Master of Science Research Thesis

Geochemical characterisation and provenance analysis of conventional Late Jurassic reservoirs, Dampier Sub-basin, Northern Carnarvon Basin, Western Australia

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This thesis is submitted to fulfil the requirements for Master of Science (Geology) by way of Thesis

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Abstract

Geochemical characterisation of Late Jurassic sediments was conducted to distinguish provenance and dispersal through deep-water systems in the Dampier Sub-basin. In spite of the economic importance of the Angel Formation, few studies have focussed on the provenance and distribution of reservoir sandstones in the basin. Geochemical data was obtained using portable-XRF analysis on both cuttings and core samples from three wells along a transect of the basin. Comparison of geochemical data with core textures, fabric, structures and composition, as well as graphical and statistical analysis of data, was used to interpret element-element and element-mineral relationships. These relationships were used to characterise the sedimentary successions of each well into chemozones of similar geochemical composition. A comparison of geochemical data of equivalent biostratigraphic age in wells allowed the interpretation of sediment supply and dispersal throughout the Dampier Sub-basin during the Late Jurassic. Transverse sediment supply from basin margins dominated the Oxfordian and Kimmeridgian based on contrasting geochemical signatures of sandstones of the Eliassen Formation in wells proximal to the basin margins and a predominance of mudstone deposition in the central part of the Dampier Sub-basin. A significant axial supply of increasingly sand-rich sediment commencing in the early Tithonian from the northeastern Dampier Sub-basin resulted in widespread Angel sandstone deposition towards the southwest through basin-floor fans. The wells along the flanks of the sub-basin showed contrasting geochemical signatures, this time with different signatures to the central part of the basin, signifying a continuation of transverse sediment input during the Tithonian, causing a mixed geochemical signature.

This study presents new insights into sediment supply and dispersal of Eliassen Formation and Angel Formation reservoir facies in the Dampier Sub-basin. These insights are important for future exploration targeting in the basin and provide a qualitative analysis of reservoir quality in the Late Jurassic sandstones. Additionally, the major axial sediment supply in the Tithonian highlights a dominantly northeast sediment source with transport to the south, in contrast to the large-scale south to north sediment transport routes that dominated the Northern Carnarvon Basin during the Triassic and Early Cretaceous.
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1. Introduction

1.1 Significance of Study

The detrital composition and provenance of siliciclastic petroleum reservoirs is important for assessing reservoir quality and understanding basin history (e.g. Dickinson and Suczek 1979; Bhatia 1983; Roser and Korsch 1988; Hurst and Morton 2014). The geochemical composition of sediments may be highly variable due to differences in source composition, sedimentary transport processes, paleoclimate and diagenesis (Cullers and Berendsen, 1998; Etemad-Saeed et al., 2011; Zaid, 2013; Ratcliffe et al., 2010). Subtle differences in elemental composition in seemingly homogeneous stratigraphic intervals help identify changes in detrital composition, which links to provenance (Pe-Piper et al., 2008; Zhang et al., 2014; Phillips et al., 2015). Correlation of sedimentary zones with similar geochemical signatures between petroleum wells can be used to gain insights into provenance pathways and sediment dispersal patterns in a basin (Pearce et al., 1999; Ratcliffe et al., 2007; Craigie, 2015; Craigie and Rees, 2016).

The Northern Carnarvon Basin (NCB) is the southernmost basin of the North West Shelf (NWS) of Australia which includes a group of basins formed during the late Paleozoic to Mesozoic breakup of East Gondwana (Stagg and Colwell, 1994; Jablonski et al., 1997). The NCB is the most productive hydrocarbon-producing basin of the NWS with a total of 2.7 billion barrels of oil and 16.7 trillion cubic feet of gas produced from the Mesozoic petroleum system in the basin (Geoscience Australia and Bureau of Resource and Energy Economics, 2014). Late Jurassic syn-rift strata represent important reservoirs in a number of fields in the Dampier Sub-basin of the NCB (Longley et al. 2002), and represent a primary exploration target in the basin.

The Late Jurassic reservoirs are interpreted to have been deposited as basin-floor fan systems in a deep water depositional setting in the Dampier Sub-basin (Barber 1994a, 1994b; Jablonski 1997; Clark 2006). Despite their economic importance, there are few published studies of these reservoirs, and the distribution of the fans, as well as the location of provenance and sediment dispersal pathways in the basin, remains uncertain (Dibona and Scott, 1990). The provenance of prominent siliciclastic reservoirs in the NWS is important for understanding reservoir distribution, within and between hydrocarbon fields, and controls on reservoir quality related to sandstone detrital composition (Southgate et al. 2011; Lewis and Sircombe 2013).
Through an integrated geochemical analysis, this study seeks to determine the distribution of Late Jurassic sandstone reservoirs in the basin using key geochemical signatures, and uses these signatures to improve understanding of sediment dispersal pathways related to fan deposition. This study examines geochemical composition vertically and laterally in the basin fill to characterise provenance of the Late Jurassic sandstones and identify any compositional changes that might indicate changes in location of source terrains and/or sediment dispersal pathways.

Additionally, reservoir quality for the selected wells is assessed in terms of the role of detrital composition and diagenetic processes as influenced by provenance of the sandstone reservoirs. This research primarily utilises portable X-ray fluorescence (pXRF) analysis in order to determine the geochemical composition of facies and has the possibility to be a readily available, inexpensive and non-destructive geochemical analytical tool for future chemical stratigraphy and provenance studies.

1.2 Regional Geology
The NCB is composed of three major structural zones (Fig. 1); a shallow, shelfal zone bordering onshore Australia (the Lambert and Peedamullah shelves), numerous sub-basins which formed major depocentres during the Triassic, Jurassic and Lower Cretaceous (the Exmouth, Barrow, Dampier and Beagle sub-basins), and a large platform area (the Exmouth Plateau) with an uplifted horst margin bordering the Dampier and Barrow sub-basins (the Rankin Platform). The Argo, Gascoyne and Cuvier abyssal plains border the outer margins of the basin (from northeast to southwest, respectively), whereas the Roebuck Basin, Pilbara Craton and Southern Carnarvon Basin border the continental margin of the basin (from northeast to southwest, respectively).

1.3 Dampier Sub-basin Geology
The Dampier Sub-basin contains a predominantly Triassic, Jurassic and Lower Cretaceous stratigraphic succession exceeding 10 000 m, dominated by deltaic to marine siliciclastic rocks, while shelfal carbonate rocks compose the Mesozoic to Cenozoic section. The sub-basin is separated from the Lambert Shelf to the east by the en echelon Flinders fault system (Kopsen and McGann, 1985) and the Rankin Platform to the west by the Rankin fault system (Stagg and Colwell, 1994). Large, complex Paleozoic-Triassic fault blocks that have been uplifted and rotated separate the Dampier
Sub-basin from the Beagle Sub-basin to the north (the De Grey Nose) and the Barrow Sub-basin to the south (Sultan Nose) (Geoscience Australia, 2016).

**Northern Carnarvon Basin**

![Map showing the Northern Carnarvon Basin](image)

**Fig. 1.** Location of the Dampier Sub-basin within the Northern Carnarvon Basin.

Two northeast-trending troughs, the Kendrew Terrace to the west and the deeper Lewis Trough to the east, separated by an anticlinal structural high (Madeline Trend) constitute the main structural components of the Dampier Sub-basin (Fig. 2). The anticlinal Legendre Trend to the east formed contemporaneously with the Madeline Trend during the Early Cretaceous as a result of the reactivation of basement faults (Colwell et al., 1993). These basinal highs host the significant Angel gas field and Wanaea and Cossack oil fields along the Madeline Trend, and multiple smaller petroleum accumulations (namely Legendre and Talisman) along the Legendre Trend.
1.4 Dampier Sub-basin Tectonic History

The tectonic evolution of the Dampier Sub-basin was primarily influenced by the formation of the NCB, and the wider NWS, during the progressive breakup of eastern Gondwana. Seven major stages punctuate the formation of the basin and its structural components commencing in the Permo-Carboniferous and continuing to the present day.

1. The Sibumasu Block breakup (Permian-Carboniferous) formed the dominant northeast-southwest structural grain of the basin due to northwest-southeast extension along the northwest of Gondwanan Australia (Gartrell, 2000).

2. During the Late Triassic, the transpressional Fitzroy Movement in the Canning Basin resulted in restructuring of tectonic units along the NWS causing the separation of the Beagle and Cossigny troughs in the Beagle Sub-basin from the Lewis Trough in the Dampier Sub-basin (Blevin et al., 1994).

3. The commencement of the series of breakup events which formed the NWS margin occurred in the Early Jurassic as a result of the breakup of the West Burma block 1 from Gondwanan Australia (Veevers, 1988; Jablonski, 1997; Jablonski and Saitta, 2004). This breakup event resulted in rapid thermal subsidence and a rifted arch setting in the NCB that formed the Lewis Trough and Rankin Platform (Veevers et al., 1991; Jablonski, 1997).

4. West Burma Block 2 separated in the Oxfordian leading to active seafloor spreading in the Argo Abyssal Plain. Extension of the block was towards the
north-northwest (Exon and Von Rad, 1994), oblique to the structural grain of the Dampier Sub-basin, resulting in the transtensional deepening and broadening of the Dampier Sub-basin towards and across the Rankin Platform, which formed the Kendrew Terrace (Barber, 1994a; Hill, 1994).

5. West Burma Block 3 broke away from a region outboard of the Bonaparte Basin during the Late Jurassic (Longley et al., 2002; Jablonski and Saitta, 2004). As a result of the changing extension direction from northwest (the Argo spreading ridge) to west-northwest (the Gascoyne spreading ridge), fault reorientation and block rotation occurred in the Dampier Sub-basin resulting in uplift and erosion of the Rankin Platform (Barber, 1994a; Wulff and Barber, 1995). Tilting of fault blocks northward in the Early Cretaceous reactivated Jurassic transfer structures and caused inversion of footwalls, resulting in the anticlinal Madeline and Legendre trends (Baillie and Jacobson, 1995; Pryer et al., 2002).

6. The major Greater India breakaway event commenced in the Early Cretaceous (Valanginian) and resulted in west-northwest extension and the formation of the Gascoyne and Cuvier abyssal plains signifying the final breakup of the northwest margin of Australia (Hill, 1994; Gartrell, 2000). Cessation of active continental breakup in the Late Cretaceous led to the formation of the passive continental margin that exists at present day (Baillie et al., 1994).

7. Collision of the Indo-Australian plate with the Banda Arc and the Eurasian Plate in the late Oligocene to early Miocene caused minor inversion along the Rosemary-Legendre Trend occurred in the Dampier Sub-basin (Cathro and Karner, 2006; Keep et al., 2007).

1.5 Dampier Sub-basin Sedimentary History

The Dampier Sub-basin contains a dominantly Early Jurassic to Early Cretaceous fill up to 10 000 m (Fig. 3). Jablonski (1997) devised a multi-phase framework for the deposition of sediments into the NCB, divided into eight megasequences; a pre-rift megasequence prior to the Triassic to a passive margin from the Santonian to present. The megasequences are defined by significant changes in sedimentary deposition and dispersal patterns marked by active rifting processes and subsequent changes in subsidence.

The pre-rift megasequence (pre-Triassic) is not well understood due to its great depth (>5 km) but consists of primarily fluvio-deltaic clastic sediments (Jablonski, 1997). The active margin megasequence (Triassic to Early Jurassic) related to the Fitzroy
Movement is composed of the transgressive Locker Shale deposited during a period of thermal subsidence, and the Mungaroo Formation atop, which was deposited in a fluvio-deltaic nearshore environment (Hocking, 1990). Increased transgression and marine flooding during this time also lead to the deposition of the Murat Siltstone (Stephenson et al., 1998). The early syn-rift phase (Toarcian to Callovian) resulted in the deposition of the fine-grained Athol Formation in a low-energy restricted offshore marine setting followed by the Legendre Formation deposited as a prograding delta over the basin (Hocking, 1992). During this period, the main tectonic features of the Dampier Sub-basin were formed (Rankin Trend, Lewis Trough and Rosemary Fault System).

In the Late Callovian, the main phase of rifting along the NWS commenced which occurred in three main periods; syn-rift 1 megasequence (Callovian to Oxfordian), syn-rift 2 megasequence (Oxfordian to Tithonian), and the late syn-rift megasequence (Berriasian to Valanginian), signifying the separation of the West Burma blocks 2 and 3 and Greater India, respectively (Jablonski, 1997). During the syn-rift 1 megasequence (Callovian to Oxfordian) the Legendre Delta was drowned, depositing shales and minor sandstones of the Calypso Formation (Barber, 1994a).

The formation of sediment filled half-graben caused isostatic disequilibrium and a compensating rise in the asthenosphere, resulted in a major sea level lowstand which formed the Main Unconformity throughout the NWS (Jablonski, 1997). As tectonism and displacement along bounding faults continued during the syn-rift 2 megasequence (Oxfordian to Tithonian), an open deep-marine environment existed which resulted in the deposition of the Dingo Claystone (Wulff and Barber, 1995). During the Oxfordian, basin-floor fan systems sourced from the basin margins led to the deposition of the Eliassen Formation, followed by the deposition of the extensive basin-floor fan systems forming the Angel Formation in the Tithonian (Barber, 1994a; Wulff and Barber, 1995; Jablonski, 1997).

A gradual decline in rifting and a gradual increase in thermal subsidence during the late-syn rif megasequence (Berriasian to Valanginian) resulted in the submergence of the Rankin Platform and the shutting off of sediment supply that sourced the Angel Formation, resulting in the deposition of the Forestart Claystone, and subsequently, the Mudorong Shale during the post breakup megasequence (Jablonksi, 1997). This was followed by the opening of the Indian Ocean and progradation of carbonate-dominated systems across the NWS to the present day, reflecting the passive continental margin setting (Longley et al., 2002).
Fig. 3. Mesozoic lithostratigraphic column of the Dampier Sub-basin with the Late Jurassic section of interest highlighted (modified from Geoscience Australia, 2016).
1.6 Late Jurassic Stratigraphy

The Late Jurassic sedimentary succession in the Dampier Sub-basin is composed of the Eliassen Formation deposited in the Oxfordian, the Dingo Claystone deposited throughout the late Oxfordian, Kimmeridgian and early Tithonian, and the Angel Formation deposited in the Tithonian (Fig. 3). The Eliassen Formation is composed of sandstones formed by coalescing basin-floor fan systems and sediment gravity flows supplied from the margins of the Dampier Sub-basin (Wulff and Barber, 1995; Jablonski, 1997). Sediment supply was primarily influenced by the Oxfordian sea level lowstand event that caused the subaerial exposure of the Rankin Platform and Enderby Terrace (Barber, 1994a; Wulff and Barber, 1995).

