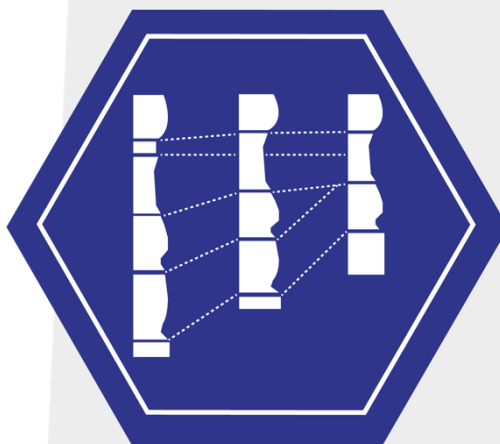




Report CAu50035 & CAu50040

Chemostratigraphic Evaluation of the Late Permian Dongara-Wagina Sandstones, Onshore North Perth Basin, Western Australia

Prepared for

**Energy Resources Ltd &
Mitsui E & P Australia
(Joint EIS Series 1 2021-22)**

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Chemostrat Australia PTY

1131 Hay Street
West Perth, WA6005
Australia

t +61 (0) 468 585 057

e AuOffice@chemostrat.com

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Tim Pearce

Director

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Executive Summary

Following the completion of the chemostratigraphic evaluation of the Late Permian Dongara – Wagina succession, onshore North Perth Basin, Chemostrat Australia Pty Ltd make the following conclusions:

- Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) analysis of 402 newly collected cuttings and 410 core samples from 15 wells has allowed for a regional chemostratigraphic correlation and geochemical evaluation of mineralogy.
- Cuttings and core to log shifts were applied based on ChemGR and previously released calculations. A few wells, notably Warradong-1, exhibit caving contamination that could not easily be excluded. There is evidence for drill bit contamination resulting in anomalous Mo and Cr values, most notably in Unit 6_3 in Hovea-3/ST1 and Apium-1.
- The interpretation has been based on the existing chemostratigraphic framework of the onshore North Perth Basin, whereby the Wagina Sandstone has been assigned to Package 6 and the Dongara Sandstone, Package 7. For this study the packages have been subdivided into seven and five units respectively.
- The earliest units recognised are sideritic calcareous sandstones on the Beharra Terrace, believed to be the lateral equivalents of the Beekeeper Formation. Subdivision of the overlying Package 6 sand-prone units is based principally on the recognition of a consistent Ti/Nb shift and fluctuations in the abundance of heavy minerals. There is a considerably expanded section in the Dandaragan Trough wells, although the precise interpretation is complicated by the generally clean nature the samples.
- Missing Package 6 units at base of Package 7 is only recognised at Hovea-3/ST1. There is no evidence from the geochemical data for significant provenance change at the transition.
- The subdivision of Package 7 is based on variability in detrital components and clay composition, and heavy mineral abundance from cored intersections on the Dongara Terrace. Package 7 is also recognised on the Allanooka Terrace and the northern Dandaragan Trough; however, it is not interpreted in Erregulla-1.
- Elemental data can be used to highlight the spatial and stratigraphic distribution of heavy mineral abundance, notably the presence of Ti oxides and RE phosphates, the latter of which contain high concentrations of Th and can impact the GR response. Overall, this decreases to the southeast, due to either dilution and / or distance from source.
- Elemental data, integrated with HyLogger and thin section (where available) demonstrates the nature and distribution of diagenetic and detrital mineralogy.

- The data shows the distribution of the chlorite responsible for inhibition of quartz cement in the Package 6 (Wagina Sandstone) reservoir for the Beharra Springs Field. Chlorite-bearing zones are also recognised in other wells, notably in units 6_2 and 6_3. These can have significant associated carbonate cements however, and the sediment immaturity means that the porosity can be ineffective.
- The best reservoir quality is observed the coarse sands of Package 7, although permeability is sensitive to the presence of clays, likely kaolinite booklets. Minor Cr enrichment is locally observed that can have a positive correlation with reservoir quality, for example Mondarra-7 where chlorite may have been preserved as a result of early hydrocarbon emplacement.
- There is little evidence for the presence of chlorite in Package 6 and 7 reservoirs to the south and east where deep burial appears to have resulted in significant quartz and / or illite cementation.

