kami deposit, where NE-SW trending $F_{1S}$ folds are gentle to open with wavelengths in the hundreds of meters, $F_{2S}$ N-S folds overprint the $F_{1S}$ folds and form type 1 fold interference patterns characterized by large domes and basins (Figure 17, 18B, and 21A; Ramsay and Huber, 1987). A weak cleavage ($S_{1S}$), shallowly to moderately dipping to the WSW, is locally observed in some of the northern deposits (e.g., Bidini; Figure 25E, 25F, 25G and 25H). The $D_{1S}$ deformation is interpreted to have been linked to N-S compression (Figure 26), but with inconclusive outcrop exposures the understanding of this early deformation remains unclear. An alternative interpretation is that the $F_{1S}$ folds represent syn-sedimentary slump folds (McClay, 1992), but the consistent orientation and fold axes, when accounting for overprinting by subsequent events, more strongly support a tectonic contractional setting for the folding. Since the $V_{2S}$ veins were observed to cross-cut albitised host rock, this first phase of deformation may have been responsible for an early phase of hydrothermal activity and an early phase of albitization of the country rocks across the Siguiri district.
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<td>Steep NNE-SSW penetrative fabric, overprints conjugate veins</td>
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Figure 26: Summary figure of the main structural elements observed in the Siguiri district and of their respective interpreted derived stress axes.
$D_{2S}$: The second deformation is associated with the formation of major folds ($F_{2S}$) and is responsible for the bulk of the folding in the metasedimentary rocks and for the N-S structural grain affecting much of the Siguiri Basin. The $F_{2S}$ fold axial planes typically strike NNE-SSW to NNW-SSE, and their fold axes plunge at variable angles that are typically steeper in rocks of the Balato Formation compared to those of the Fatoya Formation (Figure 25 and 26). The $F_{2S}$ fold typology varies from south to north, with upright horizontal isoclinal folds and upright vertical open folds in the area of the Sintroko deposit, to gentle upright to open inclined N-plunging and W-verging folds near the Kosise deposit (Figure 21C), and to open upright to inclined W- to NW-verging folds near the Bidini deposit (Figure 19B). The overall asymmetric fold geometry indicates a vergence to the west (Figure 17C). Based on the younging directions and overall W-verging fold asymmetry in the Fatoya Formation, the inversion of stratigraphy observed between the Fatoya and the Kintinian Formation in the Sanu Tinti deposit, is interpreted to have been initiated by $F_{2S}$ folding and amplified by later reverse faulting. No axial planar cleavage ($S_{2S}$) was identified as being associated with this event.

A switch to brittle deformation marks the end stage of the $D_{2S}$ folding event in the Siguiri district and is associated with the development of $V_{2S}$ veining that develop along $F_{2S}$ folds but are overprinted by later events (Figure 26). The $V_{2S}$ vein set is the oldest vein set in the Siguiri district and it is not mineralized. The orientation of this quartz-(carbonate) set varies from 320/80 in the Sintroko PB1 deposit, to 070/40, and 280/45 in the Kosise deposit. In Kosise, the former orientation displays an en-echelon geometry (Figure 21D). The $V_{2S}$ vein poles in Kosise typically plot along an E-W oriented girdle, consistent with the prominent $F_{2S}$ folding event (stereogram on Figure 21D). The $V_{2S}$ bedding parallel veins, and also the en-echelon sigmoidal vein sets, are interpreted to indicate some amount of flexural slip along bedding during late-stage $F_{2S}$ folding (Figure 21D and 27).

Based on all the early and late $D_{2S}$ structural observations (Figure 17 and 18C), we conclude that $D_{2S}$ was associated with an E-W to ESE-WNW compressional stress-field under a brittle-ductile regime.
Figure 27: Schematic evolution of the early-\(D_{25}\) compression and of the mode of formation of the bedding parallel and en-echelon \(V_{25}\) veins, in red, associated with flexural slip.

\(D_{35}\): Although formally separated into a third deformation event, \(D_{35}\) potentially marks the continuation of \(D_{25}\). The difference is that the \(D_{25}\) event is dominated by plastic deformation related to folding, whereas the \(D_{35}\) event is linked to development of a network of \(D_{35}\) faults with contrasting kinematics. These include reverse faults, normal faults, and strike-slip faults that extend sub-vertically to depths of more than 300 m (constrained by drilling; Figure 18 and 26). The \(D_{35}\) faults are typically not discrete features, but rather are expressed as sub-vertical and poorly outlined incipient faults or planar damage zones characterized by increased density of quartz veining and associated alteration haloes that crosscut both \(F_{25}\) folds and \(V_{25}\) veins (Figure 23C and 23D). Establishing a relative chronology between the different \(D_{35}\) faults was not possible in the field. These \(D_{35}\) structures include:

- Reverse faults that are moderately dipping to sub-vertical and N-S-trending (e.g., in the Kosise deposit). In other deposits, such as Kami, these structures are expressed as shear zones and damage zones displaying arrays of \(V_{35}\) veins that cut bedding.
- Local E-W trending sub-vertical normal faults, typically expressed as damage zones.

- A WNW-ESE trending fault population that dips moderately to the SSW and is sub-parallel to the axial plane of $F_{1S}$ folds. Such a fault, located in the northernmost part of the Siguiri district (Figure 17), was interpreted by Egal et al. (1999) to display sinistral movement.

- Sub-vertical NE-SW- to ENE-WSW-trending strike-slip brittle to brittle-ductile shear zones and damage zones exhibiting dextral movement.

Although no clear crosscutting relationships could be determined, all the faults crosscut $F_{2S}$ folds and are associated with similar vein arrays, suggesting a probable coeval development in between these two events. Alternatively, the kinematics observed on these faults are compatible with earlier events, such as the WNW-ESE sinistral faults that may have developed during $D_{1S}$ N-S compression or the N-S reverse faults, and possibly the E-W normal faults acting as local accommodating faults, that may have developed during or just after $D_{2S}$ E-W compression, but were all reactivated during $D_{3S}$ veining event. These faults may therefore represent reactivated earlier, more fundamental, and deeper structures that controlled the location of the Siguiri district within the sediments of the Siguiri Basin (dashed lines on Figure 16B). However, without further field work and observations addressing specifically the role of early architecture in the formation or reactivation of these structures, we interpret them as being formed more or less coevally between the last increment of $F_{2S}$ folding and $D_{3S}$ veining that develops along them.

Two vein sets were recognized along all these faults, $V_{3A}$ and $V_{3B}$. The first set, $V_{3A}$ (Figure 22C, 22D and 26), comprises ankerite-pyrite-(albite). The orientation of this vein set is poorly constrained, but varies significantly around a 240/55 mean in the Kosise deposit (stereogram on Figure 22C). This orientation is sub-parallel to the WNW-ESE sinistral structures. The $V_{3A}$ set was also observed close to NE-SW dextral shear zones in drill core and is confined to within a few tens of meters of these structures. However, the full extent of this vein set remains
unclear due to the highly weathered nature of these carbonate-dominated veins in the different deposits.

The second vein set associated with these faults, V_{3B} (Figure 23G and 26), represents the bulk of veining observed in the Siguiri district and crosscuts the V_{2S} and V_{3A} vein sets. Despite substantial variations in the orientation of S_{0}, the orientation of this quartz-ankerite-arsenopyrite-(pyrite) vein set remains constant throughout the Siguiri district (Figure 25I-25L), and it clearly overprints the first (F_{1S}) and second (F_{2S}) fold generations. Oriented at about 170/35 (V_{3B shallow}) and 160/70 (V_{3B steep}; Figure 25I-25L), the two vein orientations display a hybrid/conjugate geometry (McClay, 1992). These geometries are formed by conjugate V_{3B} shallow veins or conjugate V_{3B steep} veins. In addition, both these geometries mutually cross-cut each other (Figure 19F, 22E, 22F, 23E, 23F and 28F-28H). The veins commonly display crack-seal textures typical of orogenic-type gold deposits and consistent with fault-valve behavior (Sibson et al., 1988, 1998). The vein set with the steep orientation is the most prominent in the Siguiri district and was mined by artisanal miners within and outside of the district. Higher densities of these veins develop around all four orientations of discrete and incipient faults described for the earlier deformations and represent the main ore shoots in the district (Figure 23C, 23D, 28A and 28I). Conjugate analyses on the V_{3B} veins, together with the fault pattern geometry mapped in the pits, indicate that the stress-field associated with D_{3S} varied between NW-SE extensional and NE-SW compressional with related strike-slip deformation, which contrasts with the earlier D_{2S} E-W to ESE-WNW compression.

\textbf{D}_{4S}: The third and last fold generation recorded in the district (F_{4S}; Figure 22G) is oriented ENE-WSW to NE-SW. At the outcrop- to deposit-scale, the F_{4S} folds crenulate the F_{2S} folds and fold the V_{3S} veins (Figure 22G, 25A-25D). A penetrative planar fabric (S_{4S}; Figure 26) is axial planar to these local F_{4S} folds. The S_{4S} fabric is a sericite-bearing cleavage that transects the F_{2S} fold hinges in many areas, such as in the Kosise deposit (Figure 17), may have overprinted and erased the S_{2S} fabric and developed strain shadows surrounding arsenopyrite
grains in the selvages of $V_{3B}$ veins (Figure 19H and 19I). Overall, $D_{4S}$ is interpreted to have been associated with a NW-SE compression. The domes and basins, most notable in the Kami deposit, could have developed by overprinting of the $F_{2S}$ N-S folds by the $D_{4S}$ NW-SE compression. The $V_{3B}$ mineralized veins hosted in the domes suggest that the domes developed pre- to syn-$D_{3S}$ veining and thus cannot have formed by $F_{2S}/F_{4S}$ interference. However, $D_{4S}$ may have amplified the domes and basins.

The $S_{4S}$ dip angle and dip direction varies across the Siguiri district, from sub-vertical and ESE- to WNW-dipping in the south, to shallowly SE-dipping in the north. Variations in $S_{4S}$ dip angle and dip direction in the northern part of the district are interpreted to be related to the pre-existing faults and the rotation of cleavage trajectories around these structures, a mechanism described by Dewey et al. (1998).

**Comparison with previous studies**

The deformation events and structural features identified in the Siguiri district can be correlated with those described by Milési et al. (1989, 1992), Miller et al. (2013), and Steyn (2012). This correlation is summarized in Figure 24 and indicates that $D_{1S}$ correlates with the $D_1$ N-S compressional event recognized by these workers. Milési et al. (1989) constrained the timing of this deformation event between ca. 2100 and 2090 Ma and related it to the thrusting of rocks of the Paleoproterozoic Baoulé-Mossi domain onto those of the Archean Kenema-Man domain. No gold mineralization was found to be associated with this first deformation event by these authors.

The folds developed during $D_{2S}$ and the $D_{3S}$ ductile-brittle structures correlate with the second Eburnean tectono-metamorphic phase defined by Milési et al. (1989) and Steyn (2012) as $D_2$, and dated between 2091±33 and 2074±7 Ma in southern Mali (Liégeois et al., 1991). By comparison, Miller et al. (2013) recognized two different deformation events, $D_2$ and $D_3$, both E-W to ENE-WSW compressional events, with $D_3$ being the event associated with formation of
gold-bearing veins. The interpretation proposed by the latter authors therefore best matches
the one proposed in the present study.

The last phase of deformation recognized in the present paper, $D_{4S}$, was recognized as
$D_3$ by Milési et al. (1989) and interpreted to occur at ca. 2075 Ma. Miller et al. (2013) also
recognized this event, defined as $D_4$, a NW-SE compression. Regionally, and in many other
areas of the craton (Ashanti, Prestea, Kalana; Milési et al. 1992), this deformation event is
typically associated with the main phase of gold mineralization. However, based on the
structural and petrographic observations presented in this paper, this event does not appear
to be associated with substantial ore formation in the Siguiri district.

Finally, Steyn (2012) recognized a last deformation event, termed $D_3$, associated with
an E-W extension and which was not associated with gold deposition. This deformation event
was not recognized by the present study, Milési et al. (1989, 1992), or Miller et al. (2013), but
may correspond to late post-orogenic collapse.

Mineralization

Observations from the five key deposits highlight two main styles of gold
mineralization in the Siguiri district (Figure 19-23 and 28). Gold mineralization is either
disseminated or vein-hosted (Figure 28A). Both styles of mineralization exhibit carbonate
alteration that is typically developed as millimeter-scale siderite nodules in shale or bleaching
in greywacke (Figure 28K), and further albitization of earlier albitized host rocks.
Figure 28: Summary figure of the different controls on $D_{35}$ mineralization present in the orogenic gold deposits of the Siguiri district. Kintinian Formation in dark grey, Fatoya Formation in light blue, Balato Formation in light grey. Shale beds represented in dark blue. Veins in red. Discrete shear zones in white. Map views indicated by a north arrow.
The disseminated mineralization, specific to the Sanu Tinti deposit (Figure 28A-28C), is hosted in porous conglomeratic beds and characterized by corroded and fractured pyrite with gold, chalcopyrite, and galena filling the fractures. The timing of the Sanu Tinti disseminated mineralization is constrained between the formation of the overprinting S_{4s} cleavage and the timing of the reverse fault along which the disseminated pyrite has developed; this fault is reactivated in early-D_{3s}, but most likely have formed during D_{2s}.

The vein-hosted gold mineralization style, common at the Kosise deposit, forms the bulk of the gold endowment in the Siguiri district (Figure 28A and 28D-28K). This style of mineralization is associated with the V_{3A} and V_{3B} vein sets. The V_{3A} veins typically contain abundant free gold in fractures in pyrite. These veins are associated with local carbonate alteration of the host rock, developing millimeter-sized siderite nodules within a few centimeters to meters of the veins. This vein set typically cross-cuts the already albitized host rock and locally contains minor albite. The V_{3B} quartz-ankerite veins contain arsenopyrite and pyrite, and have siderite nodules locally along the selvages (Figure 28H). Native gold occurs in the quartz (Figure 19E) or at the contact between quartz and ankerite.

There is a first-order structural control on both the disseminated and vein-hosted gold mineralization in the Siguiri district, in that both occur within the 10-20 m of the four groups of faults mapped in this study (Figure 28A, 28I and 28J). These structures, which cut the F_{2s} folds (Figure 28J and 28K), are expressed differently across the Siguiri district. Most of these are expressed as damage zones surrounding incipient faults, such as in the Kosise deposit (Figure 28J), and are delineated by zones of dense veining (Figure 28A and 28I). The damage zones are cryptic and therefore difficult to recognize in the field and from geophysical data, but based on their regular orientation, could be linked to fundamental deeper structures (Figure 28I). However, some are represented by discrete shear zones, in some cases via bedding-parallel reverse movement (Figure 28A and 28J) or as distinct cross-cutting faults (Figure 28B).