The Dingo Claystone was formed as rifting processes slowed through the Oxfordian to Kimmeridgian and fine-grained sediment deposition dominated the central troughs of the Dampier Sub-basin in a low energy deep-marine setting below the wave base (Hocking, 1992; Jablonski, 1997). The restricted deep-marine offshore setting during this time resulted in anoxic conditions favouring the preservation of organic matter in the basin. The claystone is a major oil-prone source rock in the NCB due to its significant total organic content and provides an effective hydrocarbon seal to the Oxfordian sandstones (Bradshaw et al., 1994).

During the Kimmeridgian and Early Tithonian, the basal margins were subaerially exposed during multiple lowstand events (Stein, 1994; Wulff and Barber, 1995). In the west, the exposure of the Rankin Trend likely supplied sediment gravity flows adjacent to the platform, whereas in the east, slope aprons and basin-floor fan systems sourced from the Rosemary Fault scarp and the Enderby Terrace were deposited (Barber, 1994a). Due to the decline in tectonic related accommodation, a number of these submarine fan systems were able to extend across to the Madeline Trend (Wulff and Barber, 1995).

Increasingly sand-rich basin-floor fan systems supplied from the southeast Beagle Sub-basin and the Legendre Trend were deposited towards the southwest in the northern and central parts of the Dampier Sub-basin (Fig. 4) (di Toro, 1994; Barber, 1994b). These thick, widespread sandstones constitute the Angel Formation and represent major petroleum reservoirs in the Dampier Sub-basin. The Angel Delta supplied sediment that directly supplied basin-floor fans in the north and central Dampier Sub-basin and grade laterally into basinal facies towards the Barrow Sub-basin to the southwest. Coalescing
sand aprons also formed a major axial sediment input at the basin margins during this time (Jablonski, 1997).

**Fig. 4.** Tithonian palaeogeographic map of the Northern Carnarvon Basin with Angel Formation basin-floor fan deposition in the northern and central Dampier Sub-basin (adapted from Tao, et al., 2013, modified after Bradshaw et al., 1988, Bradshaw et al., 1998, Hocking, 1988 and Longley et al., 2002).

### 1.7 Study Aims and Objectives

The objective of this research is to determine the provenance and sediment dispersal of Angel Formation and Eliassen Formation sandstones throughout the Dampier Sub-basin during the Late Jurassic.

This study aims to:

1. Select wells across the basin to provide a transect with core and cuttings samples.
2. Describe sedimentology of cored intervals via core logging to identify textural and compositional features (i.e. detrital composition and cements).
3. Characterise the geochemical composition of Late Jurassic sandstones and mudstones from wells in the Dampier Sub-basin using portable X-ray fluorescence (pXRF) analysis on core and cuttings samples.
4. Determine detrital composition and diagenetic features in the sandstones and to assess controls on reservoir quality.
5. Integrate compositional and geochemical data to determine trends between wells in the basin using chemostratigraphy and to reconstruct likely provenance regions and sediment dispersal patterns.

6. Evaluate the effectiveness of pXRF analysis as an analytical technique for chemostratigraphic studies.

2. Materials and Methodology

2.1 Introduction

Major and trace element data can be used for the characterisation and correlation of stratigraphic successions in a basin. Three wells were selected along a 45 km transect across the Dampier Sub-basin (Fig. 5) to determine if the stratigraphic succession in each well could be correlated using geochemical composition on the basis that sediments were sourced from similar areas. The reservoir quality in the three wells was also assessed based upon detrital composition and interpreted diagenetic processes.

Whole-rock geochemical analysis for provenance has traditionally used X-ray fluorescence (XRF) analysis or inductively coupled plasma mass spectrometry (ICP-MS) to generate geochemical data, whereas portable XRF (pXRF) analysis has been selected for this research investigation. Portable XRF is rapid and can be used on a variety of surfaces without sample preparation (e.g. core). This method of geochemical analysis is able to determine a wide range of elements with a wide range of concentrations (ppm to 100%) and also has the potential to obtain high precision (up to 0.1%) (Anzelmo et al. 2013; Brand and Brand 2014). This study utilised a Thermo Scientific Niton XL3t GOLDD+ pXRF analyser.

The Niton XL3t GOLDD+ model has the ability to detect elements ranging from Mg to U with the ability to measure light elements (Mg, Al, Si, P, and S) without the need for added helium purge or vacuum during analysis required by older pXRF analyzers. Detection limits vary for elements with limits of detection as low as 50 ppm (0.005%) for Ca and other major elements and as low as 3 ppm for Rb and other trace elements (Thermo Scientific 2010). High correlations (> 0.90 $R^2$) and repeatability (< 5 % RSD) were achieved for most major, minor and trace elements when independent ICP-MS laboratory results of 160 sedimentary rock samples and standards were compared with results obtained from a handheld Niton XL3 Series 900 SDD XRF (Thermo Scientific 2010).
The analytical method resulted in elemental data for 35 elements; eight major elements reported as oxide percent by weight (SiO$_2$, TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, MnO, CaO, K$_2$O and P$_2$O$_5$), 18 trace elements reported as parts per million (Ba, Bi, Co, Cr, Cs, Cu, Mo, Nb, Ni, Pb, Rb, Sr, Th, U, V, W, Zn and Zr), and nine other elements (S, Cl, Hg, Sb, Te, As, Sc, Se and Au). Precision error for major elements is generally 3 %, and is around 5 % for high abundance trace elements (Ba, Cr, Sr, Zn and Zr). The remaining trace elements have a precision error generally lower than 10 %.

Only a small number of these elements are required for geochemical characterisation and are referred to as discriminating variables (Craigie et al., 2016). The first stage in determining which variables best characterise the data is to establish the mineralogical affinities of elements and to determine the principal controls on geochemistry and mineralogy (Ratcliffe et al., 2010; Craigie and Rees, 2016). This can be established by employing graphical and statistical analysis as well as comparing geochemical data to
observed mineralogical data (e.g. core). Biostratigraphy is also used to provide a broad framework for the comparison of age equivalent strata between the wells.

2.2 Core Description and Geochemical Analysis

The available cored sections of the three wells (Table 2) were laid out at the Western Australian Geological Survey Carlisle Core Library and logged at 1:200 scale. Logging was undertaken to describe texture, fabric, composition, structures and cements observed in the core, which could be related to particular readings of geochemical measurements.

The cored sections were subsequently analysed by pXRF with the Niton analyser held firmly against the flat side of the core in a constant position in the core trays for each measurement. The readings represent a point sample on the core material. Sampling intervals were approximately every 0.5 m on the core, although specific geological features of interest (i.e. pyrite cement and siderite nodules) were also analysed. Total analysis time for each point sample was 60 seconds using the TestAll Geo™ setting, and a description of the position and features of the sampled area were recorded.

2.3 Petrographic Analysis

Petrographic examination was also employed to identify detrital grains and major cements in thin section. This work allowed further understanding of linking whole-rock geochemical data acquired to core composition. These element-mineral relationships are used to guide interpretations of sections of the wells covered only by cuttings.

2.4 HyLogger Analysis

HyLogger™ technology was developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) and collects rapid and high-resolution visible, near and shortwave (VNIR, SWIR) infrared reflectance spectra of drill core. High-resolution imaging of the core is also conducted which, when integrated with the scanning spectra, provide information about oxides, carbonates and many hydroxyl-bearing minerals, such as micas, clays, amphiboles, chlorites, talc and sulphates present in the core material. Thermal-infrared (TIR) logging operates in the same way but is also sensitive to non-hydroxyl-bearing framework minerals and other silicates including quartz, feldspars, pyroxenes, olivines, garnets and carbonates (Huntington, 2007; CSIRO, 2012). The resulting spectral and image data were analysed interactively with the TSG-Core™ software package, from which the images in this study are derived.
The publicly available data for Wanaea-1 were obtained from the Department of Mines and Petroleum Geoview website and is used in conjunction with the XRF data to gain further insights into the compositional variation of the core in terms of detrital composition, authigenic clays and other diagenetic phases.

2.5 Cuttings Analysis

For each well ditch cuttings were recovered at the wellsite during drilling operations. The cuttings were washed and dried by the exploration company and then sent to the Department of Mines and Petroleum, where they are stored at the Carlisle Core Library. The cuttings represent an average sample of sedimentary rock typically drilled in 5-20 m intervals. For stratigraphic petroleum exploration, intervals of most interest had a shorter sample interval (1.5-5 m). This means that a cuttings sample of depth 3000 m with sample interval of 5 m consists of an average rock composition within that 5 m interval, and not the rock type specifically at 3000 m depth. The cuttings intervals in Montague-1, Wanaea-1 and Legendre-1 were variable, and this controlled the sampling intervals chosen for analysis in this study (Table 1).

Table 1: Sampling intervals of ditch cuttings collected at the wellsite for section of study interest.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Well Sampled Section (m MDRT lag corrected)</th>
<th>Sample Interval (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montague-1</td>
<td>3195 – 4045</td>
<td>5</td>
</tr>
<tr>
<td>Wanaea-1</td>
<td>2800 – 2850</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2850 – 2864</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2864 – 2950</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>2950 – 4080</td>
<td>5</td>
</tr>
<tr>
<td>Legendre-1</td>
<td>1981.20 – 2127.50</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>2127.50 – 2129.03</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2129.03 – 2354.58</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>2354.58 – 2359.15</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2359.15 – 2485.64</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>2485.64 – 2488.69</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2488.69 – 2534.41</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>2534.41 – 2538.98</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2538.98 – 2796.54</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>2796.54 – 2801.11</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2801.11 – 2865.12</td>
<td>3.05</td>
</tr>
</tbody>
</table>

2.5.1 Cuttings Sampling

Ten grams of cuttings from the Late Jurassic section of each well were sampled at selected intervals and stored in small plastic sample bags. The 10 g sample was obtained
from a larger ~ 200 g sample with care taken to ensure an average sample of grains from the larger cuttings sample bag was obtained. The average sample interval was ~ 20 m, however, this was primarily dependent on the gamma log response and the thickness of the lithological section being sampled. For example, in a 75 m section of high gamma response (likely mudstone), three samples were taken (e.g. 15 m, 40 m, 60 m in the total 75 m section), and in a 30 m section of sandstone-mudstone-sandstone (0-10 m = sandstone, 10-20 m = mudstone, 20-30 m = sandstone) a sample from each rock type was obtained (e.g. at 5 m, 15 m, and 25 m). The gamma log also provided the opportunity to ensure the cuttings sampled were at the correct depths in the well, and did not show a depth lag which may have resulted during drilling. In total, 137 cuttings samples were obtained (Table 2) and a brief description of the grains sampled for each sample was made to aid in linking geochemical data to rock type, cement types and specific minerals observed.

Table 2: Study intervals of the three wells and the number of samples analysed.

<table>
<thead>
<tr>
<th>Well</th>
<th>Core Sample Interval (m)</th>
<th>Core pXRF Measurements</th>
<th>Cuttings Sample Interval (m)</th>
<th>Cuttings XRF Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montague-1</td>
<td>3219.5-3237.5</td>
<td>30</td>
<td>3195-4045</td>
<td>51</td>
</tr>
<tr>
<td>Wanaea-1</td>
<td>2832-2845.7</td>
<td>28</td>
<td>2800-4080</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>2889-2904.5</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legendre-1</td>
<td>2127.2-2128.7</td>
<td>3</td>
<td>1981-2865</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2354.6-2359.5</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2485.6-2488.7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2534.7-2539</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total Core Measurements | 111 | Total Cuttings Measurements | 137 |

2.5.2 Cuttings Sample Preparation

Each cuttings sample collected was milled to a fine powder in the Sedimentary Geology Laboratory in the Geology Building at UWA using an agate mortar and pestle and transferred to a small sample vial. Samples were milled to homogenise the cuttings collected to ensure the geochemical data would be representative of the whole sample. A specifically agate mortar and pestle was used during the milling process to ensure no contaminants entered the sample material that could have the potential to impact the elemental data acquired.
The powdered samples were subsequently pressed into pellets (~20 c coin size) using a 10 tonne hydraulic press at the XRF Preparation Laboratory in the Soil Science Building at UWA. Pressing the powdered samples into pellets provided a flat surface for the window of the pXRF analyser for analysis. No binding agent was used in pellet preparation, as the sample pellets were structurally intact following the use of the press. The disc pellets were transferred to small sample holders for pXRF analysis.

2.5.3 Cuttings Sample pXRF Analysis

Following sample preparation, the sample disc pellets were placed on a clean piece of A4 paper for analysis. As performed on the core, the Niton XRF analyser window was placed on the centre of the sample pellet for the XRF analysis for total analysis times of 60 seconds per sample. The analyser surface was cleaned using ethanol in between each sample analysis to ensure no residue would be left on the pXRF window that could contaminate the next sample. Following each analysis the sample pellets were returned to the sample holders.

2.6 Graphical and Statistical Analysis

Graphical and statistical analysis was employed to further determine element-element and element-mineral relationships in the geochemical data obtained. These analyses were integrated with relationships determined during core logging and the comparison with geochemical data.

2.6.1 Binary Diagrams

Binary diagrams provide a simple way of visualising element-element relationships in the geochemical data. In binary diagrams, elements that have a positive relationship with one another likely share similar mineralogical affinities, whereas those that do not covary are most likely unrelated. Binary diagrams were constructed to investigate element-mineral relationships in both the sandstone and mudstone data.

2.6.2 Principal Component Analysis

Principal component analysis (PCA) is a multivariate statistical method that is commonly applied to geochemical datasets to identify element-element and therefore element-mineral relationships (Svedsen et al., 2007, Pe-Piper et al., 2008; Ratcliffe et al., 2010; Craigie et al., 2016). PCA reduces the number of variables in a dataset, elemental concentrations in this study, to a small number of principal components, while retaining as much information as possible. The principal component score
assigned to each sample is determined from eigenvectors (EV). Eigenvector 1 (EV1) accounts for the greatest variability in the dataset, while EV2 accounts for the second highest variability, and so on. The EV plots provide a means of visualising elemental relationships, whereby elements that plot close to one another in the EV plots are likely to share similar mineralogical affinities (Ratcliffe et al., 2010; Craigie et al., 2016).