Supplementary data

In addition to this report the following supplementary data is supplied.

Document Name	Description	Format
PPAU50035_40_DW Database	Excel file with elemental data, including lithological descriptions based on the ChemLith and Herron (1988) classification schemes. Also includes the assignment of sequences and packages.	.xlsx

Presented within this report are the results and conclusions of a chemostratigraphic evaluation of the Late Permian Dongara and Wagina sandstone formations from 18 well penetrations, onshore North Perth Basin (**Figure 1**). The study utilised bulk rock elemental data obtained using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma – Mass Spectrometry (ICP-MS).

The data was generated from a combination of two EIS (Exploration Incentive Scheme) supported studies for Mitsui E&P (approval no G004246 ext1), and Energy Resources Ltd (approval no. G004249). Supplementary data was available for three wells from legacy studies (Chemostrat Australia, 2019) (Chemostrat Australia, 2021) (Mitsui E&P, 2019) (**Figure 1**).

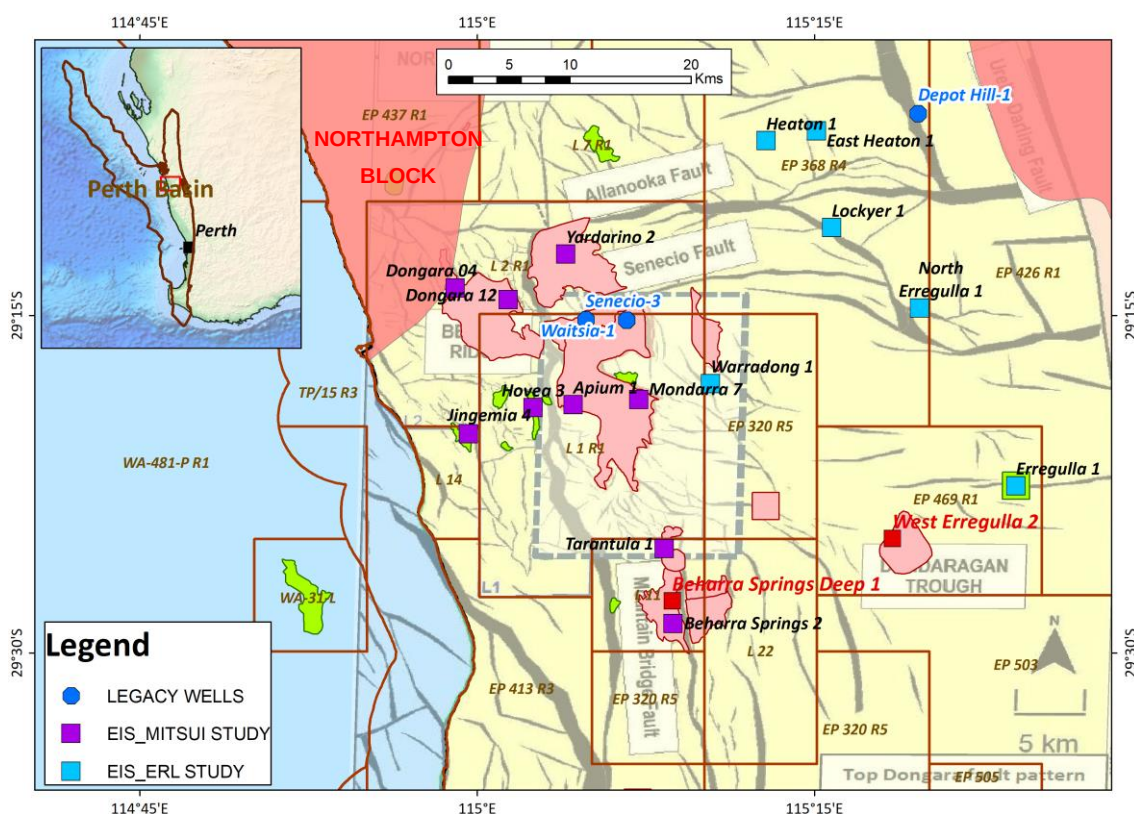


Figure 1. Location map of study wells within the Perth Basin (top Dongara structural map).