Antiformal structures and competency contrasts have a second-order control on gold mineralization in the Siguiri district. High vein densities are commonly focused in antiformal
closures, such as in the Kami and Sintroko deposits (Figure 21E, 23A, 28A and 28D). Fluid flow was focused into antiformal fold hinges, with shale-rich units acting as local seals, such as in the Sintroko PB1 deposit (Figure 23A and 28K). Whereas the V_{38} veins have the appearance in section of occurring along the F_{25} axial plane, they are actually oblique to this trend and cut the F_{25} axial planes (Figure 28K).

As initially suggested by Steyn (2011), competency contrasts also play an important role in the focusing of mineralizing fluids and on the location of the ore shoots through strain partitioning. At the scale of the Siguiri district, the more competent rocks of the Fatoya Formation host most of the deposits and this reflects the fact that this unit preferentially fractures rather than forms a penetrative cleavage. At a deposit scale, veining develops more intensely in competent greywacke (Figure 21A, 23A, 23C, 23D, 28A, and 28K). Competency and permeability contrasts also played an important role in the formation of the Sanu Tinti deposit, where gold-bearing sulfides are disseminated in the conglomerates of the Kintinian Formation, rather than in the less permeable greywacke and shale of the Fatoya Formation (Figure 28A-28C). Compared to the general characteristics described by Dube and Gosselin (2007), the styles, controls, and late timing of gold ore (syn-D_{35}) with respect to the main compressional event (D_{25}), is consistent with an orogenic gold style of mineralization in the Siguiri district.

**Finite strain analysis from D_{25} to early-D_{35}**

Based on the observed structural elements, their relative timing, and finite strain analysis, stress-field reconstruction was undertaken for the Siguiri district for the syn-D_{25} ductile and early- to late-D_{35} brittle part of the deformation history. The finite strain analysis of the syn-D_{25} ductile part of the deformation history was based on the geometry of the F_{25} folds and the orientations of their axial planes that slightly undulate around a N-S to trend. Finite strain analysis for the D_{35} brittle deformation history was based on fault and V_{38} conjugate vein orientations, assuming that locally the Andersonian fault and Mohr-Coulomb failure models
prevailed at the time of faulting and that all $V_{3B}$ conjugate veins were not following pre-existing structures. In the case of veining, instantaneous deformation is assumed and the strain ellipsoid derived from the finite strain analysis is interpreted to represent the stress ellipsoid. The orientation of $\sigma_1$ was therefore reconstructed as bisecting the acute angle between two conjugate veins, whereas $\sigma_2$ lies at their intersection and $\sigma_3$ bisects the obtuse angle of the conjugate (Anderson, 1951; McClay, 1992). This analysis was based only on the $V_{3B}$ conjugate sets because data from the $V_{3A}$ vein set were insufficient.

The globally N-S trending $F_{25}$ fold axial planes were interpreted to highlight $D_{25}$, an E-W compressional event associated with a horizontal main stress axis ($\sigma_1$) and a vertical $\sigma_3$ or overburden pressure (Figure 29A). This stress-field is compatible with the mapped N-S reverse faults and with the E-W normal faults. In this model, $D_{25}$ E-W compression forms $F_{25}$ folds with N-S trending axial planes, N-S reverse faults, and local N-S trending extension accommodated by E-W normal faults. However, the later strike-slip structures that transect the $F_{25}$ folds and also control $V_{3S}$ veining, such as the NE-SW dextral shear zone in the Kosise deposit, require $\sigma_3$ to have been horizontal. We interpret that from $D_{25}$ to $D_{35}$ there was a switch in the orientation of $\sigma_3$ from vertical to low angle. This change is thought to be responsible for the formation of the dextral NE-SW shear zones, sinistral WNW-ESE faults, and E-W normal faults. The $V_{3S}$ veins are interpreted to be part of this event. The stress switch between $D_{25}$ and $D_{35}$ may also have occurred within a single deformation event or the strike-slip faults may have developed in a second deformation event that post-dated $D_{25}$ E-W compression, but predated the development of $V_{3B}$ veins. In the first model, the stress switch is considered to be a continuation of $D_{25}$ E-W compression, whereas in the second alternative model, the main stress axis orientations define two distinct deformation events separated in time.
Transpressional model for the Siguiri District

Transpression is commonly associated with oblique plate convergence and typically accommodates fault movements on one or on a series of reverse dextral or sinistral faults to form “flower structures” (Figure 30A; Dewey et al., 1998; Fossen and Tikoff, 1998). In the Siguiri district, such structures were not observed. Instead, strike-slip and dip-slip movements were accommodated along the four different oriented faults of the district.

Field data from the Siguiri district indicate that dip-slip movement, or a pure shear component, was accommodated by the N-S reverse faults that border the low-strain central part of the Siguiri district, which is underlain by rocks of the Fatoya Formation. Strike-slip movement, or a simple shear component, was accommodated by the NE-SW dextral shear zones and the WNW-ESE sinistral shear-zones. The E-W normal faults have a geometry consistent with local N-S extension (Figure 30C) and also acted as relay normal faults between the strike-slip structures. Based on the fault configurations and their coeval movements, we
interpret strain decoupling as the mechanism responsible for the simultaneous strike-slip and dip-slip components on separate structures. This type of geometry is characteristic of decoupled transpression (Figure 30B and 30C).

Figure 30: Idealized block models of different types of transpression (modified from http://maps.unomaha.edu/) and faults relationships during transpression. A) Classic flower structure (Sanderson and Marchini, 1984) showing a coupling between structures accommodating pure and simple shear. Thick black arrows represent the orientation of sigma 1, the main principal stress axis, here in compression; B) Block model of an idealized decoupled transpression. Pure and simple shear are accommodated along distinct reverse faults and strike-slip faults, respectively. Thick black arrows as for A); C) Simplified map view of the decoupled early-D\textsubscript{3}S transpression observed in the Siguiri district. Formation and deposit colors as in Figure 17.
The change from syn-D<sub>2S</sub> compression (σ1 > σ2 > σ3; Figure 29A) to early-D<sub>3S</sub> transpression (Figure 29B) may be linked to a progressive increase in the overburden pressure (σ3), or to an increase in the amount of NW-SE extension due to changes in far field stresses. Either of these processes is interpreted to have caused a stress switch that rendered σ3 approximately equal to σ2, eventually leading to a change in the σ3 orientation (Figure 29B). This allowed the formation and reactivation of the four different fault orientations.

*Localized stress switches associated with late-D<sub>3S</sub> gold-bearing vein formation*

In addition to the district-scale stress switch from D<sub>2S</sub> compressional to early-D<sub>3S</sub> transpressional deformation, there is evidence for more localized stress switches in the Siguiri district. These have been inferred based on the analysis of individual V<sub>3B</sub> conjugate vein sets developed along faults throughout the district. The V<sub>3B</sub> conjugate vein sets mutually cross-cut each other (Figure 19F, 20C, 23E, 23F, 28A, 28F, 28G and 28I). For this structural analysis, stereograms of the paleo-orientation of σ1, σ2, and σ3 were constructed for each measured conjugate vein set (Figure 31).

*Figure 31: Stereograms of the calculated orientation of the principal stress axes during the late-D<sub>3S</sub> transtension based on conjugate mineralized V<sub>3B</sub> veins. Respectively from left to right: σ1, σ2 and σ3 orientation. Sigma 1 and σ2 orientations vary and plot on the same girdle whereas σ3 orientation remains constant.*

No spatial gradient was observed in the main stress orientations from north to south or east to west throughout the Siguiri district. The main significant finding was that, at the time of veining, σ3 remained consistently sub-horizontal and oriented to the NNW. However, σ1
and σ2 plot along the same WSW-ENE girdle, with an oblique to sub-vertical and a sub-horizontal density maximum, respectively. This unusual feature indicates that the V_{3B} conjugate vein sets varied in orientation from an oblique to sub-vertical σ1 and sub-horizontal σ2, to a sub-horizontal σ1 and oblique to sub-vertical σ2. The first stress-field configuration is characteristic of extension, whereas the second configuration is characteristic of strike-slip deformation. The simplest explanation for this relationship is that at the time of V_{3B} veining, σ1 and σ2 were of similar magnitude (e.g., a high stress-shape ratio; Figure 29C) and could easily change their orientation along the same WSW-ENE girdle. This occurred while the orientation of σ3 remained consistently sub-horizontal and oriented to the NNW. Such a stress-field configuration is indicative of transtensional deformation during V_{3B} veining (Figure 29C). The change in stress-shape ratio from early-D_{3S} transpression, where the coeval movement of dip-slip and strike-slip faults indicate that σ2 ≈ σ3 (low stress-shape ratio; Miller and Wilson, 2004; Figure 29B), to syn-V_{3B} late-D_{3S} gold deposition (with σ1 ≈ σ2; Figure 29C) is interpreted to have resulted from the joint reduction of the maximum stress (σ1) and further increase in overburden thickness (σ3 switches to σ2). Alternatively, this change in stress-shape ratio may also be explained by a joint reduction of the maximum stress (σ1), and of the intermediate and minimum stresses (σ2 and σ3) through erosion and uplift. However, this makes for a more complex geological history and a much later timing of gold mineralization during the evolution of the Eburnean orogeny. This occurred at an early stage of the D_{3S} transpressional event when all fault orientations were active as conduits for the mineralizing fluids (Figure 29B and 29C).

**Stress-switches – precursors or triggers to gold deposition?**

Gold deposition during the waning stages of the progressive D_{2S}/D_{3S} deformation is temporally associated with the transtensional regime. This reflects the greater ease for overpressured fluids to open fault-fracture meshes during transient extensional/transtensional events amidst a protracted and longer compressional/transpressional cycle (Sibson, 2013). The transient events of stress switch were interpreted in the Siguiri district to be linked to the
reduction of the deviatoric stress tensor and require a major reduction of differential stress (early-D\textsubscript{3S} and syn-V\textsubscript{3Sa}/late-D\textsubscript{3S} stress switches). Fluids became mobile through this process, permitting fault reactivation, hydraulic fracturing, and fault-valve behavior responsible for gold mineralization. Also with the near-isotropic stress field, active fluid pathways become less permeable and allow buildup of high fluid pressure, triggering pulses of mineralizing fluids (fault-valving; Sibson et al., 1988, 1998) in vertical "exit conduits" (e.g., Miller et al., 1994; McCuaig and Hronsky, 2014). It is thus proposed that late-orogenic decreases of both the differential stress and deviatoric stress tensor are required precursors for the initiation of stress switches and the formation of orogenic gold deposits.

The transient stress switch phenomena may be envisaged as a non-physical barrier to fluid flow during a prolonged phase of deformation. Prior to the switch, fluids are stored under high pressure in the rock mass and fluid mobility and veining are minor. When the switch occurs, a stress threshold is overcome allowing the barrier to be breached and fluids to migrate and form an organized vein network at the district- and deposit-scale, whereas the expression of mineralization can vary at the outcrop scale (vein-hosted versus disseminated).

**Geodynamic interpretation and drivers of stress-switches**

The different stress switches in the Siguiri district may have a local control, including continuous local overburden buildup, overburden removal associated with uplift, fault dynamics along structural irregularities, or earthquake focal behavior dynamics, or a regional-scale mechanism, such as plate convergence rate drop (Beroza and Zoback, 1993; Goldfarb et al., 2001; Upton and Craw, 2013). However, stress switches have been documented in many other orogenic gold systems around the world, including Archean examples (Bouiller and Robert, 1992; Holyland and Ojala, 1997; Nguyen et al., 1998; Goldfarb et al., 2001; Thébaud et al., 2013; McCuaig and Hronsky, 2014). In the Birimian of West Africa, stress switches have been recognized as triggers for formation of several gold deposits (Ashanti, Sadiola, Loulo, and possibly Morila: Allibone et al., 2002a; McFarlane et al., 2011; Lawrence et al., 2013a; Masurel
Mineralization in all these deposits relates to a transient episode in the Eburnean orogenesis between ca. 2080 Ma and 2070 Ma (Lawrence et al., 2013b), referred to as the “late-orogenic” phase by Milési et al. (1992). This timing suggests that the stress switches responsible for the bulk of gold mineralization in the Siguiri district, occurring between the early-D₃₅ transpression and the syn-V₃₈ (late-D₃₅) transtension, have been caused by a regional mechanism. Such a regional mechanism may have been driven either by far-field stress variations or body forces. Variations in the regional far-field stress, as documented in Goldfarb et al. (1991), Allibone et al. (2002b), Blewett et al. (2010), and Upton and Craw (2013), arise from a transient alteration of an ongoing geodynamic process, such as the modification of the collision rate, an overall change in plate motion (Fig. 9 from Goldfarb et al., 2005), or the sudden rise of magma from a hot spot (Idnurm, 2000; Goldfarb et al., 2001), whereas variations in body forces are commonly linked to readjustments of topographic highs or lithospheric delamination and subsequent uplift (Rey and Houseman, 2006).

Based on the regional extent of the stress switches identified in Siguiri and throughout the remainder of the West African Craton, we propose that the dominant stress drivers affecting the district evolved from a far-field stress dominated to a body forces dominated environment. In a far-field stress dominated environment, such as during terrane accretion and orogenic deformation, the local stress-field is controlled by the regional stress-field orientation, such as caused by motions along a plate boundary. In a body forces dominated environment, controls on the stress-field orientation can either be regional processes, such as lithospheric delamination followed by an uplift, or more local processes, such as readjustment of topographic highs. The progressive evolution from a far-field stress dominated to a body forces dominated environment, with the local expression in the Siguiri district changing from the early increase in overburden pressure linked to terrane accretion during the Eburnean orogeny, to the late syn-gold transtensional deformation linked to further increase in overburden pressure or erosion and uplift, is responsible for the reduction of the deviatoric component of the stress tensor (e.g., Engelder, 1994).
Conclusion

The clastic sedimentary rock-hosted orogenic gold deposits of Siguiri, in northeastern Guinea, are primarily hosted in the greywacke of the Fatoya Formation and to lesser extents in the shales, siltstones, and conglomerates of the adjacent Balato and Kintinian Formations. The district has been the site of a protracted and polyphase deformation divided into four local deformation stages (D$_{1S}$ to D$_{4S}$), all of which are attributed to Eburnean orogenesis. The D$_{1S}$ was a cryptic N-S compressional event. The main deformation event, D$_{2S}$, was an E-W to ENE-WSW directed compressional event responsible for the bulk of the deformation affecting the Siguiri Basin metasedimentary rocks. The D$_{3S}$ represents a progressive evolution of D$_{2S}$ compression into an E-W transpressional event, evolving into a transient period of NNW-SSE transtension. This latter episode of deformation is associated with the bulk of veining observed in the Siguiri district and is also the main stage of gold deposition. The last deformation event, D$_{4S}$, was a NE-SW compressional event that created a penetrative cleavage overprinting D$_{3S}$ gold-bearing veins in all rock units.