The grain size of the sedimentary rock plays a fundamental role in controlling sedimentary composition and therefore geochemical composition. It is therefore crucial to compare data of similar grain size (Ratcliffe et al., 2006; Ratcliffe et al., 2010; Craigie, 2015; Craigie et al., 2016). PCA was conducted on both the sandstone and mudstone datasets using XLstat software produced by Addinsoft ©. Pearson-type correlation was used for the analysis and no factor loadings were assigned to any of the samples in the dataset.

Although PCA provides a convenient way to establish broad elemental and mineralogical relationships, it should be used with caution as single samples with anomalously high or low concentrations of a certain element can provide an overriding influence on EV values (Craigie et al., 2016).

### 2.7 Biostratigraphy

Available biostratigraphic data for Montague-1, Wanaea-1 and Legendre-1 were obtained from Geoscience Australia. These data were used to provide a depositional age framework for the comparison of geochemical zones in the three wells. The biostratigraphic zoning is based on the Northern Carnarvon Basin Biozonation and Stratigraphy Chart by Kelman et al. (2013).

### 3. Results

#### 3.1 Introduction

This chapter presents the geochemical results acquired by pXRF and Hylogger analysis and the interpretation of the mineralogy in terms of detrital composition and diagenetic processes. This is achieved through the use of binary diagrams and PCA to observe elemental-element and element-mineral relationships in the data as well as the geochemistry of core and Hylogger line spectral scanning to further investigate mineralogical interpretations through whole-rock geochemistry. These techniques allow zones of similar geochemical composition to be distinguished in Montague-1, Wanaea-1 and Legendre-1 to provide interpretations of changes in detrital composition and its
relationship to changes in provenance of sediments and the dispersal of sediments across the basin through time.

3.2 Core Geochemistry

Portable XRF analysis was conducted on available core in the Late Jurassic sections of Montague-1, Wanaea-1 and Legendre-1. The cored sections are limited in terms of stratigraphic extent, however, they provide the opportunity to observe changes in geochemical composition of the sedimentary rock, and to link this to the detrital composition and cements observed in the core. The elemental data that was observed to best display the changing geochemistry in the wells in terms of detrital geochemistry and cement types were determined to be Al₂O₃ content, Rb/Cs, K₂O/Al₂O₃ and TiO₂/Al₂O₃ ratios, Zr, Cr, CaO and S contents, as well as the Fe₂O₃/Al₂O₃ ratio. These elemental ratios are closely related to specific minerals, whereby changes in these minerals observed in the core can be used to determine changes in the detrital composition of sedimentary rock (Table 3). Petrographic examination of available thin sections was used to validate geochemical and compositional interpretations.

Table 3: Significance of elements/geochemical ratios to detrital mineralogy and cement types observed in the core data.

<table>
<thead>
<tr>
<th>Geochemical Element/Ratio</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>Closely linked to total clay content</td>
</tr>
<tr>
<td>Rb/Cs</td>
<td>Linked to changing clay mineralogy</td>
</tr>
<tr>
<td>K₂O/Al₂O₃</td>
<td>Closely linked to illite/K-feldspar vs. kaolinite/plagioclase feldspar</td>
</tr>
<tr>
<td>TiO₂/Al₂O₃</td>
<td>Closely linked to titanium-bearing heavy minerals normalised over clays e.g. rutile (TiO₂) and Ilmenite (FeTiO₃)</td>
</tr>
<tr>
<td>Zr</td>
<td>Closely linked to the heavy mineral zircon (ZrSiO₂)</td>
</tr>
<tr>
<td>Cr</td>
<td>Closely linked to chromium-bearing heavy minerals e.g. Cr-spinel</td>
</tr>
<tr>
<td>CaO</td>
<td>Linked to carbonate cement e.g. calcite, dolomite, siderite and ankerite</td>
</tr>
<tr>
<td>S</td>
<td>Linked to sulphur cements e.g. pyrite (FeS)</td>
</tr>
<tr>
<td>Fe₂O₃/Al₂O₃</td>
<td>Closely linked to iron-bearing cements/minerals normalised over clays. Used in conjunction with CaO and S e.g. siderite and ankerite when CaO and Fe₂O₃/Al₂O₃ covary, and pyrite when S and Fe₂O₃/Al₂O₃ covary</td>
</tr>
</tbody>
</table>

3.2.1 Montague-1 Core (3219.5-3237.5 m)

Montague-1 core is composed of normally graded coarse-medium sandstones of turbiditic origin with detrital glauconite grains throughout. Pyrite nodules up to 3.5 cm are present, as well as minor quartz and carbonate cement. The core is composed of at least four turbidite beds with thin wavy mud lamination present at the top of the turbidite at 3235.25 m (Fig. 6).
Fig. 6: Montague-1 core (3219.5–3237.5 m) lithological and geochemical logs. The lithological log displays the observed lithologies, cements and other geological features observed in the core. The geochemical logs display the geochemistry measured at various depths on the core.
The sandstones in the core have low clay content and therefore low Rb/Cs as well as variable but predominantly low-moderate K₂O/Al₂O₃, indicating the presence of K-feldspar and/or illite in the sediments. In terms of heavy minerals, the geochemistry indicates moderate TiO₂/Al₂O₃, low-moderate Zr, and low Cr. This indicates a sediment source richer in titanium-bearing minerals compared to zircon and chromium-bearing minerals. High values of CaO between 3237.5 and 3224.5 m indicate a carbonate cemented zone which would have occurred due to the presence of carbonate minerals in the detrital composition of the sediments. Predominantly low S and Fe₂O₃/Al₂O₃ indicate low pyrite cement in the sandstones, however, extremely large values of S and Fe₂O₃/Al₂O₃ are measured at 3237 m and are due to a pXRF measurement directly of a pyrite nodule, which are common in the turbiditic beds. Increased measurements of CaO are observed to weakly covary with Fe₂O₃/Al₂O₃, which could indicate an iron-bearing carbonate cement.

3.2.2 Wanaea-1 Core (2889-2904.5 m)

Wanaea-1 core from 2889-2904.5 m is composed of medium sandstones of turbiditic origin and highly bioturbated siltstone (Fig. 7). The thick sandstone section is composed of multiple stacked turbidite beds, although not all bedding planes are obvious. The lower turbidite bed contains coaly material with a sharp boundary to a claystone interval at 2902.5 m. The uppermost bed of the large sandstone section (from 2894.75 m) fines up with normal grading to claystone at 2893.85 m. Pervasive siderite cement is observed at 2901 m as well as a dolomite cemented section in the centre (2896.5-2902 m). Mixed coarse grains of quartz, chert, mudstone rip-up clasts and glauconite are present in the middle section of the thick sandstone and the thinner sandstone section.

The sandstones are identified by low clay content and Rb/Cs with moderate K₂O/Al₂O₃ indicating the presence of K-feldspar and/or illite. Low ratios of TiO₂/Al₂O₃ and Zr, and low-moderate Cr indicate low abundance of heavy minerals in the sediments. Low concentrations of S in the sandstones indicate low pyrite cement, however, a highly carbonate cemented zone correlates with high values of CaO from 2896.5-2902 m. In this zone, a maximum value of Fe₂O₃/Al₂O₃ correlates to the pervasive siderite cemented section while the remaining carbonate section is observed to correlate with heightened values of Fe₂O₃/Al₂O₃ indicating an iron-bearing carbonate cement (e.g. siderite). A maximum value of Zr exists in the thin mud lamination interval (2902-2902.5 m). Conversely, the thin sandstone interval from 2891.3-2891.8 m does not indicate a presence of carbonate cement.
Fig. 7. Wanaea-1 (2889-2904.5 m) core lithological and geochemical logs. The lithological log displays the observed lithologies, cements and other geological features observed in the core. The geochemical logs display the geochemistry measured at various depths on the core.
The siltstones have moderate clay content with high Rb/Cs indicating rubidium rich clay with low K$_2$O/Al$_2$O$_3$ and therefore low illite and high kaolinite content. The siltstones have low TiO$_2$/Al$_2$O$_3$, high Zr, and low-moderate Cr, indicating high zircon input, as well as low concentrations of CaO, S and Fe$_2$O$_3$/Al$_2$O$_3$. The claystone intervals in the core display increased values of Al$_2$O$_3$ which is expected with increased clay material and correlates with high Rb/Cs values indicating a low Caesium content/high rubidium content of the clays.

3.2.3 Wanaea-1 Core (2832-2845.7 m)

Wanaea-1 core from 2832-2845.7 m is composed of medium sandstones of turbiditic origin and highly bioturbated siltstone (Fig. 8). Large siderite nodules are common features in the bioturbated siltstone. Sandstones contain frequent detrital glauconite grains, minor carbonate cement and chert and mudstone rip-up clasts.

The sandstones have low clay content and therefore Rb/Cs values with moderate-high K$_2$O/Al$_2$O$_3$ indicating the presence of K-feldspar and low plagioclase feldspar. The thin sandstone bed at 2840.25 m has a particularly high K$_2$O/Al$_2$O$_3$ content. Low values of TiO$_2$/Al$_2$O$_3$, Zr and Cr indicate low heavy mineral contents, while moderate-high CaO concentrations show the presence of carbonate cement that is not iron-bearing due to low values of Fe$_2$O$_3$/Al$_2$O$_3$.

The siltstones have moderate-high clay contents with high Rb/Cs and low-moderate K$_2$O/Al$_2$O$_3$ pointing towards rubidium-bearing and kaolinite-rich clays. Low values of Cr and TiO$_2$/Al$_2$O$_3$ indicate trace silt-grade chromium and titanium-bearing minerals, although high zirconium concentrations indicate a high zircon input. The siltstones display mostly low values of CaO, S and Fe$_2$O$_3$/Al$_2$O$_3$, although large spikes in Fe$_2$O$_3$/Al$_2$O$_3$ and less prominent CaO correspond to direct pXRF measurements on siderite nodules (2836.5 m and 2842.75 m) and the siderite cemented section at 2840.25 m. Spikes in Cr are also evident at the measurements of the siderite nodules pointing towards chromium being incorporated in the siderite nodules.
Fig. 8. Wanaea-1 (2832-2845.7 m) core lithological and geochemical logs. The lithological log displays the observed lithologies, cements and other geological features observed in the core. The geochemical logs display the geochemistry measured at various depths on the core.
3.2.4 Legendre-1 Core (2534.7-2539 m)

The deepest core of interest in Legendre-1 is composed of debritic claystone which contains frequent coarse floating quartz grains (Fig. 9a). A section of minor pyrite cement at is evident at 2537.7 m.

The claystone is characterised by moderate-high clay content and Rb/Cs values and low K₂O/Al₂O₃, indicating high kaolinite content. Low TiO₂/Al₂O₃, high Zr and low Cr point towards low titanium- and chromium-bearing heavy mineral and high zircon input, likely of silt-grade. The debritic claystone has low values of CaO and Fe₂O₃/Al₂O₃, although displays high values of S which are related to clays and not cements.

3.2.5 Legendre-1 Core (2485.6-2488.7 m)

This core is composed of thinly bedded turbiditic medium sandstone and claystone (Fig. 9b). The sandstones are poorly sorted with common coarse grains of quartz and chert, all with minor quartz cement. The middle two beds display minor pyrite cementation, whereas the uppermost three beds display major carbonate cementation which reacted with 10% HCl. The top claystone is observed to be a debritic claystone as it contains multiple floating medium-coarse grains of quartz.

The stacked sandstones have low clay content and therefore low Rb/Cs values with low K₂O/Al₂O₃ indicating low K-feldspar and relatively high plagioclase/kaolinite, and low values of TiO₂/Al₂O₃, Zr and Cr suggesting a source low in heavy minerals. In terms of cements, high CaO and S show the sandstones have high carbonate content (consistent with reaction with 10% HCl) and the presence of pyrite cement. Low Fe₂O₃/Al₂O₃ shows that carbonate cement is not iron-bearing. The lowermost sandstone, however, has low CaO and S suggesting it does not contain pyrite or carbonate cement, which could represent a different detrital composition as a result of a different source rock.

The claystones have moderate Al₂O₃ and high Rb/Cs with low K₂O/Al₂O₃, indicating the clays are rubidium- and kaolinite-rich. Low values of TiO₂/Al₂O₃ and Cr, and moderate Zr show low titanium- and chromium-bearing heavy mineral input but a contribution of likely silt-grade zircon. The claystones display low CaO and Fe₂O₃/Al₂O₃, however contain high concentrations of S.
Fig. 9. Legendre-1 (a=2534.7-2539 m, b=2485.6-2488.7 m, c=2354.6-2359.5 m, d=2127.2-2128.7 m) core lithological and geochemical logs. The lithological log displays the observed lithologies, cements and other geological features observed in the core.

The geochemical logs display the geochemistry measured at various depths on the core.
3.2.1 Legendre-1 Core (2354.6-2359.5 m)
The core is composed of poorly-sorted medium sandstone with frequent coarse-grained clasts of quartz, chert and mudstone, as well as detrital glauconite grains (Fig. 9c). Major carbonate cementation is evident which reacted with 10% HCl, in addition to minor quartz and pyrite cementation.

The sandstone is characterised by low clay content and therefore low values of Rb/Cs with moderate-high K₂O/Al₂O₃ indicating the presence of K-feldspar. Moderate TiO₂/Al₂O₃ and low Zr and Cr point towards a source containing titanium-bearing heavy minerals. In terms of cements moderate-high CaO, and low-moderate S and Fe₂O₃/Al₂O₃ indicate carbonate (consistent with reaction with 10 % HCl) and pyrite cements. Increased measurements of CaO are observed to covary with Fe₂O₃/Al₂O₃ in the core data indicating an iron-bearing carbonate cement.

3.2.2 Legendre-1 Core (2127.2-2128.7 m)
The shallowest Legendre-1 core of interest is composed of a small section of minor pyrite cemented and quartz cemented medium sandstone of turbiditic origin (Fig. 9d). Rare mudstone rip-up clasts are also present.

The sandstone is characterised by low values of all geochemical variables, indicating low clay content, low K-feldspar/high plagioclase feldspar, low titanium and chromium-bearing heavy minerals, low zircon and an absence of carbonate and pyrite cement.

3.3 Core HyLogger Analysis
Hylogger spectral data exists for the core in Wanaea-1, but could not be acquired for Montague-1 and Legendre-1 because the core is largely discontinuous rubble, which prohibits the acquisition of Hylogger spectral data. The data for the two cored sections in Wanaea-1 are presented in the two channels the data were measured. Channel one is visible, near and shortwave infrared (VNIR, SWIR) scanning spectrometry (Fig. 10a and d) and channel two is thermal infrared (TIR) scanning spectrometry (Fig. 10b and e), and is displayed as the dominant mineral measured in each case averaged over an interval of 0.3 m.