The primary aim of this study is to evaluate the technique of chemostratigraphy as a viable correlation tool for the Late Permian Dongara – Wagina succession. The chemostratigraphic zonation scheme described previously for the North Perth Basin (Chemostrat Australia, 2019) has been utilised and expanded for this study. The same procedures and instruments were used in this study as in previous Perth Basin analyses to ensure compatibility of results.

A secondary objective was to integrate the results with existing petrology, routine core analysis, and HyLogger spectral scanner data, to assess how the elemental data can be used to aid mineralogical prediction and impacts on reservoir quality.

GEOLOGICAL BACKGROUND

The study interval comprises the Late Permian Dongara, and Wagina sandstone dominated succession (**Figure 2**) from the onshore North Perth Basin. This interval represents one of the principal reservoirs of the North Perth Basin, including fields such as Beharra Springs, Dongara, Mondarra, Yardarino, Hovea, Jingemia and Eremia. The interval was extensively described and interpreted from core and wireline log analysis in the Oolithica report (Laker N., 2000), from which much of the petrology data has been integrated into this study.

The Late Permian succession unconformably overlies the Carynginia Formation (Jones, et al., 2011), broadly characterised as shallow marine deposits with potential for slope and basinal deposits in the subsiding Dandaragan Trough. The Carynginia Formation was progressively truncated towards the northwest and is totally eroded in the western part of the Dongara Field. The uplift and erosion of the Beagle Ridge was accompanied by subsidence along the Urella Fault to form a pronounced half-graben resulting the dramatic thickness variation across the study area.

The source of the Dongara-Wagina sands is likely the Early-Mid Paleozoic Tumblagooda succession and the igneous and metamorphic rocks of the Northampton Block to the north and northwest. The latter is widely regarded to provide the rare earth phosphates commonly described in the study interval (Rasmussen, 1992), (Laker N., 2000), (Philips, 2005). Other sediment may have come from the east, but this would have been impeded by footwall uplift of the Darling and Urella faults (Ferdinando, et al., 2021).

Overall, the Wagina and Dongara sandstones comprise a progressively shoaling sequence. As the half-graben widened and deepened to the south a submarine fan developed that was prograded over by fine-grained, shallow marine, lower shoreface sands (Wagina Sandstone) and upper shoreface (tidally influenced) coarser sands (Dongara Sandstone) (Laker N., 2000) (Ferdinando, et al., 2021). The Dongara-Wagina contact represents an initial flooding surface and is considered broadly conformable, although tidal channels may locally erode through the coastal barrier system. The Dongara Sandstone extends a lesser distance south than the Wagina Sandstone, highlighting the sediment source is to the north and an overall back-stepping nature.

In the south of the study area, authigenic chlorite is observed in several wells associated with mid shoreface, fine grained, transgressive sands (Laker N., 2000). This plays a key role in porosity preservation on the Beharra Springs Terrace which, based on regional trends, at depths of more than 3 km, would have otherwise had the primary pore space occluded by authigenic silica. Chlorite (or precursor) coatings around quartz grains formed during early diagenesis, probably after some compaction. Where chlorite rims coat the grains completely, they have restricted the growth of late diagenetic quartz cement and thereby preserved porosity.

It has been proposed (Laker N., 2000) that pervasive influx of acidic meteoric pore-water from the Northampton Block would have leached much of the chlorite and other unstable components

and have resulted in pore filling kaolinite. The isolated nature Beharra Springs structural high however, may have provided sufficient protection to retain the early diagenetic phases. Multiple hydrocarbon emplacement history may also play a role in porosity preservation, for example in the Mondarra Field (Rasmussen, 1993).