The orogenic gold mineralization in the Siguiri district is associated with two mineralization styles: a dominant vein-hosted style and a minor disseminated style of mineralization. The earlier type of veins includes gold-rich, pyrite- and ankerite-bearing brecciated veins proximal to NW-SE structures and crosscutting quartz-carbonate-arsenopyrite conjugate veins. The second, and most common vein type, is preferentially developed along four orientations of discrete faults or incipient structures, including N-S to NNE-SSW reverse faults, NE-SW to ENE-WSW dextral shear zones, E-W normal faults, and WNW-ESE sinistral shear zones. The disseminated style of mineralization also develops along these structures, when they intersect favorable lithologies such as the Sanu Tinti deposit conglomerates. These structures may represent the local expression of more fundamental and deeper structures that control the location of the Siguiri district within the Siguiri Basin.

Based on finite strain and conjugate vein analysis, the veining and gold mineralization are interpreted to have culminated late during the D$_{3S}$ progressive deformation event, as the
local stress-field was switching in response to the waning regional maximum stress. The stress switches documented in this study have been widely recognized to happen at 2080-2070 Ma across the whole West African Craton and are not restricted to the study area. The switches documented in this paper are interpreted to be related to the lowering of both the deviatoric stress and of the differential stress, and are viewed as a precursor or trigger for rapid fluid flow and orogenic gold mineralization.

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CHAPTER 4: PAPER THREE

MINERALISATION FOOTPRINTS AND REGIONAL TIMING

OF THE SIGUIRI OROGENIC GOLD DISTRICT (GUINEA, WEST AFRICA)

The following paper focuses on deposit to microscopic scale observations and presents the petrographic and geochemical characteristics of the Siguiiri district and of its gold mineralisation.

This study is based on field observations, drill core logging, petrography, geochemistry and in situ analyses by LA-ICP-MS of sulphide minerals acquired in three key deposits of the Siguiiri district. For each deposit, a log, a cross-section and numerous polished thin-sections are presented.

Based on this work, gold mineralisation characteristics were found to be consistent across the different deposits making the Siguiiri district. Gold mineralisation in the district was found to be polyphase and to have occurred mainly during D₃s, but was interpreted to have also occurred during D₄s deformation. The timing of gold mineralisation in the Siguiiri district is also constrained in this study and compared with gold mineralisation events from other orogenic gold deposits of the West African Craton. This comparison indicates that gold mineralisation in the Siguiiri district is coeval with gold events in numerous other orogenic gold deposits from the West African Craton but that a latter timing of gold mineralisation can also be recognized across the Craton. This study hence suggests that latter gold mineralisation than that recognized in the Siguiiri district could be found elsewhere in the Siguiiri Basin.
This chapter will be submitted to Mineralium Deposita and is hence formatted accordingly. It was revised a number of times by all co-authors.
Mineralisation footprints and regional timing of the Siguiri orogenic gold district (Guinea, West Africa)

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Abstract:

Siguiri is a world-class orogenic gold district hosted in the weakly metamorphosed Upper Birimian to Lower Tarkwa Group sediments of the Siguiri Basin (Guinea). The district is characterized by a protracted deformation history associated with four main deformation events: D₁ₛ is a N-S compression; D₂ₛ is an E-W compression progressively evolving into an early-D₃ₛ transpression and then into a late-D₃ₛ NNW-SSE transtension, and D₄ₛ is a NE-SW compression. Field observations, petrography and chemical analyses applied to three key deposits of the Siguiri district (Bidini, Sintroko PB1 and Kosise) suggest a polyphased hydrothermal history that can be subdivided into four distinct hydrothermal events. The first hydrothermal event is associated with the development of barren bedding-parallel and en-echelon V₂ₛ quartz-dominated-(pyrite) veins. The second hydrothermal event is characterised by the development of V₃₄ₛ pyrite-ankerite veins late during D₃ₛ. Laser ablation data show that this vein set contains an anomalous gold content of up to 43.3 ppm locked in its pyrite crystal
lattice, representing a minor first gold mineralisation event. The third and most prominently
developed hydrothermal event, also represents the second and principal gold mineralisation
event to develop late during D_{3S} deformation. This mineralisation event is associated with two
distinct mineralisation textures. The first texture is best exposed in the Kosise deposit and is
characterised by gold bearing quartz-ankerite-arsenopyrite conjugate V_{3B} veins. Although the
bulk of the gold is hosted in native gold grains in V_{3B} veins, LA-ICP-MS analyses show that gold
can also be found locked into the arsenopyrite crystal lattice (up to 55.5 ppm). The second
mineralisation texture is best expressed in the Sanu Tinti deposit and consists of disseminated
barren pyrite hosted in a polymict conglomerate.

The second and third hydrothermal events are both structurally controlled by a series of
early-D_{3S} N-S, NE-SW, WNW-ESE and E-W sub-vertical incipient structures expressed as
damage zones of higher V_{3S} vein density. A composite geochemical cross-section across
damage zones from the Kosise deposit indicates that gold mineralisation in the Siguiri district is
associated with enrichments in Ag, Au, As, Bi, Co, Mo, (Sb), S, Te and W relative to background.
Geochemical variations associated with the ore shoots in the Siguiri district are consistent with
petrographic observations and highlight an albite-carbonate-sulphide-sericite alteration
system.

The fourth and last hydrothermal event is associated with the development of a late
penetrative S_{4S} cleavage during D_{4S} deformation. This late deformation event overprints all pre-
existing hydrothermal events and is associated with the deposition of free gold, chalcopyrite
and galena along fractures in V_{3A} pyrite and V_{3B} pyrite and arsenopyrite.

Mineral and geochemical footprint and timing of the gold events in the Siguiri district, when
compared with other deposits of the West African Craton, highlight the synchronicity of gold
mineralisation in Siguiri (syn-D_{3S} and syn-D_{4S} events) with other events of gold mineralisation in
this part of the Craton, such as the early Au-Sb-Bi-(Te-W) mineralisation at the Morila deposit
in Southeast Mali.
Keywords: West Africa, Siguiri, orogenic gold, laser ablation, geochemistry, timing, polyphase, targeting

Introduction

Orogenic gold deposits typically encompass a wide variety of host rocks, metamorphic facies, mineral assemblages and textures, with variations in some cases observed within a single deposit (Goldfarb et al., 2005; Robert et al., 2005; Groves et al., 2003). Finding the footprint of orogenic gold mineralisation therefore represents a great challenge for explorers (e.g. Groves et al., 2000; Neumayr et al., 2008). However, as the geochemical and petrological footprints of orogenic gold deposits are more extensive than the ore zone itself (Eilu and Mikucki, 1998; Kishida and Kerrich, 1987), characterisation of mineral alteration assemblages at the deposit scale provides the exploration geologist with useful vectoring tools for targeting (Eilu and Groves, 2001; Eilu et al., 1999). With the development in recent years of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) techniques and associated low detection limits, studies on the characterization and quantification of trace elements in sulphides associated with orogenic gold deposits have become more common (Large et al., 2011; Large et al., 2012; Pitcairn et al., 2006). These studies typically focus on the use of LA-ICP-MS data acquired on sulphides to resolve the controversial source of mineralising fluids (Groves et al., 2003; Tomkins, 2013, Large et al., 2011). However, trace element signatures of sulphides can also be used to distinguish between different sulphide generations attesting of a complex polyphase hydrothermal history (Zhao et al., 2011).

The wide diversity of gold mineralisation types recorded in the West African Craton such as intrusion related gold (McFarlane et al., 2011), orogenic gold (Lawrence et al., 2013a; Fougerouse et al., in press; Allibone et al., 2002; Oberthür et al., 1998), paleoplacers (Hirdes and Nunoo, 1994; Davis et al., 1994), Cu-Au porphyry (Béziat et al., 2013), renders essential the detailed petrographic and geochemical characterisation of a deposit to resolve its nature and footprint. In turn, this footprint can become a backbone for exploration strategies.
This study focuses on characterisation of the mineral assemblages and mineralisation in three key deposits of the world-class orogenic gold Siguiri district (Guinea, West Africa) and its geochemical and petrological footprints. The Siguiri district is the only large (> 50 t Au) orogenic gold deposit found in the Siguiri Basin, one of the largest sedimentary basins of the West African Craton. As such, the Siguiri district provides a unique opportunity to characterise the alteration haloes associated with gold mineralisation found in the Basin. Laser ablation data are used to constrain the relative timing of the different generations of pyrite observed, allowing the creation of a district-scale paragenetic sequence, which serves to highlight the polyphase nature of gold mineralisation in the Siguiri district. Comparison between the timing of the main gold mineralisation event in the district with events from other orogenic gold systems of the West African Craton can elucidate the temporal patterns of mineralisation on the regional scale, with implications for prospectivity.

**Geological context**

The Siguiri district is located in the north-western part of the Baoulé-Mossi domain, in the West African Craton (Lebrun et al., in press 2016; Lebrun et al., 2015; Chapter 2 and 3). The district sits in the sedimentary Basin of Siguiri, Guinea (Figure 32). Mineralisation is hosted by three sedimentary formations (Figure 33), all metamorphosed to sub-greenschist facies. To the east, the Balato Formation is dominated by fine-grained pelitic sediments, such as shale and siltstone. It is overlain by the Fatoya Formation, which spreads in the centre of the district and is dominated by coarser sediments, mainly greywacke and sandstone beds. The Kintinian Formation, to the west, overlies the Fatoya and is characterised by very fine grained shale with abundant centimetric interbeds of limestone and at least two decametric to hectometric interbeds of conglomerate. The three formations have been dated at ca. 2115 Ma (Upper Birimian) and the Kintinian Formation is interpreted to be part of the Lower Tarkwa Group (Lebrun et al., 2015; Chapter 2).
Four deformation events have been recognised in the Siguiri district (Lebrun et al., in press 2016; Chapter 3). The first event, $D_{1S}$, is characterised by E-W folds and a discreet shallow dipping axial planar $S_{1S}$ cleavage. It was interpreted as the product of N-S compression. The second event, $D_{2S}$, is responsible for the bulk of the deformation and for the structural grain observed in the Siguiri Basin. The $F_{2S}$ folds crenulate $F_{1S}$ folds at a district scale and develop type 1 fold interference patterns (as defined by Ramsay and Huber, 1987) at a deposit scale. The $D_{2S}$ event is associated with W-verging folds, the axial plane of which varies from NNE-SSW to NNW-SSE in orientation. The plunge of the $F_{2S}$ fold axes varies from sub-vertical in the Balato Formation, to almost sub-horizontal in the Fatoya Formation. No axial planar $S_{2S}$ cleavage was found to be associated with this event, which was interpreted to be due to a
possible later overprint and erasure by the penetrative $S_{4S}$ fabric (Lebrun et al., in press 2016; Chapter 3). This second deformation event was interpreted as having been associated with an E-W to ENE-WSW compression associated with N-S thrust faults and E-W normal faults. This deformation event progressively evolved to an early-$D_{3S}$ transtension, characterized by the reactivation of the N-S and E-W faults, and the development of NE-SW dextral and WNW-ESE sinistral shear zones (Figure 33). In the Siguiri district, these structures are typically expressed as sub-vertical incipient structures, represented by discreet damage zones associated with a ten-fifteen meters wide halo of increased vein density, developed during the late-$D_{3S}$ NNW-SSE transtensional event (Lebrun et al., in press 2016; Chapter 3). All structural elements in the Siguiri district were overprinted during the youngest deformation event, $D_{4S}$, which is characterized by local open $F_{4S}$ folds with sub-horizontal NE-SW trending fold axes, affecting late-$D_{3S}$ structures. The $D_{4S}$ event is associated with a penetrative sub-vertical NNE-SSW $S_{4S}$ cleavage, axial planar to the $F_{4S}$ folds at the outcrop scale. This last deformation event was interpreted as having been associated with NW-SE compression (Lebrun et al., in press 2016; Chapter 3). The $S_{4S}$ cleavage parallels the supra-solidus magmatic fabric observed in the pre-to syn-tectonic Maléa monzogranite, which intrudes the Siguiri Basin sediments to the north of the district (Figure 32; Lebrun et al., 2015; Chapter 2).
Figure 33: Form line map of the Siguiri gold district and its gold deposits. Locations of the logged drill holes and areas of interest highlighted in red. After Lebrun et al., (in press 2016); Chapter 3.
Hydrothermal activity in the Siguiri district is mainly characterised by veining developed during D$_{25}$ E-W compression and late-D$_{35}$ NNW-SSE transtension. Veining developed during D$_{25}$ is expressed as bedding parallel and en-echelon V$_{25}$ vein arrays (Figure 34) interpreted to have developed by flexural slip along bedding during F$_{25}$ folding (Lebrun et al., in press 2016; Chapter 3). The V$_{25}$ veins are crosscut by the V$_{35}$ veins developed late during D$_{35}$ transtension along the early-D$_{35}$ faults. Based on drill core observations, two different vein sets were identified: V$_{3A}$ and V$_{3B}$ (Figure 34). The V$_{3A}$ vein set commonly has brecciated textures and varies significantly in orientation across the district (Figure 34C). The second vein set, V$_{3B}$, crosscut both V$_{25}$ and V$_{3A}$ sets but is overprinted by S$_{45}$. The V$_{3B}$ vein set displays conjugate geometries, with individual veins dipping steeply or moderately to the SE. This vein set represents the main source of gold mined in the Siguiri district.
Methodology

Field approach and sampling

Field approach and general sampling

Structural elements and controls on gold mineralisation in the Siguiri district are very consistent from one deposit to the next (Lebrun et al., in press 2016; Chapter 3). Three deposits were identified as representative of the Siguiri district mineralisation: the Bidini, Kosise and Sintroko PB1 deposits (Figure 33).

Sampling was designed to: 1) constrain the paragenesis of the district; 2) characterise the geochemical halo associated with a representative mineralised shear zone; 3) compare the geochemical changes between formations and host rocks, and; 4) compare the sulphide major and trace elements and gold content of each vein generation and hydrothermal events. A total of 37 representative fresh rock samples were collected from Bidini, Kosise and Sintroko PB1 deposits as well as the Kami deposit, hosted in some of the same sedimentary beds than the Kosise deposit (Table 3).