3.3.1 Wanaea-1 Core (2889-2904.5 m)
The deeper Wanaea-1 core is composed of sandstones and siltstones, as described in section 3.2.2, which display variable mineralogy as measured by Hylogger analysis.
The siltstones from 2889.0-2891.3 m and 2891.8-2894.0 m have higher orthoclase than the siltstones from 2903.3-2904.5 m which have higher illite. The sandstones from 2894-2901.3 m are separated into five zones based upon the variation in abundances of kaolinite, siderite and ankerite (Table 4). The siderite and carbonate cement areas observed in the core in terms of geochemistry, section 3.2.2, is consistent with Hylogger measurements. Elsewhere sandstones show kaolinite, as measured by Hylogger analysis, but is a minor component in the sandstones due to a low clay content as measured by whole-rock geochemistry.

### 3.3.2 Wanaea-1 Core (2832-2845.7 m)

The shallower Wanaea-1 core is composed of sandstones and siltstones, as described in section 3.2.2, which display variable mineralogy through Hylogger analysis (Fig. 10d and e). Siltstones are mostly composed of quartz with high kaolinite contents. Siderite nodules observed in the core correspond with increased siderite composition measured with Hylogger analysis. Sandstones are composed of dominant quartz, which is expected, with varying compositions of ankerite, siderite and kaolinite (Table 5). The shallower sandstone bed (2832.7-2834.9 m) shows high ankerite and siderite pointing towards an iron-bearing carbonate cement, consistent with the geochemistry of the core (Section 3.2.2). Elsewhere, sandstones have minor ankerite and siderite with a higher kaolinite signature, indicating these zones do not have carbonate cement, and instead have minor kaolinite clay content.

### 3.4 Cuttings Geochemical Analysis

#### 3.4.1 Introduction

The dataset acquired from pXRF analysis of cuttings samples in Montague-1, Wanaea-1 and Legendre-1 were divided into sandstones and mudstones as the grain size in which the geochemical data are measured plays a principal role in the geochemical expression of the data and it is, therefore, crucial to only compare data of a similar grain size. The samples were divided into mudstones and sandstones based on their SiO$_2$ and Al$_2$O$_3$ contents, as the ratio SiO$_2$/Al$_2$O$_3$. Samples which have a ratio < 4 are classified as mudstones, whereas those with a ratio of > 4 are classified as sandstones (Sprague et al., 2009). This classification scheme is also observed to correlate with the gamma ray log of each well, where low SiO$_2$/Al$_2$O$_3$ ratios corresponded with high gamma readings, suggesting mudstones, and high SiO$_2$/Al$_2$O$_3$ ratios correspond with low gamma readings, suggesting sandstones.
Fig. 10. Hylogger™ data acquired for Wanaea-1 core. a) and b) represent the deeper core (2889–2904.5 m) with a key to the predominant mineral measured in each channel (A= VNIR, SWIR and B= TIR). Note, c) is a lithological log of the core from which the spectral data was measured, key on Fig 7. d) and e) represent the shallower core (2832–2845.7 m) with a key to the predominant mineral measured in each channel (D= VNIR, SWIR and E= TIR). Note, f) is a lithological log of the core of which the spectral data was measured, key on Fig 8.
Fig. 11. Binary plots used to establish element-mineral relationships. Note, major elements are presented as oxides as % concentration, whereas trace elements are presented as ppm.
Table 4: Hylogger analysis summary of Wanaea-1 core (2889-2904.5 m).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology</th>
<th>VNIR, SWIR Analysis Minerals</th>
<th>TIR Analysis Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>2889.0-2891.3</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, low orthoclase, illite, kaolinite, microcline and albite</td>
</tr>
<tr>
<td>2891.3-2891.8</td>
<td>Sandstone</td>
<td>Muscovite, siderite, ankerite</td>
<td>Dominant quartz, minor kaolinite and illite</td>
</tr>
<tr>
<td>2891.8-2894.0</td>
<td>Siltstone and claystone</td>
<td>Entirely kaolinite</td>
<td>High quartz, low orthoclase, illite, kaolinite, microcline and albite</td>
</tr>
<tr>
<td>2894-2896.2</td>
<td>Sandstone</td>
<td>Kaolinite, minor siderite and ankerite</td>
<td>Entirely quartz</td>
</tr>
<tr>
<td>2896.2-2897.3</td>
<td>Sandstone</td>
<td>Kaolinite, siderite and minor ankerite</td>
<td>Dominant quartz, minor dolomite</td>
</tr>
<tr>
<td>2897.3-2898.5</td>
<td>Sandstone</td>
<td>Siderite, kaolinite and ankerite</td>
<td>Dominant quartz, minor dolomite</td>
</tr>
<tr>
<td>2898.5-2901.3</td>
<td>Sandstone</td>
<td>Kaolinite, siderite and ankerite</td>
<td>Dominant quartz, minor dolomite</td>
</tr>
<tr>
<td>2901.3-2903.3</td>
<td>Sandstone and minor claystone</td>
<td>Kaolinite with minor ankerite and siderite</td>
<td>Dominant quartz with minor illite and kaolinite</td>
</tr>
<tr>
<td>2903.3-2904.5</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, low illite, orthoclase and kaolinite</td>
</tr>
</tbody>
</table>

Table 5: Hylogger analysis summary of Wanaea-1 core (2832-2845.7 m).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology</th>
<th>VNIR, SWIR Analysis Minerals</th>
<th>TIR Analysis Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>2832.0-2832.7</td>
<td>Siltstone</td>
<td>High kaolinite, low muscovite</td>
<td>High quartz, low kaolinite, minor albite, orthoclase and microcline</td>
</tr>
<tr>
<td>2832.7-2834.9</td>
<td>Sandstone</td>
<td>High ankerite, low siderite and muscovite</td>
<td>Entirely quartz</td>
</tr>
<tr>
<td>2834.9-2840.1</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, orthoclase, illite, kaolinite, siderite, microcline</td>
</tr>
<tr>
<td>2840.1-2840.6</td>
<td>Sandstone</td>
<td>Kaolinite and siderite with minor ankerite</td>
<td>Dominant quartz, minor siderite and illite</td>
</tr>
<tr>
<td>2840.6-2843.3</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, low orthoclase and illite</td>
</tr>
<tr>
<td>2843.3-2843.5</td>
<td>Sandstone</td>
<td>Dominant kaolinite with minor ankerite and siderite</td>
<td>Dominant quartz, minor orthoclase</td>
</tr>
<tr>
<td>2843.5-2844.7</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, low orthoclase and illite with minor kaolinite</td>
</tr>
<tr>
<td>2844.7-2845.3</td>
<td>Sandstone</td>
<td>Dominant kaolinite with minor ankerite and siderite</td>
<td>Dominant quartz, minor kaolinite</td>
</tr>
<tr>
<td>2845.3-2845.7</td>
<td>Siltstone</td>
<td>Entirely kaolinite</td>
<td>High quartz, minor microcline, kaolinite and albite</td>
</tr>
</tbody>
</table>

The cuttings data were analysed using binary diagrams and PCA to further understand element-element and therefore element-mineral relationships. These trends are then used, in conjunction with element-mineral interpretations in the core data, to distinguish...
geochemical zones upsection in the wells of interest to identify changes in detrital composition and therefore different provenance.

3.4.2 Binary Diagrams

The binary diagrams presented (Fig. 11) were found to best characterise the geochemical data in terms of detrital geochemistry and mineral relationships, whereby variables which display strong relationships likely share similar mineralogical affinities. Samples that do not fit strong trends on binary plots can also have important implications for detrital composition and diagenetic processes. Samples that display a strong positive relationship with Al$_2$O$_3$, indicate they are principally controlled by clay content (as Al$_2$O$_3$ is closely related to the total clay content of a sample) (Ratcliffe, 2010; Craigie, 2015; Craigie and Rees, 2016). The binary diagrams that were found to best characterise the geochemical data of the wells are described in the following subsection.

**SiO$_2$ vs Al$_2$O$_3$**

The SiO$_2$ vs Al$_2$O$_3$ binary diagram (Fig. 11a) shows that most samples plot on a strong negative trend, where mudstones have higher Al$_2$O$_3$ contents and lower SiO$_2$ contents than sandstones, principally related to quartz content. A small number of samples deviate from this trend with anomalously low values of SiO$_2$ that also have low Al$_2$O$_3$ and are related to samples inferred to contain volcanic material, common siderite nodules and/or cement.

**Al$_2$O$_3$ vs TiO$_2$**

The Al$_2$O$_3$ vs TiO$_2$ binary plot (Fig. 11b) displays a strong positive trend with mudstones having greater Al$_2$O$_3$ and TiO$_2$ than sandstones. This indicates titanium is related to clay content, although some sandstone samples have elevated TiO$_2$ contents and can be related to titanium-bearing heavy minerals. A small number of sandstone samples have very high TiO$_2$ contents, but low Al$_2$O$_3$ contents and are related to samples containing volcanic material, common siderite nodules and/or cement.

**Al$_2$O$_3$ vs Fe$_2$O$_3$**

The binary diagram displaying Al$_2$O$_3$ vs Fe$_2$O$_3$ (Fig. 11c) shows that most samples fit to a strong positive trend, where mudstones have higher Al$_2$O$_3$ and Fe$_2$O$_3$ contents, indicating iron is mostly clay controlled. A number of samples that deviate from this trend with elevated iron contents can be related to high pyrite and/or iron-bearing carbonate cement content.
Al₂O₃ vs K₂O
The Al₂O₃ vs K₂O plot (Fig. 11d) demonstrates two trends, a strong positive trend with mudstones containing greater Al₂O₃ and K₂O contents, and a strong positive trend which only a small number of samples fit. The trend which most samples fit to is principally concerned with the clay content, where potassium-bearing clays such as illite increase with increasing clay content. The moderate positive trend with a small number of sandstone samples can be inferred to relate to K-feldspar content.

Al₂O₃ vs Rb
The Al₂O₃ vs Rb binary diagram (Fig. 11e) displays a strong positive trend in the sandstones, whereas the mudstone samples have higher Al₂O₃ and Rb contents but are seen to have no relationship with Al₂O₃ contents greater than 10%. This relationship indicates that rubidium is principally clay controlled in sandstone samples, but is concerned with different clay mineralogy in mudstone samples.

Al₂O₃ vs Cs
The Al₂O₃ vs Cs binary plot (Fig. 11f) shows a moderate positive trend in which mudstones display higher Al₂O₃ and Cs contents and are less clearly correlated as well as sandstone samples. This relationship indicates caesium is mostly clay controlled, where samples with higher clay content generally have higher caesium content. In sandstone samples, the variation can be related to caesium also being a minor elemental constituent of feldspars. A small number of sandstone samples are observed to plot away from this trend as they exhibit high Cs contents but low Al₂O₃ contents and are inferred to relate to samples containing volcanic material.

K₂O vs Rb
The samples within the K₂O vs Rb binary diagram (Fig. 11g) are observed to fit to two positive trends. A lower moderate positive trend with a small number of samples and a higher strong positive trend in which a large number of samples fit, where both sandstone and mudstone samples fit to both trends. The lower positive trend is related to muscovite, whereas the higher positive trend is related to K-feldspar/illite, showing that the potassium and rubidium is mostly controlled by the presence of K-feldspar and illite, not muscovite (Zhang et al., 2014).

Rb vs Cs
The Rb vs Cs binary plot (Fig. 11h) displays a weak positive trend in the sandstones, however, although the mudstone data portrays higher Rb and Cs contents, no trend is
exhibited. This is important for differentiating between changing clay mineralogy. If caesium and rubidium displayed a relationship with one another, it means they would be linked mineralogically. The fact that no trend exists in mudstone data means a ratio of Rb/Cs can be used to determine changing clay mineralogy. The positive trend in the sandstone data is due to an increase in clay content, although, those sandstone samples with high values of Cs and low Rb is due to Cs being a minor constituent of feldspars, which are present in varying amounts in sandstone samples.

SiO$_2$ vs CaO
A weak negative trend exists in the SiO$_2$ vs CaO plot (Fig. 11i), whereby mudstones display lower SiO$_2$ contents and slightly higher CaO contents than sandstones, indicating CaO is slightly clay controlled. However, a small number of sandstone samples are shown to have anomalously high CaO contents and low SiO$_2$ contents, which can be attributed to samples with high siderite nodule material and/or high carbonate cement.

TiO$_2$ vs V
The TiO$_2$ vs V binary diagram (Fig. 11j) displays a very strong positive trend between TiO$_2$ and V in samples which have greater than 0.5% TiO$_2$ showing that they are strongly related mineralogically. Sandstone samples with extremely high TiO$_2$ and V are inferred to be related to samples with volcanic material, which titanium and vanadium are greatly enriched.

TiO$_2$ vs Nb
The TiO$_2$ vs Nb binary diagram is defined by three main areas (Fig. 11k). A weak positive trend with high Nb content shows TiO$_2$ and Nb are related to clay content, where samples with high clay content have high TiO$_2$ and Nb. Samples with higher TiO$_2$ values as well as high Nb are related to samples containing titanium-bearing heavy minerals (where Nb can form a minor constituent). A small number of sandstone samples are shown to exhibit anomalously high TiO$_2$ contents, which significantly deviate from the weak positive trend. These samples are inferred to be related with volcanic material, in which titanium is enriched.

TiO$_2$ vs Zr + Cr
The TiO$_2$ vs Zr+Cr binary plot (Fig. 11l) shows a weak positive correlation where samples have high TiO$_2$, Cr and Zr contents and can be classified as originating from a mature source in which titanium- and chromium-bearing minerals and zircon have been
concentrated. In contrast, a small number of sandstone samples display anomalously high TiO$_2$ contents with low Zr+Cr content which can be related to samples interpreted as having a high amount of mafic volcanic material, where titanium is enriched. Mudstone samples show similar trends to sandstone samples.

### 3.4.3 Principal Component Analysis

Principal component analysis (PCA) was conducted on the sandstone and mudstone cuttings geochemical datasets to further investigate element-element relationships. By producing crossplots of the eigenvectors, it is possible to identify groups of elements which likely share similar mineralogical distributions. The principal element associations as predicted by the results of PCA are described in the following paragraphs.