The study interval is overlain by the Late Permian to Early Triassic Kockatea Shale comprising the basal Hovea Member, the only regional topseal recognised and primary source of hydrocarbons in many fields of the Perth Basin (Taniwaki, et al., 2021). Initial sediments deposited comprise black, carbonaceous shales interbedded with silty sandstones in a shallow, nearshore marine environment, however rapid marine transgression resulted in widespread development of anoxic conditions and microbial mats. Alternating cycles of brownish-grey, finely laminated pyritic shales and thin limestone bands were deposited in the ensuing section. At the top of the Hovea Member is typically a thin limestone interval, deposited when terrestrial input to the basin was temporarily suppressed.

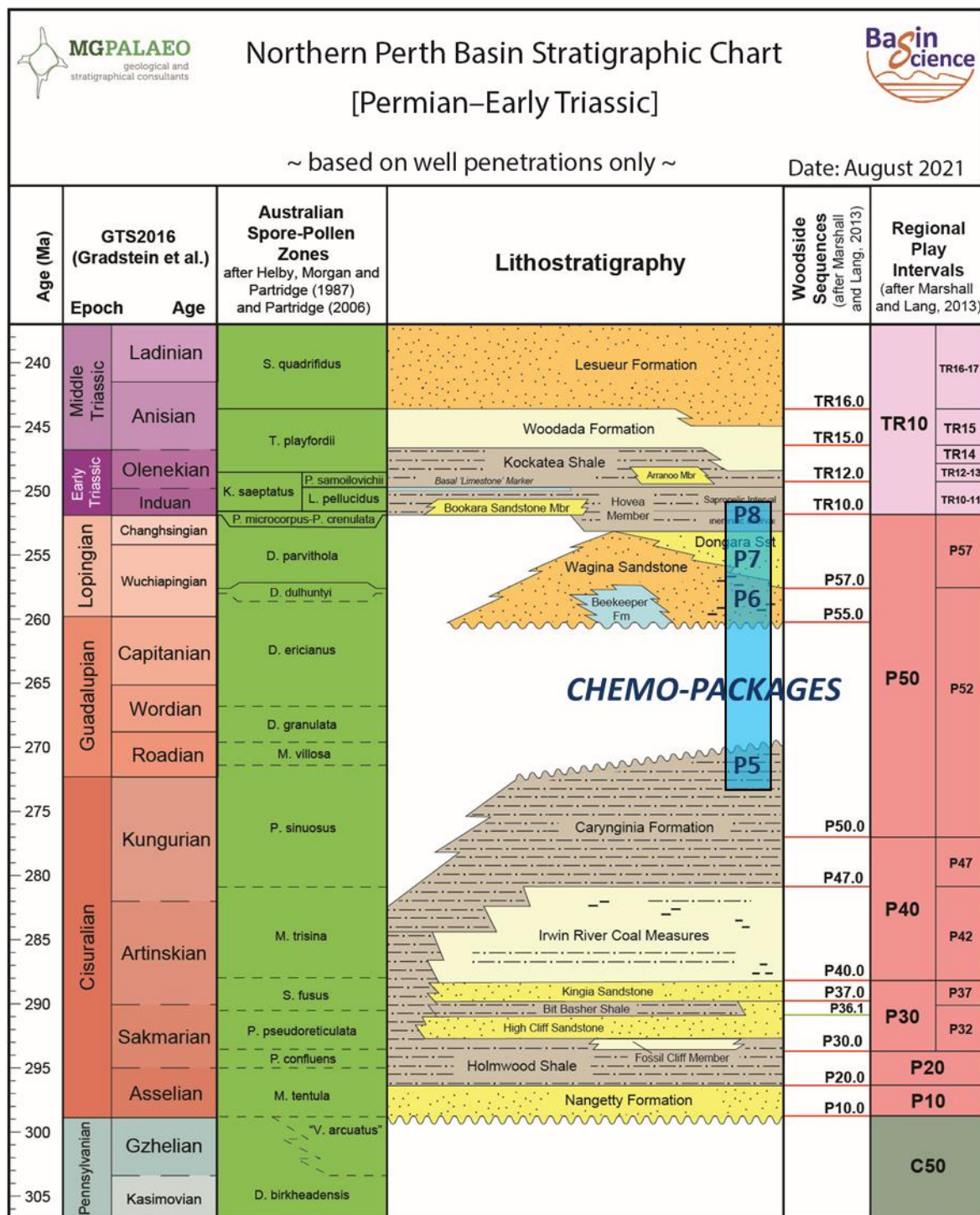


Figure 2. North Perth Basin stratigraphy (Ferdinando, et al., 2021).