Geochemical sampling

In order to characterise the geochemical variations associated with early-D<sub>3s</sub> mineralised faults, samples were collected along a NW-SE composite section, across a discrete NE-SW dextral shear zone in the Kosise deposit and across a NE-SW shear zone and a bedding-
parallel N-S reverse fault (Figure 35B). The Kosise deposit was chosen because it is hosted in the Fatoya formation, host to most of the deposits (Figure 33), and because its structural framework is relatively simple and well constrained. Veins were trimmed off from all samples to avoid nugget effects. The veins were retained and used to make polished thin sections, for subsequent LA-ICP-MS analyses on their associated sulphides.

Analytical work and data processing

Petrography and mineral chemistry

Optical microscopy, electron microscopy and semi-quantitative analyses were conducted at the Centre for Exploration Targeting (CET) and Centre for Microscopy, Characterisation and Analysis (CMCA) at the University of Western Australia (UWA). Electron Probe Micro-Analysis (EPMA) conducted at CMCA, was used to determine the Fe and As content in the different generations of sulphides. Iron concentrations were later used as internal standards for laser ablation data processing. X-Ray Diffraction (XRD) conducted at CMCA, was used to characterise the modal composition and its variations of the geochemical samples collected in the Kosise deposit. LA-ICP-MS was conducted at Curtin University and was used to provide the missing links between the different textures of the hydrothermal mineral assemblages observed in the Siguiri district.

Whole-rock major and trace element geochemical analyses

Whole-rock major and trace element compositions were measured on each sample in order to identify: 1) the geochemical variations associated with mineralisation in the three sedimentary formations hosting the Siguiri district, and; 2) the main geochemical differences between these formations.

Geochemical backgrounds for the Balato, Fatoya and Kintinian formations were calculated following the cumulative frequency method proposed by Landry et al. (1995), that follows the work conducted by Sinclair (1974, 1991). In addition, anomalous geochemical
variations across the Kosise deposit geochemical transect have been constrained by mass balance calculations following the work by Gresens (1967), MacLean and Barrett (1993) updated by Grant (2005) and further refined by Mukherjee and Gupta (2008), and by López-Moro FJ (2012) in his EASYGRESGRANT method. Least altered samples (Table 3), used for the calculations, were selected based on their distance from mineralised shear zones, visible signs of alteration in hand specimens (e.g. veining, bleaching), the amount of alteration minerals in thin section, and gold grades. Sample BD3 was used to normalise the Kintinian conglomerate samples, sample F was used for the Fatoya Formation shale samples, sample O for the Fatoya Formation greywacke samples, sample SK6 for the Balato shale samples and sample SK4 for the Balato greywacke samples. Since no least altered shale and greywacke could be sampled directly in the Kintinian Formation, Kintinian samples BD1 and BD4 were normalised to a sample of shale and greywacke representative of the Siguiri district. The Fatoya samples F and O were therefore chosen for the normalisation of BD1 and BD4, respectively. Variation in an element $i$ between the altered sample and the fresh sample ($= \Delta C_i$) is considered anomalous when its value relative to the least altered sample ($= \Delta C_i/C_{i0}$) exceeds ±70%.

Results

Bidini

Lithostratigraphy and structure

The Bidini deposit is located in the northern part of the district (Figure 33). It is hosted by the greywacke-dominated Fatoya Formation and is located east of the contact with the Kintinian Formation (Figure 35A).
Figure 35: Simplified structural maps and cross-sections of key deposits from the Siguiri district (location map on Figure 33). A) Sanu Tinti and Bidini; B) Kosise, and; C) Sintroko PB1. Locations of the drill holes and collected samples highlighted. Orthonormal scale (no vertical exaggeration).

Fatoya Formation sediments in the Bidini deposit display various sedimentary features that can be used as way-up indicators, such as: cross-bedding, rip-up clasts and ripple marks. Metre-thick beds of medium grained greywacke and sandstone dominate, however fine alternations of siltstone and shale can also be occasionally found, as well as some black shale layers. In this deposit, the Fatoya Formation is overlying up to 100 m of conglomerate interbeds, intersected in core BDRCDD009 (Figure 35A and 36).
Figure 36: Log of hole BDRCDD009 from the Bidini and Sanu Tinti deposits (location map on Figure 34). The log has been overturned to account for the stratigraphy, the Kintinian formation being younger than the Fatoya formation (Lebrun et al., 2015; Chapter 2). The alteration intensity section displays carbonate alteration in light brown and albitisation in light pink. Way-up indicators (Y) in red are based on graded bedding ripple marks and rip-up clasts. Position of the collected samples reported as coloured disks (conglomerate samples in red, shale in blue and greywacke in orange). Deformation intensity scaled arbitrarily from 0 (no deformation) to 1 (moderate deformation) and 2 (intense deformation). Background level for Au is represented by a shaded area.

These conglomerates are part of the younger Kintinian Formation and outcrop in the Sanu Tinti deposit (Figure 33). They are separated from the Fatoya Formation sediments by a moderately dipping NNE-striking reverse fault (Figure 37F). The conglomerate interbeds are
polymict, clast supported and interpreted to be the product of repeated subaqueous debris flow events (Figure 37E; Lebrun et al., 2015; Chapter 2).

Figure 37: Photographs of the main structural elements from the Bidini and Sanu Tinti deposits. A) Overview of the Bidini deposit. In the foreground, 5 to 20 m-deep holes dug by local villagers are used to reach V3B veins in one of the NE-SW trending high grade zones along which the deposit sits. A second high grade zone is visible on the right (just

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In the Bidini deposit, bedding strikes N-NE on average with multiple small-scale open $F_{25}$ folds. The deposit sits on the hinge of a refolded $F_{25}$ anticline the fold axes of which plunge shallowly to the north and south (Figure 33 and 35A). The $F_{25}$ folds are crosscut by multiple early-$D_{3S}$ sub-vertical incipient structures oriented NE-SW and N-S (Figure 37A). These incipient structures are mainly developed in the centre of the deposit and are expressed as discreet damage zones associated with areas about ten metres wide where the density of mineralised $V_{3B}$ veins increases (Figure 37B; Lebrun et al., in press 2016; Chapter 3). These damage zones can extend up to 300 metres in depth (Figure 35A). Veining in Bidini is dominated by the $V_{3B}$ vein set (Figure 37B and 37C) and some $V_{3A}$ veins. In drill core, $V_{3A}$ veins frequently have brecciated textures and range from a few mm up to 20 cm. In comparison, individual $V_{3B}$ veins typically have antitaxial textures (Passchier and Trouw, 2005) and are only a few cm to 15 cm thick but can extend for up to tens of metres. Supergene alteration has formed a centimetre wide halo of iron oxides around the $V_{3B}$ veins, preserving them from further weathering (darker zone around quartz vein in Figure 37C).

Mineral assemblages and mineralisation

Hydrothermal mineral assemblages in the Bidini deposit display contrasted styles of mineralisation dependant on the host lithology. In the greywacke or shale beds of the Fatoya Formation, hydrothermal activity has formed mineralised veins whereas in the conglomerate of the Kintinian Formation, hydrothermal alteration is disseminated throughout the matrix and clasts of the conglomerate (Figure 34D).

In the Fatoya Formation, mineralisation is controlled by early-$D_{3S}$ N-S and NE-SW damage zones, around which $V_{3S}$ veining develops. Both the $V_{3A}$ and the $V_{3B}$ vein sets were
found in Bidini. The $V_{3A}$ carbonate-pyrite veins show coeval growth of pyrite and minor arsenopyrite. Carbonate in $V_{3A}$ veins is dominantly represented by ankerite and these veins are frequently found associated with a halo of siderite grains overprinting metamorphic sericite. Minor albite can also be found in this vein set. Free gold occurs along fractures in $V_{3A}$ pyrite and is associated with chalcopyrite and galena. The $V_{3B}$ veins typically have rims of ankerite and a core of quartz, and are associated with sulphides. These sulphides are typically located along the selvages or disseminated as haloes of up to a meter thick around the veins, where arsenopyrite is dominant. However, a halo of pyrite can be found instead of, or accompanying, the arsenopyrite crystals. Pyrite associated with $V_{3B}$ veins can occasionally be found pseudomorphosing the siderite grains in the albitised host rock (Figure 38A). In drill core, each vein is typically associated with carbonate alteration of up to a few metres away from the vein and expressed as bleaching, usually related to oxidised ankerite, and/or by millimetre-sized siderite grains. The mineralised damage zones, highlighted by the $V_{3B}$ veins, therefore form widespread siderite-ankerite alteration haloes of up to a hundred metres width (e.g. BDRCD009; Figure 36). Native gold is found in the quartz or at the contact between quartz and ankerite in the $V_{3B}$ veins. Free gold can also be found in $V_{3B}$ arsenopyrite fractures, in association with chalcopyrite and galena (Figure 38B). The $V_{3B}$ veins are overprinted and folded by the $S_{45}$ cleavage (Figure 37C), which commonly develops strain shadows of pyrite, chalcopyrite, quartz and ankerite around the $V_{3B}$ arsenopyrite (Figure 38E). Pyrite and chalcopyrite can also be found along the $S_{45}$ penetrative cleavage (Figure 37D).
Figure 38: Microphotographs of A) siderite grains being pseudomorphosed by $V_{38}$ pyrite; B) Fractured arsenopyrite in a $V_{38}$ vein showing gold-chalcopyrite-(galena) infills; C) Disseminated $V_{38}$ pyrite fractured and showing gold-chalcopyrite infills; D) Sanu Tinti style $V_{38}$ pyrite overprinted by chalcopyrite veinlets; E) $V_{38}$ arsenopyrite showing
quartz strain fringes associated with the development of the $S_{45}$ penetrative cleavage. This cleavage is also responsible for the preferential orientation of the sericite and the strain shadows developing around the siderite grains; F) Textural similarities between $V_{3A}$ pyrite and arsenopyrite suggesting their coeval development; G) backscattered electron image of $V_{3A}$ pyrite displaying As-rich and As-poor growth rings and being crosscut by gold infilled fractures; H) hematite inclusions in $V_{3A}$ pyrite associated with gold. Hematite laths seem to follow the pyrite crystal lattice whereas gold displays triangular textures typical of open space infill (Taylor, 2010). Aspy: arsenopyrite, Au: gold, Ccp: chalcopyrite, Gn: galena, Hem: hematite, Py: pyrite, Qtz: quartz, Ser: sericite, Sid: siderite.

Hydrothermal mineral assemblages in the underlying Kintinian conglomerate have very distinct textures. The gold-bearing mineral assemblage is dominated by disseminated sulphides, largely pyrite, developed along the NNE-striking hangingwall of the conglomerate and exhibits little to no $V_{3B}$ veining (Figure 34D). Minor tourmaline, chalcopyrite and gold were found associated with the disseminated pyrite. Free gold was commonly found as inclusions or within fractures in the pyrite and associated with chalcopyrite (Figure 38C). Gold bearing pyrites are crosscut or have strain shadows of chalcopyrite, hematite and chlorite (Figure 38D). The hematite-chlorite association was also found with magnetite (pseudomorphosed by pyrrhotite) and titanite (also pseudomorphosed by pyrrhotite). High-grade mineralisation zones are associated with pyritisation, carbonate alteration dominated by ankerite and intense albitionisation.

**Sintroko PB1**

**Lithostratigraphy and structure**

Sintroko PB1 is one of the southernmost deposits of the Siguiri district and is hosted by the Balato Formation (Figure 33). Rocks at Sintroko PB1 consist of centimetre- to decimetre-thick beds of shale-siltstone interlayered with medium to fine-grained greywacke and sandstone beds. A distinctive 10 to 20 m thick black shale layer runs through the centre of the deposit (Figure 35C and 39A).
Figure 39: Photographs of the main structural elements found in the Sintroko PB1 deposit. A) Overview of the deposit. The main ore shoot found in this deposit follows the black shale layer (left) and cuts across the $F_{35}$ sub-vertical fold found on the eastern side of the deposit (right). B) Photograph of an ore shoot, expressed as a sub-vertical damage zone (area between blue dashed lines) associated with dense $V_{1h}$ veining. C) Another example of a...
Bedding is sub-vertical in this deposit. In the central black shale area, bedding is oriented NNW-SSE whereas the eastern and western sides of the deposit show open \(F_{25}\) folding with sub-vertical fold axes. Isoclinal \(F_{25}\) folds with vertical fold axes are also commonly observed (Lebrun et al., in press 2016; Chapter 3). The \(F_{25}\) folds are associated with bedding-parallel \(V_{25}\) veins typically \(\sim 5\) cm thick and locally up to tens of centimetres thick. These veins can extend over several tens of metres along bedding. En-echelon \(V_{25}\) veins in Sintroko PB1 are commonly thinner than the bedding-parallel variation in \(V_{25}\), and rarely exceed \(4\) cm in thickness. In cross-section, en-echelon vein arrays extend over \(2-3\) m, but individual veins typically extend for a maximum of \(50\) cm only. The \(F_{25}\) folds and associated \(V_{25}\) veins are crosscut by an early-\(D_{3S}\) NE-striking sub-vertical shear zone sub-parallel to the central black shale unit (Figure 35C). This shear zone, the most visible structural element in the deposit, is accompanied by two other sub-vertical NE-SW damage zones that cut across bedding. These damage zones exhibit an increased density of veins (Figure 39B and 39C). The veins associated with these incipient structures are dominated by the \(V_{3B}\) vein set and no \(V_{3A}\) veins were observed in Sintroko PB1. The \(V_{3B}\) vein set commonly has conjugate geometries characterised by NE-SW striking veins dipping either moderately to the SE or steeply to the SE or the NW (Figure 39F).

Mineral assemblages and mineralisation

The hydrothermal mineral assemblages in Sintroko PB1 are hosted in the veins developed in and around the NE-SW shear zone sub-parallel to the central black shale layer (Figure 35C) and NE-SW damage zones. Veining becomes more prominent in more competent units such as greywacke and is refracted in shale beds (Figure 39D). The mineralogy of \(V_{25}\) veins
consists of quartz and minor ankerite. Free gold is hosted within V\textsubscript{3B} quartz-ankerite-sulphide vein and located in the quartz core of the veins or at the contact between the quartz and the ankerite rims. Arsenopyrite, developed in and around the V\textsubscript{3B} veins (Figure 39E) is the main sulphide phase in shale beds whereas pyrite becomes more common in greywacke and sandstone beds. In drill core, high-grade mineralised zones are typically associated with a carbonate alteration halo characterised by disseminated millimetre-sized siderite grains, ankerite and extending up to a couple tens of metres across (e.g. SKRCDD040; Figure 40). Sericite is developed mainly along the S\textsubscript{45} cleavage and pyrrhotite, chalcopyrite and quartz can be found in the strain shadows around V\textsubscript{3B} arsenopyrite (Figure 38E and 39E).
Figure 40 (previous page): Log of hole SKRCDD040 (location map on Figure 35). This log highlights the strong link between brittle deformation, veining, sulphidation and carbonate alteration with gold. The alteration intensity section displays carbonate alteration in light brown and overprinting chloritisation in green. Way-up indicators (Y) in red are based on graded bedding ripple marks and rip-up clasts. Position of the collected samples reported as coloured disks (shale samples in blue, greywacke in orange). Deformation intensity scaled arbitrarily from 0 (no deformation) to 1 (moderate deformation) and 2 (intense deformation).