Eigenvector (EV) analysis of the sandstone dataset indicated that eigenvector 1 (EV1, defined as the most important source of statistical variation in the dataset) and EV3 (defined as the third most important source of statistical variation) account for 50.26% and 6.74% of the variance in the dataset, respectively. The crossplot of EV1 and EV3 (Fig. 12a) accounting for a total of 57% of the variability in the element concentrations of all of the sandstone samples define five broad element groups:

1. **Group 1:** SiO$_2$ is concentrated in quartz
2. **Group 2:** CaO is linked with carbonate minerals, principally as cement in the sandstones, however, when grouped with Fe$_2$O$_3$, represents iron-bearing carbonate minerals (e.g. ankerite, siderite).
3. **Group 3:** Represents a group strongly controlled by volcanic material. These elements are observed to have strong positive correlations and produce a dark red coloured powder when cuttings samples were crushed. For these elements to be significantly enriched in a sample (with high iron and calcium concentrations also observed in the raw geochemical data), breakdown of mafic volcanic material is required.
4. **Group 4:** Zr, Cr and Nb represent zircon, and chromium-bearing and niobium-bearing heavy minerals, respectively. The other elements that plot close to these elements are also likely linked to heavy minerals and/or rock fragment material.
5. **Group 5:** Al$_2$O$_3$ closely correlates with total clay content, while K$_2$O and Rb are also linked to feldspars. This group represents clay minerals and feldspars.
Fig. 12. a) EV plot of sandstone data using EV 1 and 3 accounting for 57% of the variability in the data, b) EV plot of mudstone data using EV 1 and 2 accounting for 50% of the variability in the data. Note, variables that plot close to one another have a positive relation while variables that plot opposite one another have a negative relation.
Eigenvector (EV) analysis of the mudstone dataset indicated that EV1 and EV2 account for 32.01% and 18.29% of the variance in the dataset, respectively. The crossplot of EV1 and EV2 (Fig. 12b) accounting for a total of 50.3% of the variability in the element concentrations of all of the mudstone samples define eight broad element groups:

1. Group 1: SiO$_2$ is concentrated in silt-grade quartz.
2. Group 2: Zr is concentrated in the heavy mineral zircon and as it plots close to SiO$_2$, it is likely controlled by silt-grade material in the mudstones.
3. Group 3: This broad group of elements situated close to Al$_2$O$_3$ represents clay minerals, with K$_2$O and Rb representing the breakdown of K-feldspar to the clay mineral illite.
4. Group 4: Nb represents niobium-bearing heavy minerals (e.g. rutile) but is also controlled by clays.
5. Group 5: CaO represents carbonate minerals.
6. Group 6: This broad group of elements is principally related with volcanic material, as described for the sandstone data.
7. Group 7: Cr represents chromium-bearing heavy minerals (e.g. Cr-spinel), while Pb and Sr plot close on the EV plot and likely can also be related to heavy mineral material.
8. Group 8: This group can be related to pyrite, where Zn and As likely represent minor constituents.

3.5 Key Geochemical Variables

The relationships between elements observed in the binary diagrams and the EV plots have been used to gain wider interpretations between element-mineral relationships. When combined with the observations and geochemical data of the cored sections, a number of key discriminating variables are found to be able to explain trends in the geochemistry of core and cuttings samples (Table 3). The insights gathered using the observational, graphical and statistical techniques can be used to guide interpretations of changing mineralogy and therefore changing detrital composition in the cuttings data of the wells used in this study. Changing detrital composition upsection in wells can be used to indicate changing provenance of sediments through time, and can be correlated across wells in the basin to gain an understanding of sediment dispersal patterns in the Dampier Sub-basin.
Table 3: Summary of geochemical variables and their significance to mineralogy as determined by core geochemical analysis and Hylogger data, and cuttings geochemical analysis including binary diagram element relationships and principal component analysis.

<table>
<thead>
<tr>
<th>Geochemical Element/Ratio</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>Closely linked to total clay content. Strong positive relationship with Fe₂O₃, TiO₂, K₂O, Rb and Cs which are components of clay minerals.</td>
</tr>
<tr>
<td>Rb/Cs</td>
<td>Linked to changing clay mineralogy in mudstones</td>
</tr>
<tr>
<td>K₂O/Al₂O₃</td>
<td>Closely linked to illite/K-feldspar vs. kaolinite/plagioclase feldspar. High values indicate presence of K-feldspar in sandstones and illite in mudstones, whereas low values indicate an absence of K-feldspar/illite and/or high plagioclase in sandstones and high kaolinite in mudstones</td>
</tr>
<tr>
<td>TiO₂/Al₂O₃</td>
<td>Closely linked to titanium-bearing heavy minerals [e.g. rutile (TiO₂) and Ilmenite (FeTiO₃)] and volcanic material when normalised by clays. Strong positive relationship with vanadium, manganese, barium, caesium and tellurium exist in interpreted volcanic material</td>
</tr>
<tr>
<td>Zr</td>
<td>Closely linked to the heavy mineral zircon (ZrSiO₂). Linked to SiO₂ in mudstones (silt-grade zircon)</td>
</tr>
<tr>
<td>Cr</td>
<td>Closely linked to chromium-bearing heavy minerals e.g. Cr-spinel</td>
</tr>
<tr>
<td>CaO</td>
<td>Linked to carbonate cements e.g. calcite, dolomite, ankerite and siderite</td>
</tr>
<tr>
<td>S</td>
<td>Linked to sulphur cements e.g. pyrite (FeS)</td>
</tr>
<tr>
<td>Fe₂O₃/Al₂O₃</td>
<td>Closely linked to iron-bearing cements/minerals when normalised over clays. Used in conjunction with CaO and S e.g. siderite and ankerite when CaO and Fe₂O₃/Al₂O₃ covary, and pyrite when S and Fe₂O₃/Al₂O₃ covary, respectively</td>
</tr>
</tbody>
</table>

3.6 Geochemical Characterisation

The wells on the flanks of the basin (Montague-1 bordering the western margin and Legendre-1 bordering the eastern margin), are predominantly composed of sandstones throughout the Late Jurassic section of interest, as shown by the gamma-ray logs and the grain size of samples collected as inferred from the SiO₂/Al₂O₃ ratios, as described in section 3.4.1. Wanaea-1, however, which is situated in the centre of the basin on the Madeline Trend, is predominantly mudstone-rich at the base of the section of interest and sandstone-rich at the top.

The wells are characterised by marked zones of varying geochemical composition, with each zone differing from the zone above and below by more than one discriminating variable (Table 3). In this case, an individual chemostratigraphic zone or ‘chemozone’ is created. Within a chemozone in which a small section differs by only one or two
variables, an individual ‘subzone’ is created, which forms part of the larger chemozone. The variables in the rest of the chemozone, besides the subzone, remain similar. Chemozones essentially reflect chemofacies, whereby the similarities in geochemical composition likely reflect similar sediment provenance. A description of the discriminating variables of each identified chemozone for Montague-1, Wanaea-1 and Legendre-1 is described in the following subsections.

3.6.1 Montague-1

The section of interest in the Montague-1 well is divided into 12 chemozones with a mix of both sandstone and mudstone samples analysed (Fig. 13 and Table 4).

**Chemozone 1:** The deepest zone of interest in Montague-1 is characterised by mixed sandstones and mudstones. The sandstones occur as multiple thin intervals with a high clay content containing caesium-rich clays and low K₂O/Al₂O₃ indicating a high plagioclase/kaolinite content and low K-feldspar/illite. Low TiO₂/Al₂O₃, low- moderate Zr and high Cr show that zircon and chromium-bearing heavy minerals are present, while moderate S that covaries with Fe₂O₃/Al₂O₃ indicates the presence of pyrite cement. A subzone is reflected by a zone containing an uncharacteristically low Cr content. The mudstones in this chemozone have high clay content that is rubidium-rich with high kaolinite clay content. Moderate Zr and Cr point towards the presence of zircon and chromium-bearing heavy minerals. Moderate S and Fe₂O₃/Al₂O₃ indicate the presence of pyrite cement.

**Chemozone 2:** This zone is distinguished by sandstones with markedly higher carbonate content compared to sandstones of chemozone 1, as well as clays higher in rubidium and a higher Fe₂O₃/Al₂O₃ ratio, indicating more abundant pyrite cement.

**Chemozone 3:** This zone is characterised by sandstones distinguished from the zone below by significantly lower clay content and Cr-bearing heavy minerals, and higher carbonate cement, with CaO at its maximum concentration in the well.

**Chemozone 4:** This chemozone is identified by mudstones with greater zircon and sulphur content and slightly lower rubidium clay mineralogy than the mudstones of chemozone 1. A subzone is due to mudstones with significantly lower Cr-bearing minerals than the rest of the chemozone.
Fig. 13: Montague-1 discriminating variable tracks displayed with gamma ray log. Note, ‘s’ in the chemostrat zone column is an abbreviation of ‘subzone’.

**Chemozone 5:** Sandstone characterises this zone with slightly higher clay content, lower heavy mineral content and significantly lower carbonate cement than the sandstones of chemozone 3. Slightly higher S contents correspond with minor pyrite cement, absent in chemozone 3.

**Chemozone 6:** This zone is differentiated from the zone below by significantly higher K₂O/Al₂O₃ indicating increased K-feldspar/illite content and higher TiO₂/Al₂O₃ pointing towards increased Ti-bearing heavy mineral (HM) content.

**Chemozone 7:** Sandstones with markedly high ratios of TiO₂, CaO, S and Fe₂O₃/Al₂O₃, as well as higher caesium clay mineralogy discriminate this zone from chemozone 6 below. These elements that strongly covary are likely related to the input of volcanic material during this time in the Montague-1 area of the basin.

**Chemozone 8:** This chemozone is identified by sandstones that are differentiated from chemozone 7 by much lower values of TiO₂, CaO, S and Fe₂O₃/Al₂O₃, related to the absence of volcanic material input. The chemozone also corresponds with higher Rb-bearing clay content and zircon material.
Table 4: Summary of Montague-1 chemozone division discriminating variables.

<table>
<thead>
<tr>
<th>Chemozone</th>
<th>Lithology</th>
<th>Clay Content</th>
<th>$K_2O/Al_2O_3$</th>
<th>Heavy Minerals</th>
<th>Cements</th>
<th>Subzones/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sandstone</td>
<td>High, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low, high Cr-bearing HM</td>
<td>Moderate S and Fe$_2O_3/Al_2O_3$ indicate pyrite cement</td>
<td>Subzone has absence of Cr-bearing heavy minerals</td>
<td></td>
</tr>
<tr>
<td>2 Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite</td>
<td>Low, high Cr-bearing HM</td>
<td>Low-moderate S and Fe$_2O_3/Al_2O_3$ indicate pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase/low K-feldspar</td>
<td>Low-moderate zircon</td>
<td>Very high CaO and Fe$_2O_3/Al_2O_3$ indicate major iron-bearing carbonate cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Moderate zircon and Cr-bearing HM</td>
<td>Absence of major carbonate and pyrite cement</td>
<td>Subzone has significantly low Cr-bearing HM</td>
<td></td>
</tr>
<tr>
<td>5 Sandstone</td>
<td>Moderate, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low HM content</td>
<td>Low-moderate CaO and S, moderate-high Fe$_2O_3/Al_2O_3$ indicate iron-bearing carbonate minor pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Sandstone</td>
<td>Low</td>
<td>Moderate, presence of K-feldspar/illite</td>
<td>Moderate Ti-bearing HM</td>
<td>Moderate S and Fe$_2O_3/Al_2O_3$ related to pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low-moderate, presence of K-feldspar/illite</td>
<td>High Ti-bearing HM</td>
<td>Very high CaO, S and Fe$_2O_3/Al_2O_3$</td>
<td>Very high Ti, CaO, S and Fe$_2O_3/Al_2O_3$ related to volcanic material</td>
<td></td>
</tr>
<tr>
<td>8 Sandstone</td>
<td>Moderate, Rb-rich</td>
<td>Low-moderate, presence of K-feldspar/illite</td>
<td>Low HM, minor zircon</td>
<td>Low, slightly increasing CaO, S and moderate Fe$_2O_3/Al_2O_3$ relate to minor carbonate and pyrite cement</td>
<td>Subzone marked by higher K-feldspar/illite</td>
<td></td>
</tr>
<tr>
<td>9 Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low HM</td>
<td>Absence of major carbonate and pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Sandstone</td>
<td>Low</td>
<td>High, presence of K-feldspar/illite</td>
<td>Low HM</td>
<td>Low-moderate S, moderate Fe$_2O_3/Al_2O_3$ indicate pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Sandstone</td>
<td>Moderate, Rb-rich</td>
<td>High, presence of K-feldspar/illite</td>
<td>Low zircon and Cr-bearing HM</td>
<td>Absence of major carbonate and pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Zircon and high Cr-bearing HM</td>
<td>Absence of major carbonate and pyrite cement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note, HM means heavy mineral and a low $K_2O/Al_2O_3$ ratio does not necessarily indicate high plagioclase feldspar/kaolinite content, it can also indicate a low concentration of both plagioclase feldspar/kaolinite and K-feldspar/illite in the sediments.
**Chemozone 9:** This zone is characterised by sandstones distinguished from zone 8 below by slightly lower clay, K-feldspar, zircon and carbonate cement. A subzone is characterised by markedly higher K-feldspar/illite.

**Chemozone 10:** Sandstones characterise this zone with higher K\(_2\)O/Al\(_2\)O\(_3\) indicating sediments with increased concentrations of K-feldspar and/or illite. Low-moderate S and moderate Fe\(_2\)O\(_3\)/Al\(_2\)O\(_3\) point towards the presence of pyrite cement, not present in chemozone 9.

**Chemozone 11:** This chemozone is identified by sandstones with greater clay content, slightly lower K\(_2\)O/Al\(_2\)O\(_3\), slightly higher zircon concentration and an absence of pyrite cement in comparison to chemozone 10.

**Chemozone 12:** The shallowest chemozone is characterised by sandstones with markedly higher clay content and increased zircon and chromium-bearing heavy minerals than those sandstones directly below.

### 3.6.2 Wanaea-1

The section of interest in the Wanaea-1 well was differentiated into 13 chemozones with a mix of both sandstone and mudstone lithologies (Fig. 14 and Table 5). The geochemistry indicates a complete absence of K-feldspar grains/illite clay and titanium-bearing heavy minerals in this well.

**Chemozone 1:** The deepest zone of the section of interest in Wanaea-1 is characterised by sandstones with high clay content that is caesium-rich with high kaolinite content. The sandstones contain high zircon content and moderate Cr-bearing heavy minerals, while iron-bearing carbonate and pyrite cements are present.

**Chemozone 2:** This zone is identified by a thick section of mudstones with high clay content that has rubidium-bearing clays and high kaolinite content. Moderate zircon material and high chromium-bearing heavy minerals are present, as is pyrite cement.