**Kosise**

**Lithostratigraphy and structure Kosise**

The Kosise deposit is hosted by the Fatoya Formation and is located to the west of the contact with the Balato Formation (Figure 33). Sedimentary beds in Kosise are typically a metre thick and commonly display sedimentary features, such as graded bedding, ripple marks, rip-up clasts as well as loading and cross-bedding structures. These sedimentary features were used as way-up indicators and show that the Fatoya Formation in this deposit is normally graded. Kosise lithostratigraphy is dominated by beds of medium to coarse-grained greywacke and some beds of sandstone can also be found in the north of the deposit. Rare alternations of thin siltstone and shale beds can also be found.

Kosise is located in a F_{2S} syncline oriented N-S with a sub-horizontal fold axis (Figure 35B). This open fold has a vergence to the west (Figure 41A) and presents bedding-parallel and en-echelon V_{2S} veins along both limbs. A number of early-D_{3S} sub-vertical structures crosscut the F_{2S} syncline, including: NE-SW dextral shear zones, a N-S thrust fault developed along the steep limb of the fold, and an E-W normal fault (Figure 41C; Lebrun et al., in press 2016; Chapter 3). Most of the early-D_{3S} structures present in this deposit are damage zones and incipient faults, highlighted only by the increase in vein density developed late-D_{3S} in the first ten-fifteen metres around them (Figure 41B). The two different V_{3S} vein sets (V_{3A} and V_{3B}) were observed around the damage zones, both in the field and drill core. The V_{3A} vein set develops in the first few metres of the damage zones whereas the V_{3B} vein set commonly extends up to fifteen metres across. In the Kosise deposit, the orientation of V_{3A} veins is extremely variable
with individual veins showing brecciated textures. In contrast, $V_{3B}$ veins are conjugate and oriented around 150/40 and 145/70, with common antitaxial textures (Figure 34G).

Figure 41: Photographs of the main structural elements found in the Kosise deposit. A) Overview of the deposit. The northern part of the deposit (centre) hosts a bedding parallel thrust fault that develop intense $V_{3S}$ veining (B). B) Veining developed in the northern part of the deposit. The $V_{3B}$ veins are stratigraphically controlled and mainly hosted in the greywacke and sandstone beds. C) Close-up photograph of one of the rare discrete structures controlling gold grades in the Sigui district, a dextral NE-SW shear zone. Gold grades across this shear zone are
over 100 g/t Au. D) Siderite grains developed around the ore shoots. The sub-vertical S\textsubscript{4S} cleavage overprints these grains.

Mineral assemblages and mineralisation

The XRD analyses on the Kosise samples show that the greywacke host rock is comprised of >40 vol% albite, 7 vol% carbonate (calcite vol% + ankerite vol% + siderite vol%), >5 vol% chamosite (chlorite family), 15 vol% white micas and 27 vol% quartz. In shale beds, chamosite and white mica increase to 8 vol% and 28 vol%, respectively and quartz decreases to 17 vol%. These abundances vary by only a few percent across the ore shoots (Table 3). The V\textsubscript{2S} en-echelon veins crosscut the already albitised and sericitised host rock. In Kosise, these veins are dominated by quartz with rare ankerite and albite. No free gold was observed in V\textsubscript{2S} pyrite. The rest of the hydrothermal mineral assemblages in the Kosise deposit are controlled by the N-S, NE-SW and E-W structures. The deposit sits at their intersection (Figure 35B) and gold grade within some of the shear zones can be greater than 100 g/t (Figure 41C). Similar to Sintroko PB1, vein distribution is also partly controlled by the host rock rheology, with veining becoming more abundant in more competent units (Figure 41B). Artisanal miners primarily excavate the V\textsubscript{3B} veins and ignore the V\textsubscript{2S} and V\textsubscript{3A} vein sets. However, petrography confirms that both V\textsubscript{3A} and V\textsubscript{3B} vein sets carry gold. Ankerite-pyrite V\textsubscript{3A} veins show the early to coeval growth of minor arsenopyrite along with pyrite (Figure 38F) and SEM imaging coupled with qualitative EDS on V\textsubscript{3A} pyrites shows As zoning (Figure 38G) and rare monazite inclusions, less than 20 μm. Gold in the V\textsubscript{3A} pyrites is located in fractures or as inclusions with triangular textures, characteristic of infill (Taylor, 2010). Gold is associated with chalcopyrite and hematite (Figure 38H). As in all other deposits, sulphides associated with V\textsubscript{3B} veins change according to the host lithology with arsenopyrite dominating in shale beds and pyrite modal percentages increasing in greywacke and sandstone beds. Alteration around the ore shoots is characterised by carbonate alteration haloes associated with bleaching typically due to ankerite oxidation and millimetre-sized siderite grains (Figure 41D).
**Whole-rock multi-element geochemistry**

**Baseline geochemistry**

Baseline geochemistry from each three formations hosting the Siguiiri district displays variations in a suite of elements (background values are reported in Table 7 and some, shown in Figure 42). In particular, baseline geochemistry of the Kintinian Formation is associated with increased background concentrations of Ca, F, Ga, Li, Mg, Ni, Sc, Sn, Sr, U, V, W and decreased concentrations of As, Cu, Si and Zr when compared to the Fatoya and Balato formations (Figure 42; Table 7). Baseline geochemistry of the Balato Formation, when compared to those for the Kintinian and Fatoya formations, is associated with a marked increase in Ba, Be, Zn, Zr, minor increases in concentration of Cu, Th, marked decreases in Au, Sb and a minor decrease in W (Figure 42; Table 7). The baseline geochemistry of the Fatoya Formation is associated with increased background concentrations in Na, As, Mo, Te, minor increases in Bi and Si, whereas decreases in Ca, K, Li, S, Sn, Sr can be observed when compared to the Kintinian and Balato formations (Figure 42; Table 7).

**Mineralisation geochemical footprint**

Mass balance calculations and comparisons between least altered samples and altered/mineralized samples of each rock types and in each formation allow for the characterization of the suite of elements enriched or depleted towards the ore zones (Table 8). Overall, geochemical changes towards the ore shoots are characterised by major anomalous increases in Ag, Au, As, Bi, Te and W, accompanied by additional minor increases in Co, Mo, Na/Al (molar), S and Sb and minor decreases in 3K/Al (molar), P, Rb and V, whereas Ca and Mg change widely.
In details, ordered by Formation and then by host rock: in the mineralised Kintinian conglomerate from the Bidini deposit, mineralisation is associated with major increases in Au, Bi, Cu, S, Te, W, Zn, minor increases in Ba, Cr, K, Li and minor decreases in As compared to the least altered conglomerate sample. Geochemical variations linked to mineralisation in the Kintinian Formation shale beds are associated with major increases in Au, Ca, Na, S, Sr, W, minor increases in Mg, Pb, Sb and decreases in Ba, Cu, K and Rb compared to the least altered shale sample from the Fatoya Formation. Geochemical alteration in the Kintinian Formation greywacke is characterised by enrichments in Au, Be, Ca, Cs, F, Li, Mg, S, W and minor
depletions in Cu and Mo. Geochemical variations linked to mineralisation in the Fatoya shale beds from the Bidini, Kami and Kosise deposits are associated with major increases in Au, As, Bi, Mo, Na, S, Te, W, minor increases in Ag, Ca, Cu, Sr and minor decreases in Ba, K, Rb, Zn. Comparison of the geochemical variations between the altered greywacke from the Fatoya Formation and the least altered greywacke from the same formation indicates major enrichments in Ag, Au, As, Bi, S, Te, W, minor enrichments in Co, Mo, Na, Sb and minor depletions in Ba, K, Mg, Rb, Tl, Zn associated with mineralisation, whereas Cu and Ca display minor positive or negative variations. Geochemical variations linked to mineralisation in the Balato Formation shale beds from the Sintroko deposit are associated with major increases in Au, As, Cr, Cu, Na, Ni, Sc, Te, V, W, minor increases in Bi, Co, Ge, Mg, Sr and decreases in Mo, P, Pb and S compared to the least altered shale sample from this formation. Comparison of the geochemical variations between the altered greywacke from the Balato Formation and the least altered greywacke from the same formation indicates major enrichments in Au, As, Ca, Pb, S, Te, minor enrichments in Sb, Sr, Zn and minor depletions in Cu associated with mineralisation.

In addition to these district scale geochemical variations between each Formation and host rock, high-grade mineralised zones in Kosise (some over 100 g/t Au; Lebrun et al., in press 2016; Chapter 3) are associated with a geochemical alteration halo at least 15 metres wide, characterized by an increase towards the ore shoots in: Ag, Au, As, Bi, Co, Mo, Na, S, (Sb), Te and W (Figure 43 and Table 3 and 8). In detail, Au increases from 3 to 8931 ppm, As increases from 50 to 3996 ppm, Bi increases from 0.06 (just above detection limit; \( = 0.05 \) ppm) to 0.97 ppm, Mo increases from 0.3 to 2.3 ppm, Sb increases from 0.6 to 3.2 ppm, S increases from 0.06 to 4.47 ppm, and W increases from 3.5 to 34.9 ppm. Within the same alteration halo around the ore shoot, Cs, (Li), Mg, (Mn), P, Rb, (Sc), (Tl), (V) and (Zn) decrease (Figure 43 and data in Table 3 and 8). Concentrations of Ca display a peculiar behaviour, increasing a few tens of metres away from the main ore shoot. Silicon in the host rock does not show significant variation, due to the removal of all veins from the analysed samples. Saturation indices (molar
ratios) for muscovite (3K/Al) and albite (Na/Al; Kishida and Kerrich, 1987) vary from 0.07 to 0.66 and from 0.26 to 0.84 respectively, and clearly show a respective increase and decrease towards the ore shoots (Figure 43). Collectively these results suggest that regardless of the hosting Formation or lithology, altered rocks in the Siguiri district are enriched in Ag, Au, As, Bi, Co, Mo, (Sb), S, Te and W.
Figure 43: Composite log and geochemical cross-section from the Kosise deposit. Two mineralised zones were identified (around samples J, K, L, M and samples A, B, C, D) and are in proximity to shear zones and a thrust fault (Figure 35B, 41A and 41C). The main mineralised zone (samples J, K, L, M) is associated with typical orogenic gold enrichments in Au-As-Sb-Te and W. Mass balance calculations were conducted for each individual sample and sample O and F were used as least altered greywacke and shale sample, respectively. The composite geochemical cross-sections also show enrichments in Bi, Mo and S around the main mineralised zone (samples J, K, L, M). Ca increases away from the main mineralised zone and is interpreted to represent the reaction front. The fact that Si does not show any variation across the ore shoots is attributed to the removal of the veins in each sample (host rock characterization only). Molar and normalised 3K/Al and Na/Al saturation indices (Kishida and Kerrich, 1987) highlight both mineralised zones. Each geochemical sample was normalised to the corresponding greywacke or shale least altered sample (O and F, respectively). Shaded areas represent a 70% variation in a considered chemical element or species concentration relative to the least altered sample.

LA-ICP-MS and EPMA

Pyrite

Pyrite associated with the V_{25}, V_{3A} and V_{3B} vein sets, with the S_{45} cleavage (syn-D_{45}) and disseminated pyrite hosted in the Kintinian conglomerate were analysed by LA-ICP-MS. Major
and trace element signatures of the V$_{2S}$, V$_{3A}$, V$_{3B}$ and D$_{4S}$ pyrite vary in the Ag-As-Au-Cu-S-Sb-Se-Zr geochemical space (Figure 44F, 44G, 44H and 44J). Major and trace element signatures of pyrite associated with V$_{2S}$ and V$_{3A}$ veins cluster in the high Ag-As-Au-Sb – low Cu-S-Se-Zr part of this geochemical space whereas V$_{3B}$ pyrite, Sanu Tinti conglomerate pyrite and syn-D$_{4S}$ pyrite major and trace element contents cluster in the in the low Ag-As-Au-Sb – high Cu-S-Se-Zr part of this space. This clustering, first noticed when plotting pyrite data from greywacke beds from the Fatoya Formation only, was also observed when considering pyrite hosted in all formations, host rocks and deposits (Figure 44).
Comparison between the major and trace element signatures of pyrite from the Fatoya and Kintinian formations show variations in Co, ranging from below detection limit up to 1962.3 ppm in the Fatoya Formation, and from below detection limit to 32.6 ppm in the Kintinian Formation. Values for Ni range from below detection limit to 1248 ppm in the Fatoya Formation, and from below detection limit to 57 ppm in the Kintinian Formation. Values for Cu range from below detection limit to 3688 ppm in the Fatoya Formation, to 2 ppm and 4393 ppm in the Kintinian Formation. In addition, laser ablation data shows that V$_{3a}$ pyrite hosted in greywacke from the Kosise deposit (Fatoya Formation; Figure 44A) has gold grades up to 43.3 ppm, whereas the other pyrite generations do not reach grades higher than 3 ppm (the three higher values reported on Figure 44E were obtained from gold inclusions). In summary, pyrite from the Fatoya Formation is associated with increased concentrations in As, Au, Co, Ni (and minor Bi, Mn), and a depletion in Cr, Cu, S, Si, Sn, Zr when compared to the major and trace element signatures of pyrite hosted in the Kintinian Formation (data in Table 5). Moreover, the crystal lattice of the different generations of pyrite shares similar Ag/Au and Ni/Co ratios, around 7.5 and 2.81 respectively (Figure 44E and 44I).

**Arsenopyrite**

Arsenopyrite was found associated only with V$_{3b}$ veins. Aside from their differences in major element concentrations, arsenopyrite and all generations of pyrite can also be distinguished when comparing their respective trace element signatures in Bi, Mo, Pb, Sb, Se (and to some extent Co, Cr and Ni). Compared to all generations of pyrite, V$_{3b}$ arsenopyrite is enriched in all these elements (Figure 44F, 44G, 44H and 44J and Table 5).
Concentrations of As (obtained by EPMA) and Sb vary with Au grades in the Balato and Fatoya samples, increasing from ~43.2 wt% to ~46.2 wt% As and from ~125 ppm to ~1600 ppm Sb, respectively. Also, V$_{38}$ arsenopyrite lattice contains significant gold concentrations of up to 55.5 ppm (higher values reported on Figure 44E were obtained on a gold inclusion). The V$_{38}$ arsenopyrite has similar Ag/Au and Ni/Co ratios to all pyrite generations, around 7.5 and 2.81 respectively (Figure 44E and 44I). In summary, whereas no arsenopyrite was found in the Kintinian Formation, arsenopyrite from the Balato Formation shows enrichment in Ag, Co, Cr, Cu, Sb, Ti (and minor Mn) and depletion in As when compared to the arsenopyrite hosted in the Fatoya Formation (Table 5).

Discussion

*Polyphase hydrothermal activity and gold mineralisation*

Field observations of vein cross-cutting relationships, core logging and petrographic descriptions from Bidini, Sintroko PB1 and Kosise, permit the construction of local paragenetic sequences for each individual deposit studied. When compared to one another, the local paragenetic sequences are homogeneous across the Siguiri district and are characterised by four distinct hydrothermal events. These events were correlated in the district-scale paragenetic sequence (Figure 45) summarized below. Together, the laser ablation data (Figure 44) and the general paragenetic sequence of the district, reflect the polyphase character of gold mineralisation in Siguiri and three distinct gold mineralisation events were identified.
The mineralogy of the least altered host rock in the Siguiri district is dominated by plagioclase, quartz and shows moderate to intense sericitisation and albitisation. Minor biotite and chlorite, possibly detrital, were also found in the host rock mineral assemblage as well as numerous detrital zircons.

The first hydrothermal event occurs during D$_{25}$ E-W compression and is characterised by the development of the bedding-parallel and en-echelon V$_{25}$ quartz-(ankerite) veins. The V$_{25}$ veins are associated with minor albite, sericite, pyrite and traces of rutile. These veins do not present significative gold mineralisation and show little development of alteration around their margins.

The second hydrothermal event, occurs late during D$_{35}$ NNW-SSE transtension and is represented by the V$_{3A}$ ankerite-pyrite-(albite) brecciated veins that crosscut the V$_{25}$ veins. The

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*Figure 45: Paragenetic sequence for the Siguiri district.*
V_{3A} veins represent the most proximal expression of V_{3S} veining developed along the early-D_{3S} N-S, NE-SW, WNW-ESE and E-W damage zones. The V_{3A} veins have developed in the core of the sub-vertical structures controlling gold mineralisation. V_{3A} veins are associated with minor sericite, quartz, chlorite, rare monazite and arsenopyrite, pyrrhotite and late chalcopyrite and sphalerite, found in the altered host rock and occasionally in the veins themselves. V_{3A} veins are also characterized by a halo of carbonate alteration and pyritisation. Carbonate alteration is expressed as millimetre-sized siderite grains and bleaching of the host rock typically due to oxidation of pervasively developed ankerite. The V_{3A} vein set also represents the first episode of gold mineralisation recognized in the Siguiri district. Gold was found locked in the V_{3A} pyrite crystal lattice (up to 43.3 ppm Au; Figure 44; Table 5).

The third hydrothermal event also occurred late during D_{3S}, and developed along the ten to fifteen metre-thick sub-vertical damage zones formed early during D_{3S} deformation. This event is mainly characterised by intense V_{3B} quartz-ankerite-arsenopyrite veining and is ubiquitous in the Siguiri district. The conjugate V_{3B} veins moderately to steeply dip to the SE and are associated with minor albite and pyrite. This vein-hosted mineralisation is also characterized by minor sericitisation and carbonate alteration mainly expressed as millimetre-sized siderite grains. The third hydrothermal event is also represented by a distinct disseminated texture, only observed in the Bidini and Sanu Tinti deposits. The disseminated mineralisation texture found in the Kintinian polymict conglomerate is represented by disseminated pyrite, accompanied by tourmaline, rare monazite and traces of late chalcopyrite, sphalerite, hematite and ilmenite. Minor sericitisation and carbonate alteration is also associated with this disseminated mineralisation texture. This disseminated mineralisation shows some degree of structural control (Kintinian-Fatoya N-S thrust contact) but is mainly stratigraphically controlled by the Kintinian conglomerate. Comparison of major and trace element signatures by LA-ICP-MS and EPMA between the disseminated pyrite and the other generations of pyrite associated with D_{2S}, D_{3S} and D_{4S} deformation indicates that the Sanu Tinti disseminated pyrite presents geochemical affinities with D_{3S} and D_{4S} pyrite associated with the
V$_{3B}$ veins and the S$_{4S}$ cleavage, respectively (Figure 44). Since petrographic observations indicate that the Sanu Tinti disseminated pyrite is overprinted by the S$_{4S}$ cleavage, we propose that both V$_{3B}$ and Sanu Tinti disseminated pyrite formed coevally late during D$_{3S}$. Both the vein-hosted and disseminated mineralisation textures developed along the early-D$_{3S}$ N-S thrust at the contact between the Kintinian and the Fatoya Formation. The change between the vein-hosted to the disseminated mineralisation texture is common in orogenic gold deposits (Dubé and Gosselin, 2007; Bierlein and Maher, 2001; Groves, 1993) and interpreted to be linked to porosity and competency contrasts in Siguiri, where the Kintinian conglomerate has higher porosity and lower competency compared to the greywacke-dominated sedimentary rocks of the Fatoya Formation. The second and main episode of gold mineralisation identified in Siguiri was found to be associated with both the vein-hosted and disseminated mineralisation textures. In the V$_{3B}$ vein-hosted mineralisation, gold was found in the veins and in the lattice of the arsenopyrite crystals (up to 55.5 ppm Au; Figure 44; Table 5). In the disseminated pyrite, gold was found free along fractures associated with chalcopyrite, hematite and galena. The crystal lattice of the disseminated pyrite was however found to be barren (~3 ppm Au maximum; Figure 44; Table 5).

The last hydrothermal event is a late overprint, which developed during D$_{4S}$ NW-SE compression and formed the S$_{4S}$ cleavage. This cleavage is characterised by strain shadows of sericite, quartz, ankerite and albite around V$_{3B}$ arsenopyrite crystals. Chlorite, hematite, pyrite, chalcopyrite, pyrrhotite, sphalerite, magnetite can also be found in these strain shadows or in veinlets overprinting the syn-V$_{3B}$ disseminated pyrite in the Kintinian conglomerate. Even though no significant gold was found locked in syn-D$_{4S}$ pyrite (~3 ppm Au maximum), free gold was observed in both Bidini and Kosise deposits infilling fractures or strain shadow of early mineralised V$_{3B}$ pyrite and arsenopyrite with chalcopyrite, hematite and galena. Two alternative models can be proposed to explain this infill. In the first model, a new gold input may be related to the late syn-D$_{4S}$ hydrothermal event. In the second alternative model, gold may have been remobilised during D$_{4S}$, relocating the invisible gold locked in the V$_{3A}$ and V$_{3B}$
pyrite and arsenopyrite crystal lattice into fractures and pressure shadow. Such remobilisation
behaviour has been described by a number of authors in recent years (Cook et al., 2013; Large
et al., 2011; Wilkinson et al., 1999). The present dataset does not allow to conclude in regards
to D$_{4S}$ gold occurrence and further work would be required to assess whether gold
remobilisation occurred or not.

**Geochemical footprint of the ore shoots**

The alteration associated with the superimposition of all four hydrothermal events
was geochemically characterised across the Siguiri district (Figure 42 and 43). In the different
deposits and in the representative Kosise deposit in particular, the geochemical variations
associated with this style of mineralisation are characterised by enrichments in Ag, Au, As, Bi,
S, (Sb), Te and W within at least fifteen meters around the ore shoots (Figure 43). These
enrichments are characteristic of hypozonal to mesozonal orogenic gold deposits (Groves et
al., 1998; Eilu et al., 1999; Groves et al., 2003) and are usually accompanied, in Siguiri, by
additional increases in Co, Mo, Na/Al (molar), and decreases in Ca, 3K/Al (molar), P, Rb and V
across the main ore shoot. These variations can be directly related to the hydrothermal
mineral assemblage associated with the V$_{3A}$ and V$_{3B}$ gold mineralisation event. In detail, Co is
found as a trace element in pyrite and arsenopyrite. The increase in S is related to
sulphidation, and the peculiar behaviour of Ca and Mg along the geochemical transect in the
Kosise deposit (Figure 43) is interpreted to mark the carbonate reaction front. The decrease in
3K/Al and increase in Na/Al molar ratios (Eilu and Groves, 2001) can both be linked to
albitisation developed around the veins, overprinting and replacing the early bulk sericitisation
of the country rock. Decrease in V can also be related to a decrease in micas towards the ore
shoot (Bateman and Hagemann, 2004). The absence of silica variation across the ore zones is
interpreted as linked to the removal of all veins from the analysed samples. Together, these
geochemical indicators and their variations can assist exploration by highlighting hydrothermal
alteration trends and define vectors to mineralisation, altogether increasing the size of the targets (Christie and Brathwaite, 2003).

Mineralising fluids

If we consider that sulphide major and trace element signatures reflect the composition of the mineralising fluid responsible for their formation (Pitcairn et al., 2006), then the compositional clustering between $V_{2S}$ and $V_{3A}$ pyrite, on one side, $V_{3B}$ and syn-$D_{4S}$ pyrite on the other side (Figure 44), suggests that at least two distinct mineralising fluids can be distinguished. The first fluid was responsible for the deposition of $V_{2S}$ and $V_{3A}$ vein-hosted mineralisation whereas the second fluid deposited syn-$V_{3B}$ and syn-$D_{4S}$ mineralisation. Two hypotheses can be formulated on the possible origins of the compositional variations between these two fluids.

The first hypothesis involves a unique source fluid (Salier et al., 2005) and the effect of physico-chemical processes, to trigger compositional changes and the evolution of this unique source fluid into two distinct mineralising fluids between the $V_{3A}$ and the syn-$V_{3B}$ hydrothermal events. Such changes are typically caused by changes in the fluid-rock or fluid-fluid interactions, such as the modification of the fluid pathway (Voicu et al., 2000) or fluid mixing (Boiron et al., 2003; Ridley and Diamond, 2000).

The second hypothesis that can be proposed involves two different source fluids, pumped through the Siguiri district at different time. Change from the first fluid to the second may have been caused by a change of source reservoir or by a change in the fluid source chemistry. In this hypothesis, fluid-rock and fluid-fluid interactions (Heinrich, 2007) only play a minor role on the final composition of the two fluids. Further work beyond the scope of this study (e.g. fluid inclusion, stable isotope studies, seismic profiles) would be required to potentially characterise the source(s) of these fluids (Ho et al., 1992; Ridley et al., 2000; Tomkins, 2013).
However, on the basis of the data presented in this paper, some aspects of the fluid chemistry can still be identified, particularly about the role of As. Field observations of arsenopyrite crystallisation in shale beds versus pyrite crystallisation in greywacke beds, and the differences of the geochemical baseline between the Kintinian, Fatoya and Balato formations (average As contents in the Kintinian Formation conglomerate 5 to 10 times lower than in the greywacke and shale of the Fatoya and Balato formations), we suggest that As is not provided by the fluid(s) but is rather mainly provided by the host rock. From the same observations, As is also interpreted to control the crystallisation of arsenopyrite over pyrite. This last result is supported by other studies (Pitcairn et al., 2006; Price and Pichler, 2006).

Variations in As content have a direct impact on the unit cell parameters of the pyrite crystal lattice (a, b, c distances between atoms and α, β, γ angles between a, b and c) which affects the capacity of this mineral to contain gold (Large et al., 2011; Savage et al., 2000). This conclusion is highlighted by the covariance in the LA-ICP-MS and EPMA datasets of Au and As in V_{3A} pyrite: more Au is incorporated into the pyrite crystal lattice along with the increase in As (Figure 44F). The low As content of the Kintinian Formation is therefore best interpreted to be responsible for the low Au content of the syn-V_{3B} pyrite disseminated in the Kintinian conglomerate below the Bidini deposit and outcropping in the Sanu Tinti deposit.

**Bracketing the timing of gold mineralization in Siguiri**

The Siguiri district gold mineralisation events timing can be bracketed using crosscutting relationships. All gold events developed in the Kintinian conglomerate and Kintinian, Fatoya and Balato sedimentary formations, dated at, 2124 ± 7 Ma, 2113 ± 5 Ma and 2113 ± 10 Ma respectively (Lebrun et al., 2015; Chapter 2).

The latest gold event observed in Siguiri is syn-D_{4S}, a deformation event responsible for the development of the NNE-SSW S_{4S} cleavage. This cleavage is sub-parallel to the supra-solidus magmatic fabric observed in the Malea monzogranite, outcropping to the north of the district (Figure 32) and emplaced along with the Saraya volcanic breccia at 2089 ± 12 Ma and
2092 ± 5 Ma, respectively (Lebrun et al., 2015; Chapter 2). Based on the orientation of the $S_{4s}$ cleavage parallel to the supra-solidus magmatic fabric in the Malea monzogranite, we interpret the emplacement of this intrusive and of the Saraya volcanic breccia to be coeval with the formation of the $S_{4s}$ cleavage recognized in the Siguiiri district. The timing of the gold mineralisation events in the Siguiiri district is therefore bracketed by the minimum deposition age of the Balato Formation and the crystallisation age of the Saraya volcanic breccia, between ca. 2103 Ma and ca. 2087 Ma respectively.