**Chemozone 3:** Sandstones with an absence of heavy minerals and high iron-bearing carbonate cement differentiate this chemozone from chemozone 1.
Fig. 14. Wanaea-1 discriminating variable tracks displayed with gamma ray log.

**Chemozone 4:** This chemozone is distinguished from chemozone 3 by a higher rubidium clay content with the presence of zircon and chromium-bearing heavy minerals. It also has a lower carbonate cement content with pyrite cement present.

**Chemozone 5:** Mudstones characterise this zone and are similar to the mudstones of chemozone 2, however, they display an absence of pyrite cement and the presence of a carbonate cement.

**Chemozone 6:** This zone is identified by sandstones with higher zircon and chromium-bearing heavy minerals than chemozone 4 sandstones, and a lower Fe₂O₃/Al₂O₃ value, indicating the carbonate cement is not iron-bearing.
Table 5: Summary of Wanaea-1 chemozone division discriminating variables.

<table>
<thead>
<tr>
<th>Chemozone</th>
<th>Lithology</th>
<th>Clay Content</th>
<th>$\text{K}_2\text{O}/\text{Al}_2\text{O}_3$</th>
<th>Heavy Minerals</th>
<th>Cements</th>
<th>Subzones/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sandstone</td>
<td>High, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>High zircon, moderate Cr-bearing HM</td>
<td>Low-moderate CaO, moderate S and moderate-high Fe$_2$O$_3$/Al$_2$O$_3$ show iron-bearing carbonate/pyrite cement</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Moderate zircon, high Cr-bearing HM</td>
<td>Moderate S and Fe$_2$O$_3$/Al$_2$O$_3$ indicate pyrite cement</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sandstone</td>
<td>High, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low HM content</td>
<td>High CaO and Fe$_2$O$_3$/Al$_2$O$_3$ show iron-bearing carbonate cement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sandstone</td>
<td>High, Rb-rich and Cs</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Moderate zircon, Cr-bearing HM</td>
<td>Moderate CaO, S and Fe$_2$O$_3$/Al$_2$O$_3$ show carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Moderate zircon, high Cr-bearing HM</td>
<td>Moderate CaO indicates carbonate cement</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Sandstone</td>
<td>Moderate Rb and Cs</td>
<td>Low, high plagioclase/kaolinite</td>
<td>High zircon, Cr-bearing HM</td>
<td>High CaO and moderate S and Fe$_2$O$_3$/Al$_2$O$_3$ show carbonate and minor pyrite cement</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Moderate zircon and Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Moderate zircon and Cr-bearing HM</td>
<td>Low S and Fe$_2$O$_3$/Al$_2$O$_3$ indicate minor pyrite cement</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>High zircon, moderate Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Sandstone</td>
<td>Moderate, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Moderate zircon, Cr-bearing HM</td>
<td>Low S and Fe$_2$O$_3$/Al$_2$O$_3$ indicate minor pyrite cement</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase</td>
<td>Low zircon and Cr-bearing HM</td>
<td>Low CaO, S and Fe$_2$O$_3$/Al$_2$O$_3$ show minor carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase</td>
<td>Low HM content</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase</td>
<td>Low zircon and Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Moderate zircon, high Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
</tbody>
</table>

Note, HM means heavy mineral and a low $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio does not necessarily indicate high plagioclase feldspar/kaolinite content, it can also indicate a low concentration of both plagioclase feldspar/kaolinite and K-feldspar/illite in the sediments.
**Chemozone 7:** This chemozone is composed of both mudstones and thin beds of sandstone. The sandstones have higher clay content than chemozone 6 sandstones and lower zircon and chromium-bearing heavy minerals, as well as an absence of major carbonate and pyrite cements. The mudstones have lower chromium-bearing heavy minerals, an absence of carbonate and presence of pyrite cement in comparison to chemozone 5 mudstones. A subzone is distinguished by a significantly higher chromium-bearing heavy mineral content.

**Chemozone 8:** Sandstones in this chemozone have higher zircon and lower chromium-bearing heavy minerals than the chemozone below, as well as slightly higher rubidium-rich clays.

**Chemozone 9:** This zone is identified by sandstones with lower clay, zircon and chromium-bearing heavy mineral content than chemozone 8. The sandstones also contain minor pyrite cement, which is absent in the sandstones below.

**Chemozone 10:** This chemozone is differentiated by the sandstones of chemozone 9 by lower clay, zircon and chromium-bearing heavy mineral content, as well as the presence of minor carbonate cement.

**Chemozone 11:** Sandstones in this chemozone have an absence of zircon and chromium-bearing heavy minerals which are present in chemozone 10. An absence of pyrite and carbonate cement also distinguishes this chemozone from the chemozone below.

**Chemozone 12:** This chemozone is characterised by sandstones with low zircon and chromium-bearing heavy minerals which are not present in the sandstones of chemozone 11.

**Chemozone 13:** Mudstones characterise the shallowest zone of interest in Wanaea-1 and have higher zircon and chromium-bearing heavy mineral contents than the mudstones of chemozone 7.

### 3.6.3 Legendre-1

The section of interest in the Legendre-1 well was differentiated into 14 chemozones dominantly composed of sandstones throughout the section with minor mudstones (Fig. 15 and Table 6). Legendre-1 samples were consistently high in chromium, which could be related to drilling additives used in drilling the well. It is for this reason that chromium concentrations should be used with caution.
**Chemozone 1:** The deepest zone of the section of interest in Legendre-1 is characterised by sandstones with moderate clay content that has a high content of caesium clay minerals and low-moderate K$_2$O/Al$_2$O$_3$ indicating the presence of K-feldspar/illite. A low content of titanium-bearing heavy minerals and a high content of zircon and chromium-bearing heavy minerals as well as the presence of pyrite and carbonate cement characterise chemozone 1.

**Fig. 15.** Legendre-1 discriminating variable tracks displayed with gamma ray log.

**Chemozone 2:** This zone is characterised by sandstones without the presence of K-feldspar/illite and lower zircon and chromium-bearing heavy minerals in comparison to chemozone 1. They also indicate higher pyrite cement and an absence of carbonate cement.

**Chemozone 3:** The sandstones in this zone have lower clay content and significantly higher contents of titanium-bearing heavy minerals compared to chemozone 2, as well as an absence of chromium-bearing heavy minerals.

**Chemozone 4:** This zone is identified by sandstones with lower titanium-bearing heavy minerals and higher chromium-bearing heavy minerals than chemozone 3. The sandstones have also slightly higher clay contents.
Table 6: Summary of Legendre-1 chemozone division discriminating variables.

<table>
<thead>
<tr>
<th>Chemozone</th>
<th>Lithology</th>
<th>Clay Content</th>
<th>K₂O/Al₂O₃</th>
<th>Heavy Minerals</th>
<th>Cements</th>
<th>Subzones/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low-moderate, presence of K-feldspar/illite</td>
<td>Low Ti-bearing HM, high zircon and Cr-bearing HM</td>
<td>Moderate-high CaO, S and Fe₂O₃/Al₂O₃ show pyrite and carbonate cement</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low Ti- and Cr-bearing HM and zircon</td>
<td>High S and moderate Fe₂O₃/Al₂O₃ indicate pyrite cement</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Very high Ti-bearing HM, low zircon</td>
<td>High S and Fe₂O₃/Al₂O₃ show pyrite cement</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon, Ti-bearing HM, high Cr-bearing HM</td>
<td>High S and Fe₂O₃/Al₂O₃ indicate pyrite cement</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sandstone</td>
<td>Moderate, Rb and Cs</td>
<td>Low-moderate, presence of K-feldspar/illite</td>
<td>Very high zircon, moderate Cr-bearing HM</td>
<td>Moderate S and low Fe₂O₃/Al₂O₃ indicate minor pyrite cement</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Sandstone</td>
<td>Low</td>
<td>Low, high plagioclase</td>
<td>Moderate Ti- and Cr-bearing HM</td>
<td>Low CaO, S and moderate Fe₂O₃/Al₂O₃ indicate minor carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Sandstone</td>
<td>High, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Moderate zircon, high Cr-bearing HM</td>
<td>High S and low Fe₂O₃/Al₂O₃ show minor pyrite cement</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>High Ti-bearing HM, low zircon and Cr-bearing HM</td>
<td>High S and Fe₂O₃/Al₂O₃ indicate pyrite cement</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Sandstone</td>
<td>High, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon, high Cr-bearing HM</td>
<td>High CaO and moderate Fe₂O₃/Al₂O₃ indicate iron-bearing carbonate cement</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon and Cr-bearing HM</td>
<td>Moderate CaO, S and low-moderate Fe₂O₃/Al₂O₃ indicate minor pyrite and carbonate cement</td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Low zircon, high Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Sandstone</td>
<td>Moderate, Cs-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon, Ti- and Cr-bearing HM</td>
<td>Low carbonate and moderate S and Fe₂O₃/Al₂O₃ indicate pyrite and minor carbonate cement</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Mudstone</td>
<td>High, Rb-rich</td>
<td>Low, high kaolinite/low illite</td>
<td>Moderate zircon and Cr-bearing HM</td>
<td>Subzone marked by very high Fe₂O₃/Al₂O₃, lower Cr and S</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Sandstone</td>
<td>High, Cs to Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon and Cr-bearing HM</td>
<td>Absence of carbonate and pyrite cement</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Sandstone</td>
<td>High, Rb-rich</td>
<td>Low, high plagioclase/kaolinite</td>
<td>Low zircon</td>
<td>Increasing Rb/Cs ratio, changing clay mineralogy, and CaO</td>
<td></td>
</tr>
</tbody>
</table>

Note: HM means heavy mineral and a low K₂O/Al₂O₃ ratio does not necessarily indicate high plagioclase feldspar/kaolinite content, it can also indicate a low concentration of both plagioclase feldspar/kaolinite and K-feldspar/illite in the sediments.
**Chemozone 5:** This zone is characterised by sandstones with higher clay content containing higher rubidium-bearing clay minerals, as well as a slight increase in the presence of K-feldspar/illite, an absence of titanium-bearing heavy minerals, a significantly higher zircon content and a lower pyrite cement content compared to the sandstones of chemozone 4.

**Chemozone 6:** Sandstones with lower clay and K-spar/illite content, an increase in the content of titanium-bearing heavy minerals, an absence of zircon, and higher CaO, S and Fe₂O₃/Al₂O₃ indicating the presence of carbonate and greater pyrite distinguish this chemozone from chemozone 5.

**Chemozone 7:** This chemozone is composed of sandstones with higher clay content, lower titanium-bearing heavy minerals, higher zircon and chromium-bearing heavy minerals and an absence of carbonate cement, in comparison to sandstones of chemozone 6.

**Chemozone 8:** This zone is characterised by sandstones with lower clay content, a higher volume of titanium-bearing heavy minerals and a lower content of zircon and chromium-bearing heavy minerals, as well as greater pyrite cement, compared to chemozone 7.

**Chemozone 9:** Sandstones characterise this zone with higher clay content, lower titanium-bearing heavy minerals, higher chromium-bearing heavy minerals and the presence of iron-bearing carbonate cement in comparison to chemozone 8.

**Chemozone 10:** This zone is composed of both mudstones and sandstones. The sandstones have lower clay content that is more rubidium-rich than the sandstones of chemozone 9 and have lower chromium-bearing minerals, less carbonate cement and the presence of pyrite cement. The mudstones have high clay content that contains rubidium-rich clays with low zircon and high chromium-bearing heavy minerals.

**Chemozone 11:** This chemozone is characterised by sandstones with less clay content that is more caesium-rich than the sandstones of chemozone 10, as well as containing titanium-bearing heavy minerals and greater pyrite cement. A subzone in this chemozone is characterised by lower chromium-bearing heavy minerals and higher Fe₂O₃/Al₂O₃.
**Chemozone 12:** This thin chemozone is characterised by mudstones with higher zircon and lower chromium-bearing heavy minerals in comparison to the mudstones of chemozone 10.

**Chemozone 13:** Sandstones with higher clay content and a greater content of rubidium-rich clays, particularly in the upper section of the chemozone, an absence of titanium-bearing minerals and higher carbonate cement differentiate this chemozone from the sandstones of chemozone 11.

**Chemozone 14:** This chemozone is distinguished from chemozone 13 by higher clay content and rubidium-rich clays, an absence of chromium-bearing heavy minerals and the presence of pyrite cement.

**4. Discussion**

**4.1 Dampier Sub-basin Late Jurassic Geochemical Characterisation**

The geochemical characterisation of Montague-1, Wanaea-1 and Legendre-1 using data acquired from pXRF analysis is principally controlled by the detrital mineralogy, clay content and mineralogy, feldspar content and heavy mineral (zircon and chromium- and titanium-bearing heavy minerals) content, and diagenetic processes, carbonate and pyrite cement. Montague-1, on the western margin of the basin, is characterised by 12 chemozones mostly composed of sandstones, Wanaea-1, in the centre, is comprised of 13 chemozones with both mudstones and sandstone sections, and Legendre-1, on the eastern margin of the basin, is characterised by 14 chemozones with mainly sandstone composition. The chemozones divide the sedimentary columns of each well into discrete zones of geochemical composition and, therefore, divide zones that have different detrital mineralogy and diagenetic phases.

A general detrital geochemical trend throughout the basin is a decrease in the caesium content and an increase in the rubidium content of clays through time, however, the composition of K-feldspar/illite and plagioclase feldspar/kaolinite, heavy minerals and cement types vary throughout the basin from sediments of equivalent age and through time (Fig. 16). It is therefore difficult to correlate sedimentary rock of equivalent biostratigraphic age across the Dampier Sub-basin, due to the major variation in geochemical composition in different areas of the basin.

The major variation in detrital mineralogy is caused by varying provenance, sediment feeder pathways and sediment dispersal in different areas of the basin at equivalent
biostratigraphic ages. There also appears to be mixing of sediment inputs into the basin, particularly during the Tithonian (Table 7). Age equivalent mudstones show similar geochemistry, which is expected as these lithologies are deposited throughout a large area as relatively homogenous hemipelagic sedimentation. A depositional history of the Late Jurassic stratigraphy is described in the following section. This history is based on a comparison of the chemozones characterised in each well across the basin deposited at equivalent biostratigraphic ages.

4.2 Dampier Sub-basin Late Jurassic Depositional System

4.2.1 Depositional History

The Late Jurassic sediments deposited in the Dampier Sub-basin can be described in terms of differing mineralogy during equivalent biostratigraphic ages (Table 7). The differing mineralogy of sediments in different areas of the basin signify discrete sedimentary sources and feeder pathways into the basin. A history of the deposition and dispersal of sediments into the western, central and eastern areas of the Dampier Sub-basin is described in the following section.