**Comparison with other West African orogenic gold deposits**

The Siguiiri mineralisation footprint has many similarities with other West African orogenic gold deposits. In particular, mineralisation at the Massawa deposit in Eastern Senegal (Treloar et al., 2014; Figure 46) is structurally controlled and hosted along sub-vertical NE-trending shear zones similar to the Kosise deposit. Mineralisation consists of disseminated arsenopyrite and pyrite similar to that found in the Bidini-Sanu Tinti conglomerate and is associated with carbonate-sericite alteration. This first mineralisation event in Massawa is overprinted by late Au-Sb-Te veining absent in Siguiiri. This overprint is associated with coarse visible gold. Mineralisation at the Sadiola Hill deposit in Western Mali (Masurel et al., in press 2015a; Figure 46) is structurally controlled and hosted along sub-vertical N-S and NNE-trending shear zones. Au-As-Sb mineralisation is mainly associated with disseminated sulphides but can also be found associated with sulphide veinlets and quartz-carbonate-sulphides-(biotite-tourmaline) veins. Potassic alteration dominates at the Sadiola Hill deposit and is associated with carbonate alteration. Mineralisation at the Yalea deposit in Western Mali (Lawrence et al., 2013a; Figure 46) is structurally controlled and hosted along sub-vertical N-S and NNE-trending shear zones. Mineralisation comprises quartz-ankerite-sulphide veins, similar to the Kosise style of mineralisation, and is also associated with chlorite-carbonate-sericite-quartz-albite alteration.
The timing of gold mineralisation at Massawa, Sadiola Hill and Yalea can be constrained in between the maximum age of crystallisation of the South Faleme pluton and Boboti granodiorite, 2082 ± 1 Ma and 2080 ± 1 Ma (Hirdes and Davis, 2002), and the Saraya granite (2079 ± 2 Ma; Lawrence et al., 2013a). The South Faleme pluton and Boboti granodiorite were interpreted to be coeval with the development of iron skarns, overprinted by regional orogenic gold mineralisation in the Kédougou-Kénieba Inlier (KKI; Masurel et al., 2015b). The Saraya granite emplacement was coeval with gold mineralisation at Loulo (Lawrence et al., 2013a), a deposit presenting similar mineral alteration and gold timing to the Sadiola Hill deposit (Masurel et al., 2015b). The minimum age of gold mineralisation in Loulo is constrained by the age of crosscutting dolerite dated at 2072 ± 7 Ma (Lawrence et al., 2013a). Gold mineralisation for these deposits is therefore bracketed in between ca. 2083 and ca. 2077 Ma.
Early Au-Sb-Bi-(Te-W) mineralisation at the Morila deposit in Southeast Mali (McFarlane et al., 2011; Figure 46) is categorised as intrusion-related but is overprinted by As-Au-Ag orogenic style mineralisation. This late overprint is hosted along a NNE-trending shear zone. Mineralisation is characterised by disseminated arsenopyrite containing polygonal gold blebs and is associated with albitionisation and the development of titanite. The timing of the intrusion-related mineralisation at Morila is bracketed between the crystallisation age of the intrusives that host gold, dated at 2098 ± 4 Ma and 2091 ± 4 Ma (McFarlane et al., 2011). The overprinting orogenic gold mineralisation, associated with datable titanite, was dated at 2074 ± 14 Ma by the same authors.

Mineralisation in the Obuasi gold mine in Ghana (Fougerouse et al., 2015; Figure 46) is similar to that in the Siguiri district. Mineralisation in Obuasi is structurally controlled and displays two distinct textures: disseminated gold-bearing sulphides (predominantly arsenopyrite in shale) and quartz-carbonate veins associated with native gold. Obuasi mineralisation is also associated with chlorite-quartz and carbonate alteration (e.g. ankerite, siderite grains; Fougerouse et al., 2015). Other examples of similar mineralisation footprint in West Africa include Wassa, Benso, Damang (Parra-Avila et al., 2015; Pigois et al., 2003; Figure 46).

Based on the aforementioned references and the structural framework and geochronology of the KKI, Guinea, Mali, Ghana, and other West African references (Milési et al., 1989; Milési et al., 1992), gold mineralisation in West Africa between ca. 2110-2060 Ma can be split into two main events (Figure 47). Both gold mineralisation events are chronologically associated with two distinct suites of intrusive rocks previously distinguished by Hirdes and Davis (2002).

The first gold mineralisation event occurs between ca. 2102-2085 Ma and is coeval with a first episode of magmatism characterised by the emplacement of granodiorite and felsic flows in the KKI and quartz-diorite in the Morila deposit (McFarlane et al., 2011; Parra-Avila, 2015; Figure 47). This first magmatic event was interpreted as associated with the syn-D₃lo
gold-tourmaline event in Loulo (KKI) and with the syn-D$_{2m}$ intrusion related gold mineralisation in Morila and early gold mineralisation at Obuasi (Fougerouse et al., 2015; Lawrence et al., 2013a; Lawrence et al., 2013b; McFarlane et al., 2011; Figure 46).

**Figure 47:** Synthetic time chart comparison of some key late Eburnean gold mineralisation events and their timing. From A: Dia et al. (1997), B: Hirdes and Davis (2002), C: Lawrence et al. (2013a) and Lawrence et al. (2013b), D: Lebrun et al. (in press 2016) and Lebrun et al. (2015), Chapters 2 and 3, E: McFarlane et al. (2011), F: Parra-Avila (2015) and Parra-Avila et al., (2015).
The second gold mineralisation event was coeval with a younger episode of magmatism responsible for the emplacement of the Saraya granite, Falémé calc-alkaline pluton, Boboti granodiorite and Loulo dolerite in the KKI (Lawrence et al., 2013a; Hirdes and Davis, 2002; Masurel et al., in press 2015a; Figure 47). This younger episode of magmatism, dated between ca. 2085-2054 Ma, is coeval with the second episode of gold mineralisation, recognized in the deposits of Loulo in the KKI, Morila in Mali, as well as Damang and Obuasi in Ghana (Fougerouse et al., 2015; Hirdes and Davis, 2002; McFarlane et al., 2011; Figure 46).

In comparison, the Siguiri district syn-D$_3$S orogenic gold mineralisation (V$_{3A}$ and V$_{3B}$ veining) was overprinted by a latter phase of gold mineralisation or remobilisation, syn-D$_{4S}$, coeval with the emplacement of the Malea monzogranite and Saraya volcanic breccia, that coincides with the first episode of magmatism discussed above (Figure 47). Thus, it is proposed that the gold events in Siguiri (syn-D$_{3S}$ and syn-D$_{4S}$) occurred during the ca. 2102-2085 Ma episode of gold mineralisation recognized across the West African Craton. These conclusions suggest that younger economic gold mineralisation coeval with the second episode of magmatism at ca. 2085-2054 Ma, such as the late gold overprint in Morila, may have yet to be discovered in the Siguiri Basin.

**Conclusion**

The Siguiri district, hosted by the weakly metamorphosed sediments of the Siguiri Basin (Guinea) is characterized by a polyphase hydrothermal history and two textures (or style of mineralisation) of the hydrothermal mineral assemblages. The dominant texture, or Kosise style of mineralisation, displays vein haloes structurally controlled by early-D$_{3S}$ N-S, NE-SW, WNW-ESE and E-W damage zones. In comparison, the other texture, or Sanu Tinti style, is only found in the conglomerate interbeds of the Kintinian Formation. The hydrothermal mineral assemblage associated with this style is disseminated and dominated by pyrite. A discreet structural control on gold mineralisation and alteration development can be observed along a N-S thrust fault marking the contact with the Fatoya Formation.
Both styles are associated with gold. The first episode of gold mineralisation is related to the development of the Kosise style \( V_{3A} \) pyrite-ankerite veins in which gold can be found locked in the pyrite crystal lattice (Au values up to 43.3 ppm). The second episode of gold mineralisation is associated with the Kosise style \( V_{3B} \) quartz-ankerite-arsenopyrite conjugate veins and with the Sanu Tinti style syn-\( V_{3B} \) disseminated pyrite. Native gold can be found in the \( V_{3B} \) veins and invisible gold (up to 55.5 ppm) can be found locked in the arsenopyrite crystal lattice. Both these gold episodes are overprinted by a late penetrative NNE-SSW \( S_{45} \) cleavage associated with minor free gold, chalcopyrite and galena infilling \( V_{3A} \) pyrite and \( V_{3B} \) pyrite and arsenopyrite fractures.

Geochemistry conducted in different deposits and a composite geochemical cross-section across ore shoots reveals that gold mineralisation in the Siguiri district is associated with enrichments in: Ag, Au, As, Bi, (Sb), Te and W, typical of mesozonal to hypozonal orogenic gold deposits. These enrichments are also accompanied by additional increases in Co, Mo, Na/Al (molar), and S and decreases in Ca, 3K/Al (molar), Mg, P, Rb and V across the main ore shoot. These chemical changes can be linked to the paragenetic sequence, are indicative of an albite-carbonate-sulphide-sericite alteration associated with the ore shoots and may increase the size of the targets for exploration.

Comparison of the syn-\( D_{35} \) and syn-\( D_{45} \) gold mineralisation timing at the Siguiri district with other orogenic gold deposits from West Africa indicates that these gold mineralisation events are coeval with other gold events recognized Craton wide at ca. 2102-2085 Ma. The overprinting gold mineralisation event recognized Craton wide at ca. 2085-2054 Ma is not represented in the Siguiri district, whereas it represents the main source of gold in other deposits of the West African Craton (e.g. Morila, Loulo, Sadiola).

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CHAPTER 5: CONCLUSIONS

4D EVOLUTION OF THE SIGUIRI DISTRICT –

IMPLICATIONS FOR THE WEST AFRICAN CRATON AND

GOLD EXPLORATION

This thesis presents an integrated lithostratigraphic, geochronological, structural and
geochemical study of the Siguiri district and of its hosting sedimentary basin, the Siguiri Basin.
Eleven deposits from the district were studied as well as a number of key locations across the
Basin. A wide variety of datasets, tools and analytical techniques were used, ranging from
fieldwork and the taking of structural readings to in-situ LA-ICP-MS. The work was organised
to: 1) characterise the Siguiri Basin lithostratigraphy and its tectonic context during the
Eburnean orogeny; 2) determine the controls on gold mineralisation affecting the Siguiri
district, 3) understand the evolution of the Siguiri district and its current architecture, and; 4)
characterise the district mineralisation and footprint. The major findings of this thesis and their
implications in the understanding of the West African Craton formation and for gold
exploration are detailed below.
LITHOSTRATIGRAPHY AND TECTONICS

- The Siguiri district is hosted in three distinct sedimentary Formations. From east to west: the Balato, Fatoya and Kintinian Formations.
- The Kintinian Formation is stratigraphically on top of the Fatoya Formation, itself overlying the Balato Formation.
- The three Formations are mainly derived from granitic rocks dated at around ca. 2015 Ma.
- The Balato and Fatoya Formations and their facies association are characteristic of a basal regressive sequence, whereas the overlying Kintinian Formation display stacks of polymict conglomerate interpreted to be the product of debris flow events.
- However, comparison of the lithostratigraphy and geochronology of the Kintinian Formation with the rest of the West African Craton suggests that this Formation is part of the Lower Tarkwa Group, typically described as "late orogenic basin"-type sediments.
- The Kintinian stacks of polymict conglomerate were interpreted to represent an olistostrome and can be followed throughout the whole Siguiri Basin.
- The deposition of this olistostrome is interpreted to mark a change in the dynamics of the Siguiri Basin opening, and the possible onset of renewed tectonic activity during the Eburnean Orogeny.
- The peculiar shape of the Kintinian olistostrome highlights the early architecture of the Siguiri Basin and is controlled by N-S, NE-SW and WNW-ESE faults presumed to represent fundamental structures that controlled the location of the Siguiri district in the Basin.
DEFORMATION EVENTS

- Four deformation events were recognized to affect the sediments of the Siguiri district: a cryptic N-S compression ($D_{1S}$), an E-W to ENE-WSW compression ($D_{2S}$) that is interpreted as progressively evolving into a transpression (early-$D_{3S}$) and then into a NNW-SSE transtension (late-$D_{3S}$), and finally a NW-SE compression ($D_{4S}$).

- The $D_{1S}$ deformation event is mainly characterized by $F_{1S}$ recumbent folds with E-W to NW-SE and NE-SW striking axial traces. A discreet $S_{1S}$ cleavage, shallowly to moderately dipping to the WSW was locally observed in the northernmost part of the Siguiri district.

- The $D_{2S}$ deformation event is responsible for the N-S structural grain observed across the Siguiri district and Siguiri Basin. This event is characterised by $F_{2S}$ upright folds with NNE-SSW to NNW-SSE striking axial planes that refolds $F_{1S}$ folds and create fold interference patterns. While no axial planar cleavage was found associated with the $F_{2S}$ folds, bedding parallel and en-echelon $V_{2S}$ veins developed during flexural slip along these fold hinges.

- The early-$D_{3S}$ deformation is responsible for the development (or reactivation) of N-S thrusts, E-W normal faults, NE-SW dextral shear zones and WNW-ESE sinistral shear zones.

- The N-S, E-W, NE-SW and WNW-ESE structures control the development of late-$D_{3S}$ veining ($V_{3S}$) and the location of ore shoots across the Siguiri district.

- The $D_{4S}$ deformation event overprinted all previously developed structural features, locally refolds $V_{3S}$ veins and develops a sub-vertical NE-SW striking $S_{4S}$ cleavage.

- The mineralised structures are often found to be discreet incipient structures developed as ten to fifteen meters wide sub-vertical areas of dense $V_{3S}$ veining,
lacking structures marked by discrete planes of fabric development across which there is offset.

- Finite strain and paleo stress-field analysis indicate that the stress-field variations from D$_{2S}$ E-W compression to early-D$_{3S}$ transpression and then to late-D$_{3S}$ NNW-SSE transtension may have had a regional origin.
- The homogenisation of the stress-tensor and reduced differential stress, responsible for these stress-switches, is interpreted to be a prerequisite for the development of orogenic gold mineralisation.

**HYDROTHERMAL ACTIVITY, MINERALISATION AND GEOCHEMISTRY**

- Hydrothermal activity in the Siguiri district was found to be polyphase and characterised by four distinct events, taking place during D$_{2S}$, D$_{3S}$ and D$_{4S}$ deformations.
- The first three hydrothermal events are mainly associated with the development of three generations of veins (V$_{2S}$, V$_{3A}$ and V$_{3B}$) whereas the last event (syn-D$_{4S}$) is characterised by pervasive hydrothermal activity associated with a penetrative cleavage (S$_{4S}$).
- LA-ICP-MS was used to compare the different trace element signatures of the sulphides associated with these hydrothermal events and constrain their relative timing.
- Three of these four hydrothermal events are gold bearing: the pyrite lattice from V$_{3A}$ veins contains up to 43.3 ppm of gold, V$_{3B}$ veins contain native gold and the lattice of the arsenopyrite associated with these veins also contains up to 55.5 ppm of gold, and D$_{4S}$ deformation is interpreted to fracture previously developed sulphides and precipitate gold in their fractures.
- High grade zones are typically associated with carbonatation, bleaching and minor albitisation of the host rock.
• Geochemical variations across the ore shoots of the Siguiri district show enrichments in: Ag, Au, As, Bi, Co, Mo, Sb, Se, SO$_3$, Te and W. CaO was found to mark the reaction front of the mineralising fluids and 3K/Al and Na/Al modal saturation indices were found to highlight the discreet ore shoots over distance up to 10 to 15 meters.

• Comparison between the timing of gold mineralisation in the Siguiri district and other gold deposits in the West African Craton, indicates that syn-D$_{35}$ gold is uncommon in the rest of the Craton whereas economic syn-D$_{45}$ gold could be found in the Siguiri Basin.