1. *W. spectabilis* time (Oxfordian):

Western margin: Rare sandstones with low zircon and moderate chromium-bearing heavy minerals were deposited in the western area. These systems are interpreted to be restricted in their basinal extent due to contrasting mineralogical composition to sandstones deposited in the eastern and central areas of the basin.

Central basin: Mostly mudstones, although thin, rare sandstones with high zircon, moderate chromium-bearing heavy minerals and pyrite cement are present. Similar geochemical composition to the eastern margin sandstones, point towards a likely eastern margin sediment source.

Eastern margin: Thick, gradually waning sandstone deposition sourced from the eastern margin due to contrasting geochemical composition to sandstones of the western margin. Highly fluctuating mineralogical composition signifies a highly variable sediment provenance during the Oxfordian supplying the eastern margin.
Fig. 16. Biostratigraphic correlation of Montague-1, Wanaea-1 and Legendre-1 with chemozones displayed. Note, the dinoflagellate zones Cret= Cretaceous (above Late Jurassic stratigraphy), P. iehene=r, UD. j= upper D. jurassicum, LD. j= lower D. jurassicum, O. mo= O. montgomeryi, C. pe= C. perforans, D. sw= D. Swanense, W. cl= W. clathrata, W. sp= W. spectabilis, and Call= Callovian (Middle Jurassic, below Late Jurassic Stratigraphy) based on the Northern Carnarvon Basin Biozonation and Stratigraphy Chart (Kelwan et al, 2013). Red lines separate biostratigraphic zones.
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Biostratigraphic Age</th>
<th>Chemo-zones</th>
<th>Montague-1</th>
<th>Chemo-zones</th>
<th>Sediment Detrital Mineralogy</th>
<th>Chemo-zones</th>
<th>Legendre-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxfordian</td>
<td>W. spectabilis</td>
<td>1</td>
<td>No Ti-bearing HM, low zircon, moderate Cr-bearing HM, no carbonate but moderate pyrite cement</td>
<td>1</td>
<td>Mostly mudstones, however, sandstones have no Ti-bearing HM, high zircon, moderate Cr-bearing HM, no carbonate but moderate pyrite cement</td>
<td>1</td>
<td>High Ti- and Cr-bearing HM, high zircon, low carbonate and high pyrite cement</td>
</tr>
<tr>
<td></td>
<td>D. swanense</td>
<td>2</td>
<td>No Ti-bearing HM, high Cr-bearing HM, high carbonate and pyrite cement</td>
<td>4</td>
<td>Mostly mudstones, sandstones have no Ti-bearing HM, moderate Cr-bearing HM, high carbonate and moderate pyrite cement</td>
<td>10</td>
<td>Low Ti-bearing HM, moderate Cr-bearing HM, low carbonate and moderate pyrite cement</td>
</tr>
<tr>
<td>Kimmeridgian</td>
<td>W. clathrata</td>
<td>1</td>
<td>No Ti-bearing HM, high Cr-bearing HM, high carbonate and pyrite cement</td>
<td>4</td>
<td>Mostly mudstones, sandstones have no Ti-bearing HM, moderate Cr-bearing HM, high carbonate and moderate pyrite cement</td>
<td>10</td>
<td>Low Ti-bearing HM, moderate Cr-bearing HM, low carbonate and moderate pyrite cement</td>
</tr>
<tr>
<td></td>
<td>D. swanense</td>
<td>2</td>
<td>Low Ti- and Cr-bearing HM, high iron-bearing carbonate cement, no pyrite cement</td>
<td>7</td>
<td>No sandstones</td>
<td>11</td>
<td>Low Ti-bearing HM, moderate Cr-bearing HM, low carbonate and moderate pyrite cement</td>
</tr>
<tr>
<td></td>
<td>C. perforans</td>
<td>3</td>
<td>Low Ti- and Cr-bearing HM, high iron-bearing carbonate cement, no pyrite cement</td>
<td>7</td>
<td>Absence of Ti-bearing HM, moderate Cr-bearing HM, no carbonate or pyrite cement</td>
<td>11</td>
<td>Low Ti-bearing HM, moderate Cr-bearing HM, low carbonate and moderate pyrite cement</td>
</tr>
<tr>
<td></td>
<td>O. montgomeryi</td>
<td>4</td>
<td>No sandstones</td>
<td>7</td>
<td>Absence of Ti-bearing HM, moderate Cr-bearing HM, no carbonate or pyrite cement</td>
<td>11</td>
<td>Low Ti-bearing HM, moderate Cr-bearing HM, low carbonate and moderate pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower D. jurassicum</td>
<td>5</td>
<td>Moderate K-feldspar/illite, low zircon, high Ti-bearing HM, low Cr-bearing HM, volcanic material, pyrite cement</td>
<td>7</td>
<td>Low K-feldspar/illite, high zircon, low Ti-bearing HM, high Cr-bearing HM, no volcanic material, no pyrite cement</td>
<td>13</td>
<td>Low K-feldspar/illite, high zircon, low Ti-bearing HM, low Cr-bearing HM, no volcanic material, no pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>Moderate K-feldspar/illite, low zircon, high Ti-bearing HM, low Cr-bearing HM, volcanic material, pyrite cement</td>
<td>7</td>
<td>Low K-feldspar/illite, high zircon, low Ti-bearing HM, high Cr-bearing HM, no volcanic material, no pyrite cement</td>
<td>13</td>
<td>Low K-feldspar/illite, high zircon, low Ti-bearing HM, low Cr-bearing HM, no volcanic material, no pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper D. jurassicum</td>
<td>8</td>
<td>Moderate K-feldspar/illite, low zircon, low Cr-bearing HM, pyrite cement, no carbonate cement</td>
<td>9</td>
<td>Low K-feldspar/illite, low zircon, moderate Cr-bearing HM, no carbonate cement, low pyrite cement</td>
<td>13</td>
<td>Low K-feldspar/illite, low zircon, low Cr-bearing HM, carbonate cement, low pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>Moderate K-feldspar/illite, low zircon, low Cr-bearing HM, pyrite cement, no carbonate cement</td>
<td>9</td>
<td>Low K-feldspar/illite, low zircon, moderate Cr-bearing HM, no carbonate cement, low pyrite cement</td>
<td>13</td>
<td>Low K-feldspar/illite, low zircon, low Cr-bearing HM, carbonate cement, low pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>High clay content and Cr-bearing HM, absence of carbonate and pyrite cement</td>
<td>12</td>
<td>Low clay content and Cr-bearing HM, absence of carbonate and pyrite cement</td>
<td>14</td>
<td>High clay content and low Cr-bearing HM, minor carbonate and pyrite cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Comparison of sandstone detrital geochemistry (chemozones) through Late Jurassic biostratigraphic zones.
2. *W. clathrata* and *D. swanense* time (Kimmeridgian):

Western margin: Infrequent sandstones with high chromium-bearing heavy minerals, carbonate and pyrite cement, sourced from a western margin source due to different mineralogical composition to the central and eastern sandstones.

Central basin: Thin sands with moderate chromium-bearing heavy minerals and carbonate and pyrite cement, likely sourced from the eastern margin due to similar mineralogical composition.

Eastern margin: Thick sandstones with low titanium-bearing heavy minerals, moderate Cr-bearing heavy minerals, low carbonate cement and moderate pyrite cement sourced from the Enderby Terrace. Kimmeridgian biostratigraphic zones in Legendre-1 are uncertain at this time and may be a result of erosion during this time period. This erosion may have sourced the Kimmeridgian sediments of Wanaea-1 through submarine fan systems.

3. *C. perforans* time (Tithonian):

Western margin: Sediment gravity flow sandstones with low titanium- and chromium-bearing heavy minerals and an iron-bearing carbonate cement. An absence of sandstone deposition in the central area of the basin indicates a restricted sediment dispersal along the western margin of the basin.

Central basin: No sandstone deposition during this time period, basinal mudstone deposition.

Eastern margin: Thick sandstones with low titanium-bearing heavy minerals, moderate Cr-bearing heavy minerals, low carbonate cement and moderate pyrite cement sourced from the eastern margin as an absence of sandstone deposition in the central part of the basin and differences in composition between the western and eastern margins represent basin margin restricted deposition at this time.

4. *O. montgomeryi* time (Tithonian):

Western margin: No sandstone deposition during this time period, mudstone deposition.

Central basin: Sandstones with moderate chromium-bearing heavy minerals, although lacking carbonate and pyrite cement. Source is likely from the eastern margin with extrabasinal carbonate grains not being transported to the centre of the basin resulting in different diagenetic processes.
Eastern margin: Thick sandstones from the Enderby Terrace area with low chromium-bearing heavy minerals, moderate chromium-bearing heavy minerals and the presence of moderate carbonate and pyrite cement. No sandstone deposition along the western margin represents a restricted system in the east, with depositional systems of significant transport distances transporting sand to the central area of the basin.

5. **Lower D. Jurassicum time (Tithonian):**

Western margin: Thick sandstones with moderate K-feldspar/illite, low zircon, high titanium-bearing heavy minerals, low chromium-bearing heavy minerals and pyrite cement. Volcanic material is present in this area of the basin marked by a high content of mafic material punctuated by high values of iron, calcium, titanium, vanadium, barium, manganese and caesium. The sandstones are a mix of basin-wide axial basin-floor fan sandstones with restricted sediment input from the western margin, resulting in a mixed geochemical signature.

Central basin: Common thin sandstones containing low K-feldspar/illite, high zircon, low titanium-bearing heavy minerals, high chromium-bearing heavy minerals and an absence of pyrite cement and volcanic material. These rocks are sand-rich and do not contain volcanic material from the western margin. It is therefore likely that the sandstones solely reflect the mineralogical composition of the major axial sediment system in the basin at this time.

Eastern margin: Thick sandstones with low K-feldspar/illite, high zircon, low titanium- and chromium-bearing heavy minerals with an absence of volcanic material and pyrite cement. These sediments are sourced from a mix of axial basin-floor fan sandstones as well as transverse input from the eastern margin with low chromium-bearing heavy minerals. The mineralogical composition is different from both the central area of the basin and the mixed eastern transverse and axial input, reflecting the restricted nature of the transverse sediment pathways.

6. **Upper D. Jurassicum time (Tithonian)**

Western margin: Thick sandstones with moderate K-feldspar/illite, low zircon, low chromium-bearing heavy minerals and pyrite cement. These sandstones are again different from the central area sandstones, reflecting continued, restricted transverse sediment supply from the western margin of the basin.
Central basin: Thick sandstones with low K-feldspar/illite, low zircon, moderate chromium-bearing heavy minerals and low pyrite cement. The sandstones being deposited in this area continued to be sourced from the major axial basin-floor fan system.

Eastern margin: Thick sandstones with low K-feldspar/illite, low zircon, low chromium-bearing heavy minerals, carbonate cement and low pyrite cement. The detrital signature is similar to the transverse basin-floor fan sandstones being deposited in the central and western parts of the basin, however, sediment from a carbonate-bearing source on the eastern margin is also being supplied during this time period, reflecting carbonate cement in these sandstones.

7. *P. Iehenese* time (Tithonian)

Western margin: Thick sandstones that grade into mudstones in upper Tithonian time. Axial input of chromium-bearing heavy mineral-rich sediments from the western margin again is mixed with axially supplied sands.

Central basin: Thick sandstones that grade into mudstones in upper Tithonian time. The sandstones continued to be deposited as basin-floor fan systems from an axial source.

Eastern margin: Thick sandstones are a mix of axial basin-floor fan systems that are deposited in the western and central areas of the basin and axial input of carbonate containing sediments from the western margin, resulting in a carbonate signature restricted to sandstones along the eastern margin.

4.2.2 Sediment Provenance and Dispersal

Sandstone deposition in the deep-water Dampier Sub-basin during the Oxfordian, Kimmeridgian and early Tithonian was dominantly transverse, based on interpretations of sediment dispersal through geochemical composition (Fig. 18 and Table 7). Restricted sandstone deposition is interpreted from contrasting geochemical compositions at wells along the basin margins and a general lack of sandstone deposition in the central area of the basin during this time. Sediment deposition in the west was likely controlled by a western margin source (Rankin Platform), and sediment deposition in the east was controlled by an eastern margin source (Enderby Terrace and Lambert Shelf). The sandstones deposited during this time period are classified as the Eliassen Formation, and are predominantly related to active rifting processes (Barber, 1994a; Jablonski, 1997).
The relatively restricted nature of sandstone deposition proximal to the basin margins can be related to sediment gravity flows and coalescing slope aprons from the unstable faulted margins. Erosion of Late Triassic Legendre Formation sediments from the basin margins and/or remobilization of shallow marine sediments from the shallow basin margin regions into the deeper troughs of the Dampier Sub-basin may also represent major sediment sources throughout the Late Jurassic during periods of sea level lowstand. Rare basin-floor fans with significant transport distances are interpreted to have supplied sand to the central part of the basin during this time.

In the Kimmeridgian, transverse sediment supply continued from the Oxfordian, supplying restricted sediments at the basin margins, however, rare thin sandstones were deposited in the central area of the basin. The composition of these sandstones is similar to the sandstones deposited along the eastern margin of the basin. Basin-floor fans with significant transport distances supplied sand to the central area of the basin. Throughout this time period, thick hemipelagic deposition resulted in the deposition of the Dingo Claystone, which has a common geochemical signature throughout the basin.

During the Early Tithonian, a major transverse sediment pathway sourced from the northeast (Beagle Sub-basin and/or Legendre Trend) resulted in the thick and increasingly sand-rich prolonged deposition of basin-floor fan sandstones in the Dampier Sub-basin. The basin-floor fan systems were sourced from the Angel Delta, in the Beagle Sub-basin and Lambert Shelf, and the Dupuy Delta, along the Lambert Shelf (Wulff and Barber, 1995; Jablonski, 1997; Longley et al., 2002; Tao et al., 2013). These deltas along the continental shelf directly fed the basin-floor fan systems that were widespread along the slope and deep water basinal areas of the northern Dampier Sub-basin.

During this time, however, axial sediment input continued in the basin, and mixed with the transverse basin-floor fan systems based on mixed geochemical compositions of the sediments at the basin margins. Based on different geochemical signatures of the sediments in the western and eastern areas of the basin, axial input from the western margin provided sediments to the west of the Dampier Sub-basin, and input from the eastern margin provided sediments to the east of the basin. The deep-water depositional systems did not have sufficient transport distances to supply sediments to the central areas of the basin, which occurred during the Kimmeridgian, and therefore do not correlate in terms of geochemical signature across the basin.
Clastic material of a strong volcanic nature, which was significantly different in geochemical composition compared to the other sediments deposited in the basin during this time, was deposited in the western area of the basin during Lower *D. jurassicum* time (middle Tithonian). The transverse sediments containing volcanic material are likely sourced from remobilized sediments from the western basin margin (Rankin Platform) or a volcanic source related to rifting processes proximal to the western margin of the Dampier Sub-basin (Exmouth Plateau).

Basin-floor fan sedimentation from the northeast was terminated at the end of the Late Jurassic due to a major sea-level transgression that cut-off of major sediment supply routes (Jablonski, 1997). This resulted in the gradual decrease of sandstone deposition in the basin observed in each well, grading into mudstones. The Late Jurassic also signified the end of rifting along the western margin of Australia providing stability along the basin margins of the Dampier Sub-basin and preventing further transverse input from the basin margins.

The interpretations made by this study are consistent with the heavy mineral analysis by Dibona and Scott (1990) of 14 wells in the Dampier and Barrow Sub-basins which had little success in correlating sedimentary rocks of the Late Jurassic. Heavy mineral suites were found to be highly variable between wells which were interpreted to reflect small-scale systems with localized/fault-controlled sources of input (Dibona and Scott 1990). These small-scale systems reflect the restricted transverse sedimentation from basin margins throughout the Late Jurassic, as determined by the geochemical characterisation of the three wells in the basin.

**4.2.3 Sediment Transport Models**

Sediment dispersal and transport in the Dampier Sub-basin during the Oxfordian, Kimmeridgian and Early Tithonian follows the tectono-sedimentary model of a normal rift basin presented by Gawthorpe and Leeder (2000) (Fig. 17). Deep troughs related to subsidence of the central Dampier Sub-basin formed a deep-water depositional environment during the Late Jurassic. Mass failure of the unstable hangingwall and footwall slopes (Rankin Platform and Enderby Terrace) likely resulted in slumps, slides and debris flows, all of which supplied transverse sediment input to the rift basin, forming the Eliassen Formation. The restricted nature of these transverse sediment systems resulted in the contrasting compositions at the basin margins and a lack of sandstone deposition in the central area of the Dampier Sub-basin. Elsewhere,
sedimentation was dominated by fine clastic and biogenic hemipelagic material, which formed the Dingo Claystone in the Dampier Sub-basin.

Fig. 17. Sedimentary processes occurring in the late stages of a normal fault array rift basin, akin to the Dampier Sub-basin during the early Late Jurassic. Deep sediment starved basins are formed due to subsidence and displacement along major border faults. Deepwater depositional systems dominate and are particularly axial with turbidites, slumps, slides and debris flow sedimentation (Gawthorpe and Leeder 2000).

Sediment supply in the Dampier Sub-basin was sufficiently greater during the Tithonian than during the Oxfordian and Kimmeridgian due to widespread basin-floor fan sandstone deposition. These fan sandstones were sourced from the Angel Delta in the Beagle Sub-basin and Lambert Shelf (Jablonski, 1997). The delta-fed turbidite systems also received transverse input of sediments from the basin margins, which continued from the Oxfordian and Kimmeridgian. The Maastrichtian Pab Sandstone turbidite system of Pakistan is analogous to the Angel Formation sandstones deposited in the Dampier Sub-basin during the Tithonian (Fig. 18). The Pab basin-floor fan sandstones were sourced from a prograding sand-rich slope-fan ramp complex which also received axial input from sediment gravity flows sourced from an unstable slope (Eschard et al., 2004).
4.3 Northern Carnarvon Basin Sediment Provenance

Southgate et al. (2011) and later Lewis and Sircombe (2013) determined that overall Middle to Upper Triassic Mungaroo Formation sediments of the NWS were likely sourced from igneous and metamorphic terranes of India and/or Antarctica located in Eastern Gondwana, signifying source material derived from a large area with long sediment transport routes (Fig. 19a). Local sources of detrital zircon material, for instance zircons from Triassic volcanic material, were also found to supply the Triassic Mungaroo Formation. Detrital zircons from the Early Cretaceous lower Barrow Group show similar age spectra to the Mungaroo Formation with dominant sediment provenance from southern sources and a general transport route from south to north (Fig. 19b) (Lewis and Sircombe, 2013).

The Triassic Mungaroo Formation and the Early Cretaceous lower Barrow Group are the major sandstone sequences below and above the Late Jurassic Angel Formation, respectively. It is evident from the work of Southgate et al. (2011) and Lewis and Sircombe (2013), that a dominant south to north sediment transport system existed along the western margin of Australia prior to and following the deposition of Late Jurassic sediments in the Northern Carnarvon Basin.
Fig. 21. Paleogeography and sediment transport pathways to the North West Shelf in the; a) Late Triassic and, b) Early Cretaceous (Lewis and Sircombe 2013).

This study suggests, however, that a dominant north to south sediment transport direction was prevalent in supplying the sandstones in the Northern Carnarvon Basin (Dampier Sub-basin) during the Late Jurassic. Sediment transport during this time was likely from the Pilbara/Yilgarn cratons and/or supply from river systems through the Officer and Canning basins that drained southern and central Australian. These rivers directly fed the Angel and Dupuy deltas on the Lambert Shelf which sourced the widespread basin-floor fans in the Dampier Sub-basin. Following the conclusion of
major rifting along the northwestern margin of Australia and a major sea-level transgression that led to the termination of Angel Formation sandstones, major sediment supply from the south which fed the Mungaroo Formation, was restarted and began feeding the Lower Barrow Delta in the Early Cretaceous (Jablonski, 1997; Southgate et al., 2011; Lewis and Sircombe, 2013).

4.4 Detrital Controls on Reservoir Quality and Diagenetic Processes
Differences in geochemical composition of sediments may not only signify differences in provenance, but also indicate potential differences in reservoir quality related to the detrital composition of sediments. Depositional facies and detrital composition of reservoirs strongly influence the types and distribution of diagenetic processes and, therefore, the reservoir quality of sandstone units (Morad et al., 2000; Morad et al., 2010). An understanding of the distribution of cements and authigenic clays is of great importance to the petroleum industry in evaluating porosity and permeability for hydrocarbon accumulations (Mcbride, 1985; Morad et al., 2000). A qualitative understanding of the distribution of framework grains important to the understanding of reservoir quality is provided by elevated elemental concentrations and/or singicantly high/low ratio values (Table 8).

Table 8: Summary of detrital grains and diagenetic effects on reservoir quality related to geochemical signatures (adapted from Morad et al., 2010).

<table>
<thead>
<tr>
<th>Type of Framework Grains</th>
<th>Common Related Diagenetic Alterations</th>
<th>Impact on Reservoir Quality</th>
<th>Geochemical Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Feldspar</td>
<td>Mesogenetic albitization</td>
<td>Promotes illite authigenesis and permeability deterioration</td>
<td>High $K_2O/Al_2O_3$ signature</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>Eogenetic kaolinization</td>
<td>Permeability deterioration</td>
<td>Low $K_2O/Al_2O_3$ signature</td>
</tr>
<tr>
<td>Volcanic material</td>
<td>Unstable grains leading to the formation of smectite, chlorite, zeolite, calcite, microquartz and opal</td>
<td>Severe loss of permeability</td>
<td>High $TiO_2/Al_2O_3$, $V$, $Cs$, $Mn$, $Ni$, $Ba$, $CaO$ and $Fe_2O_3$</td>
</tr>
<tr>
<td>Carbonate grains</td>
<td>Extensive carbonate cementation</td>
<td>Deterioration of reservoir porosity and permeability</td>
<td>High $CaO$</td>
</tr>
<tr>
<td>Clays</td>
<td>Formation of matrix</td>
<td>Reduction of reservoir porosity and permeability</td>
<td>High $Al_2O_3$</td>
</tr>
</tbody>
</table>
Diagenetic features that could not be qualitatively analysed but represent significant impacts on reservoir quality include quartz cement, which was observed to be a significant diagenetic cement during core analysis and is related to increases in the value of SiO₂. However, sediments containing a higher degree of quartz grains drown out the signal that would be measured during geochemical analysis indicating extensive silica cement. Pyrite cement is another significant diagenetic cement observed in the geochemical data of core and cuttings analyses marked by high Fe₂O₃/Al₂O₃ and S values. Its formation, however, is controlled by organic matter, sulfur-rich pore waters and a reducing deep-water environment, as opposed to the detrital grains contained in sandstones.

Zones in the Late Jurassic stratigraphy of Montague-1, Wanaea-1 and Legendre-1 of importance to reservoir quality are the:

- Lower *D. Jurassicum* sediments in Montague-1 marked by significant volcanic material, likely have severe loss of permeability due to the breakdown of unstable grains.
- Lower and Upper *D. Jurassicum* sediments in Montague-1 with high K₂O/Al₂O₃ ratios signifying a high degree of K-feldspar/kaolinite resulting in permeability deterioration.
- General elevated CaO in the Oxfordian and Kimmeridgian zones of all three wells indicating loss of reservoir porosity and permeability by carbonate cementation.

The *P. Iehenese* zones in all wells have low K₂O/Al₂O₃, CaO, Fe₂O₃/Al₂O₃ and S generally signifying that these sediments do not have significantly reduced reservoir potential due to a loss of porosity and permeability. This is consistent with the sandstones from this zone forming important reservoirs for large, producing petroleum accumulations in the Dampier Sub-basin.

### 4.5 Geochemical Characterisation using pXRF Analysis

Portable X-ray fluorescence analysis is a rapid geochemical tool for geochemical studies. The data collected in this study are of sufficient quality and allowed the geochemical characterisation of deep marine sandstones and mudstones. The technique permitted analysis of both core and cuttings samples, with core analysis providing geochemical data of specific lithologies, cements and geological features in real-time, guiding geochemical interpretations that are not normally achieved through core logging.
The use of pXRF analysis following the methodology of this study, however, did come with shortfalls in terms of data that are able to be collected rapidly as well as the analytical technique itself. The most advanced pXRF analyser used in this case, Thermo Scientific Niton XL3t GOLDD+ analyser, is unable to measure concentrations of sodium, due to the elements low molecular weight and, therefore, ability to be measured by portable X-ray fluorescence spectroscopy. Analysis times of 60 seconds per sample were also unable to measure concentrations of magnesium, and using the TestAllGeo® setting on the analyser, data are not acquired for rare earth elements.

In this study, that concerned identifying differences in detrital composition to guide interpretations of different areas of provenance in a basin, interpretations could be made with the results obtained. In a study that requires geochemical data to contain concentrations of magnesium and sodium, for example fluvio-deltaic systems of the Mungaroo Formation (Ratcliffe et al., 2010), to characterise sediments deposited in varying paleoclimes and weathering conditions, the methodology and analytical techniques used in this study would not be suitable. Studies that require data for rare earth elements, such as discriminating different source compositions of different tectonic settings (Bhatia, 1985; Pearce and Jarvis 1992a, 1992b; Strachan, 2012), would also not be suitable for using pXRF analysis as information on these elements were not acquired.

The use of an agate mortar and pestle for the preparation of cuttings samples significantly increased the time required to crush and mill samples. To ensure a more rapid study, the use of mechanical agate milling equipment, which was not available for this study, is recommended. Common milling equipment used for geochronology studies that achieve a rapid milling procedure, including chrome-steel, sylan and tungsten carbide are not recommended as they have the potential to contaminate samples being prepared for geochemical analysis.

5. Conclusion

Portable XRF analysis was used to obtain geochemical data from both core and cuttings samples from important Late Jurassic reservoir sandstones in wells along a transect of the Dampier Sub-basin. The sedimentary successions of each well were divided into specific chemozones, defined by zones of similar geochemical composition related to detrital framework grain composition, heavy mineral components and cements.
Differences in geochemical composition of the Eliassen and Angel Formation sandstones of equivalent biostratigraphic age in each well was used to interpret sediment dispersal patterns and provenance in the basin through the Late Jurassic. Despite the economic importance of the reservoir sandstones, relatively few published studies have focussed on the distribution of sandstones, potential provenance and related reservoir quality.

During the Oxfordian, sandstone deposition was dominantly restricted to the basin margins based on an absence of sandstones in the central Dampier Sub-basin, and differing geochemical signatures in sandstones along the basin margins in the east and west. In the Kimmeridgian, sediment supply to the basin remained dominantly transverse, however, basin-floor fans with significant transport distances transported sand from the eastern margin of the basin to the central area, and could be correlated based on geochemical composition. A significant supply of sediments from the northeast of the basin during the Tithonian caused widespread basin-floor fan sandstone deposition throughout the northern Dampier Sub-basin towards the southwest. Contrasting geochemical signatures in wells along the flanks of the basin during this time are interpreted to represent mixed transverse sediment supply from the basin-floor fans and axial sediments from the rift-basin margins.

Provenance of sediments and their dispersal in the Dampier Sub-basin have important implications for reservoir quality of the important Eliassen and Angel Formation sandstones. Different diagenetic processes related to different detrital compositions of sandstones have major impacts on reservoir quality that is of relevance to the petroleum industry. Tithonian sedimentary rock containing high degrees of volcanic material and K-feldspar in Montague-1 likely have decreased permeabilities due to the breakdown of unstable volcanic grains into clays and K-feldspar into kaolinite, whereas chemozones in all wells throughout the Oxfordian and Kimmeridgian show high degrees of carbonate cement likely occluding porosity. Additionally, the distribution of sandstones in the basin has important implications for future exploration targeting, particularly stratigraphically trapped basin-floor fans deposited in the Kimmeridgian.
6. Future Studies

The following recommendations to build upon the interpretations of this study are to:

- Conduct further geochemical studies on wells throughout the Dampier Sub-basin for comparison to gain a greater degree of confidence in the interpretations made in this study.

- Conduct a detrital U-Pb zircon geochronology study of the Angel Formation sandstones to gain an improved understanding of provenance areas supplying the Angel Delta and the basin-floor fan systems it feeds in the Dampier Sub-basin. This research would build on interpretations made by studies of other important reservoirs in the Northern Carnarvon Basin (Southgate, 2011; Lewis and Sircombe, 2013) to provide a greater understanding of changing large-scale provenance of sediments into the basin.

- Conduct a high-resolution seismic study to map Eliassen Formation distribution in the Dampier Sub-basin and mixing of Angel Formation sediments from axial basin-floor fan and transverse sediment gravity flow deposition by imaging seismic geomorphology of deep water sediment systems.

- Assess the petroleum potential of stratigraphically trapped Kimmeridgian sandstones present along the central and eastern areas of the Dampier Sub-basin, trapped and sourced by the prolific Dingo Claystone.
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