CONCLUDING REMARKS AND FUTURE WORK

In terms of academic research, this work improves the understanding of the Siguiri Basin formation and of its tectono-stratigraphic position in the evolution of the West African Craton throughout the Eburnean orogeny. This work identifies the fundamental structures which control the morphology of the Basin, the main lithostratigraphic Formations exposed and gives an interpretation of their environment of formation. In addition, this work also introduces the concept of stress-switch as a critical process and a pre-requisite (or cause) for orogenic gold mineralisation rather than as a passive effect of the fault-valve process.

In terms of gold exploration, this thesis highlights the necessity of using a multi-scale and multi-disciplinary approach to understand the genesis and controls affecting world-class orogenic gold districts. In the case of the Siguiri district, the new understanding of the early architecture of the Siguiri Basin emphasises the role it played as a first order control on the location of the Siguiri district. This conclusion emphasises the importance of understanding the overall tectonic history of a province to aid mineral exploration. Geochronology, geophysics and structural geology are crucial tools to be used during this first step. Down one scale to the Siguiri Basin to district scale, second and third order structures can be targeted through the use of geophysics, structural geology and to some extent, geochemistry. At a deposit scale,
field observations and geochemistry appeared to be the most important tools to target ore
shoots in the Siguiri district.

However, several key questions remain to be answered. Even though a model is
proposed, further work would be required to fully assess how the Siguiri Basin opened and
how was the extension oriented. Multiple deformation events and cleavages were observed in
the Siguiri district and even though the main events and most visible cleavages are now well
constrained, further work would be required to assess the importance of the D_{2S} N-S
compression in the Siguiri Basin and the development of its associated cleavage. The number
of fluids responsible for the four hydrothermal events observed in the Siguiri district and their
respective composition could not be constrained in this thesis but could be constrained by a
fluid inclusion and stable isotope study. These studies could potentially also give an answer as
to where the fluid(s) and the gold originated from, even though this question has been the
subject of a still ongoing debate in the literature.
ELECTRONIC APPENDICES

TABLE 1: SHRIMP DATA FOR THE SIX GEOCHRONOLOGICAL SAMPLES.

TABLE 2: SUMMARY TABLE OF THE PAST PRODUCTION OF THE SIGUIRI DISTRICT. GOLD GRADE (IN G/T) AND GOLD EXTRACTED (IN T) FOR SOME OF THE MAIN DEPOSITS DISCUSSED IN THE TEXT ARE DETAILED.

TABLE 3: GEOCHEMISTRY AND XRD DATA. ANALYSES BELOW DETECTION LIMIT IN RED.

TABLE 4: SUMMARY TABLE OF THE METHODOLOGY USED FOR THE LA-ICP-MS ANALYSES.

TABLE 5: LA-ICP-MS AND EPMA (FOR FE AND AS) DATA. CERTIFIED SULFIDE STANDARD LAFLAMME PO726 WAS USED TO CONSTRAIN LA-ICP-MS RESULTS FOR AU AND S. ANALYSES BELOW DETECTION LIMIT OR MISSING (NAN) ARE HIGHLIGHTED IN RED.

TABLE 6: SUMMARY TABLE OF THE LIMITS OF DETECTION ASSOCIATED WITH THE GEOCHEMICAL DATA.

TABLE 7: BASELINE GEOCHEMICAL_THRESHOLDS OF SOME RELEVANT ELEMENTS. DETERMINATION OF THESE_THRESHOLDS EXPLAINED IN FIGURE 41 CAPTION.

TABLE 8: RESULTS OF THE MASS BALANCE CALCULATIONS ($\Delta C/C_0$) FOR ALL SAMPLES. ENRICHMENTS AND DEPLETIONS EQUAL OR OVER 70% ARE HIGHLIGHTED IN GREEN.

SUPPLEMENTARY MATERIALS – EXTENDED METHODOLOGY
Electronic Supplementary Materials

3 Extended methodology

3.1 Field approach and sampling

3.1.1 Field approach

Structural elements and controls on gold mineralisation in the Siguiri district are very consistent from one deposit to the next (Lebrun et al., in press 2015a). For this reason, key deposits were selected based on the formation and host rocks, the understanding of the deposit structural framework, and the accessibility to fresh outcrops and core intersects. Three deposits were identified as representative of the Siguiri district mineralisation: the Bidini, Kosise and Sintroko PB1 deposits (Figure 2).

3.2.2 General sampling

Sampling was designed to: 1) constrain the paragenesis of the district; 2) characterise the geochemical halo associated with a representative mineralised shear zone; 3) compare the geochemical changes between formations and host rocks, and; 4) compare the sulphide major and trace elements and gold content of each vein generation and hydrothermal events. A total of 37 representative fresh rock samples were collected. Due to the weathering profile reaching depths over 200 m, drill core logging was conducted and used to guide sampling. Samples were collected from drill core and the sample size was kept consistent to a quarter core of 50 cm long (~1 kg) for most samples and about 2 to 3 kg for conglomerate samples. Seven samples were collected in the Bidini deposit from hole BDRCDD009 (Figure 4A), which starts in the Fatoya Formation and ends in the Kintinian Formation. Five of these samples were collected from the conglomerate interbeds (samples BD2, BD3 and BD5 to BD7; Table 1) whereas the last two samples were of greywacke and shale beds from the Kintinian Formation (samples BD1 and BD4; Table 1; Figure 5). Eighteen samples
were collected along holes KSDD018, KSDD020, KSDD022 and KSDD024 from the Kosise deposit (samples A to R; Table 1, Figure 4B). All of these drill holes intersect the Fatoya Formation only. Sampling was focused on the greywacke beds, which are the dominant lithology in the Fatoya Formation. Six extra samples of Fatoya greywacke were collected from the Kami deposit (hole KMRCDD293), hosted in the same folded sedimentary beds than the Kosise deposit. Six samples were also collected from hole SKRCDD040 in the Sintroko PB1 deposit (Figure 4C). This hole intersects the Balato Formation only. Sampling was focused on both shale and fine greywacke beds within and ~75 m away from the main ore zone (samples SK1 to SK6; Table 1).

3.2.3 Geochemical sampling

Geochemical sampling was designed to obtain the baseline geochemistry of each sedimentary Formation. In order to characterise the geochemical variations associated with early-D3S mineralised faults, samples were collected along a NW-SE composite section, across a discrete NE-SW dextral shear zone in the Kosise deposit and across a NE-SW shear zone and a bedding-parallel N-S reverse fault (Figure 4B). The Kosise deposit was chosen because it is hosted in the Fatoya formation, host to most of the deposits (Figure 2), and because its structural framework is relatively simple and well constrained. Sample spacing was modified according to the shear-zone proximity, grade distribution and apparent alteration. Sampling at intervals of about 10 metres was used in the distal part of the section whereas shorter intervals of a few metres were used around proximal alteration zones. Veins were trimmed off from all samples to avoid nugget effects. The veins were retained and used to make polished thin sections, for subsequent LA-ICP-MS analyses on their associated sulphides.

3.2 Analytical work and data processing

3.2.1 Petrography and mineral chemistry

The paragenetic sequence was characterised mainly through the use of optical and electron microscopy. Optical microscopy was conducted on a Nikon Eclipse LV100 POL at the Centre for
Exploration Targeting (CET) at the University of Western Australia (UWA). Electron microscopy and semi-quantitative analyses complemented the optical microscopy work. They were conducted at the Centre for Microscopy, Characterisation and Analysis (CMCA) at UWA, on a Tescan Vega3 XM SEM equipped with an Oxford instrument X-ACT energy dispersive detector (EDS). Operating conditions for the SEM-EDS included an accelerating voltage of 15-20 kV, a working distance of 15 mm, a beam current of 1.5 nA and a detector process time of 4 s.

Electron Probe Micro-Analysis (EPMA) was used to determine the Fe and As content in the different generations of sulphides. Iron concentrations were later used as internal standards for laser ablation data processing. Analyses were carried out on a JEOL 8530F Hyperprobe, at the CMCA. Operating were 40 degrees take-off angle with a beam energy of 20 keV, beam current of 80 nA, and the beam was fully focussed. The elements were acquired using analyzing crystals LiF for Fe kα, Co kα, Ni kα, Au lα, Sb lα, Ti kα and Te lα, PETJ for S kα, and TAP for As lα. The standards used for instrument calibration were a series of proprietary sulphides, oxides and metals. The counting time was 20 seconds for Fe kα, S kα, 60 seconds for As lα, Co kα, Ni kα, Ti kα, Sb lα, Te lα, and 100 seconds for Au lα. Mean atomic number background intensity and on-peak interference corrections were applied throughout (Donovan and Tingle, 1996; Donovan et al., 1993). Detection limits ranged from 40 ppm for Ti, 70 ppm for S, 90 ppm for Ni, 150 ppm for As and 360 ppm for Au lα. The matrix correction method was ZAF utilising the algorithm of Armstrong/Love Scott (Armstrong, 1988).

X-Ray Diffraction (XRD) was used to characterise the modal composition and its variations of the geochemical samples collected in the Kosise deposit. Analyses were conducted on a Panalytical Empyrean multi-purpose research XRD spectrometer at the CMCA, UWA. Spectra were processed with the HighScore Plus software and the final weighted R profile values were all between 5.89 and 11.4 with an average of 8.7.

LA-ICP-MS was conducted on all generations of pyrite and arsenopyrite found in the district (V2S, V3A, V3B and syn-D4S), as well as on unconstrained disseminated pyrite hosted in the conglomerate of the Bidini deposit (Table 2). Samples of pyrite from V2S, V3A, V3B veins and syn-D4S all came from the
Fatoya and Kintinian formations (Kosise and Bidini deposits). Small amounts of pyrite were found in
the Balato Formation (Sintroko PB1 deposit) and could not be linked to any of the four generations.
Samples of arsenopyrite came from the Balato and Fatoya formations (Sintroko PB1 and Bidini
deposits). Samples were separated according to the nature of their host rock (either greywacke,
shale or conglomerate; Table 3). Laser ablation was used to provide the missing links between the
different textures of the hydrothermal mineral assemblages observed in the Siguiri district. In
particular, laser ablation and EPMA data allowed the comparison of the major and trace element
signatures from the multiple pyrite generations from Kosise and Sintroko PB1 and the pyrite found in
the Bidini conglomerate. Analysis of sulfides in thin section was determined utilizing a Resonetics
RESOlution M-50A-LR incorporating a Compex 102 excimer laser, coupled to an Agilent 7700s
quadrupole ICP-MS at the GeoHistory Facility, John de Laeter Centre, Curtin University. Following a
20 s period of background analysis, samples were spot ablated for 60 s at a 7 Hz repetition rate,
using a 75 μm beam and laser energy of 2.5 J cm⁻². The sample cell was flushed with ultrahigh purity
He (0.68 L min⁻¹) and N₂ (2.8 mL min⁻¹) and high purity Ar was employed as the plasma carrier gas.
International glass standard GSD-1G was used as the primary reference material, to calculate
elemental concentrations (using ⁵⁷Fe determined by EPMA as the internal standard element) and to
correct for instrument drift on all elements except Au. Certified sulfide standard Laflamme Po726
(synthetic pyrrhotite doped with platinum group elements and Au) was utilized as the primary
standard for Au and S calculation. Standard blocks, included secondary standards treated as
unknowns, were run every 10 unknowns. The mass spectra were reduced using Iolite (Paton et al,
2011 and references therein). Data were collected on a total of 21 elements;
(¹⁰⁷Ag, ⁷⁵As, ¹⁹⁷Au, ¹³⁷Ba, ²⁰⁹Bi, ⁶⁹Co, ⁵²Cr, ⁶³Cu, ⁵⁵Mn, ⁹⁵Mo, ⁶⁰Ni, ²⁰⁸Pb, ¹²¹Sb, ⁷⁷Se, ²⁸Si, ¹¹⁸Sn, ⁴⁷Ti, ²⁰⁵Tl, ⁵
¹⁵V, ⁶⁶Zn and ⁹⁰Zr). Precision, as determined on secondary standards ranged from <1 % to 4 % (Table 2
and 3).
3.2.2 Whole-rock major and trace element geochemical analyses

Whole-rock major and trace element compositions were measured on each sample in order to identify: 1) the different geochemical variations associated with mineralisation between the three sedimentary formations hosting the Siguiri district, and; 2) the main geochemical differences between these formations.

Geochemical analyses (Table 1) were carried out by Intertek Genalysis Laboratories in Perth, using a combination of analytical techniques detailed in Table 4. The Geological Survey of Western Australia (GSWA) Bunbury basalt and Kerba granite standards were included to monitor instrument precision (Morris, 2007). Data precision for both standards was typically within 3 % for major elements and 10 % for trace elements. Detection limits for each element are provided in Table 4. XRF analyses, reported as oxides by Intertek Genalysis Laboratories, were converted in Microsoft Excel into elemental weight percent.

Data were separated according to formation, host rock types and least altered samples for each formation and host rock type were chosen. Geochemical backgrounds for the Balato, Fatoya and Kintinian formations were calculated following the cumulative frequency method proposed by Landry et al. (1995), that follows the work conducted by Sinclair (1974, 1991).

In addition, anomalous geochemical variations across the Kosise deposit geochemical transect have been constrained by mass balance calculations following the work by Gresens (1967), MacLean and Barrett (1993) updated by Grant (2005) and further refined by Mukherjee and Gupta (2008), and by López-Moro FJ (2012) in his EASYGRESGRANT method. Density of the samples, used for the mass balance calculations, were measured at UWA using a precision scale (0.01 g error). Each sample was weighted out (Mair) and in distilled water (Mwater), density was calculated following the following formula:

\[ \rho = \frac{M_{air}}{M_{air} - M_{water}} \]
Least altered samples (Table 1), also used for the calculations, were selected based on their distance from mineralised shear zones, visible signs of alteration in hand specimens (e.g. veining, bleaching), the amount of alteration minerals in thin section, and gold grades. Sample BD3 was used to normalise the Kintinian conglomerate samples, sample F was used for the Fatoya Formation shale samples, sample O for the Fatoya Formation greywacke samples, sample SK6 for the Balato shale samples and sample SK4 for the Balato greywacke samples. Since no least altered shale and greywacke could be sampled directly in the Kintinian Formation, Kintinian samples BD1 and BD4 were normalised to a sample of shale and greywacke representative of the Siguiri district. The Fatoya samples F and O were therefore chosen for the normalisation of BD1 and BD4, respectively. Variation in an element $i$ between the altered sample and the fresh sample ($= \Delta C$) is considered anomalous when its value relative to the least altered sample ($= \Delta C / C_0$) exceeds $\pm 70\%$. Geochemical data were plotted using ioGAS.