STUDY MATERIAL AND METHODS

Study Material

A total of 812 new samples comprising cuttings (402) and core samples (410) were analysed over the 15 study wells. The study intervals and samples numbers are summarised within **Table 1**. These samples were analysed by inductively coupled plasma - optical emission spectrometry (ICP-OES) and inductively coupled plasma - mass spectrometry (ICP-MS), resulting in quantitative data for 50 elements (**Appendix 1: Elements & Chemical Symbols**). All the elemental data is included within the supplementary data. Where the data was sampled from core, depths were chosen to align with core plugs utilised for petrological and routine core analysis.

Table 1. Analysed samples from study wells for ICP-OES-MS

All depths are MD

Well	Top (m)	Base (m)	Interval Thickness (m)	Number of Cutting Samples	Number of Core Samples
Apium-1	2757.3	2860	102.7	23	30
Beharra Springs-2	3322	3397	75	19	16
Dongara-4	1688.1	1723.5	35.4	2	28
Dongara-12	1615.4	1670.6	55.2	4	44
East Heaton-1	2025	2335	310	63	
Erregulla-1	3806.1	4243.4	437.3	71	13
Heaton-1	2106.2	2343.9	237.7	40	
Hovea-3/ST1	1989	2100	111	11	59
Jingemia-4	2400	2482	82		82
Lockyer-1	3162	3327	165	26	19
Mondarra-7	2704.9	2767.3	62.4		55
North Erregulla-1	2799.1	3444.2	645.1	37	27
Tarantula-1/ST1	3206	3299	93	31	
Warradong-1	3182.1	3405	222.9	51	4
Yardarino-2	2333	2444.5	111.5	24	33
Total			2746.2	402	410

Analytical Methods – ICP-OES-MS

The cuttings samples were initially washed in a mild detergent to remove surface contamination and any loose clay-grade material. The washed cuttings samples were dried then examined under a binocular microscope and individual rock chips were picked by hand from each sample. By doing so, any cavings and drilling contaminants that may be present can usually be recognised and ignored.

The picked chips were ground by hand to a powder in an agate pestle and mortar, with the sample powders prepared for ICP-OES-MS analyses using the lithium metaborate (alkali) fusion procedure advocated by Jarvis & Jarvis (1992a&b). All samples were analysed by ICP-OES and ICP-MS, resulting in quantitative data for 50 elements (**Appendix 1: Elements & Chemical Symbols**).

The precision of the geochemical data acquired by the ICP-OES, and ICP-MS analyses has been determined by replicate analyses of certified rock 'standard reference materials' (SRMs - samples of a known chemical composition) together with the analyses of the cuttings samples from the study wells. The closer the comparison between the data obtained from the SRMs across the entire analytical run and their known element concentrations, the better is the precision of the inorganic geochemical data acquired during the run. Any deviations from the known concentrations of the SRMs can be readily identified in the dataset and corrected for.

Precision error for the major element data is less than 1% to 2% overall and is between c.3% and 5% for the high abundance trace element data. However, the quality of the TI and W data are poor, as these elements occur in low concentrations that are close to the detection limits of the analytical machinery. Consequently, although these data may be reported they are sometimes inaccurate and imprecise (precision error of $\pm 20\%$) and thus are not used in any later interpretations.

For brevity throughout the report, all the elements are referred to by their appropriate chemical symbol, with the symbols for the major elements being taken to imply oxides, e.g., K = K₂O, Al = Al₂O₃, Mg = MgO and so forth. In addition, the rare earth elements are referred to as REEs and have been categorised into light rare earth elements (LREEs - La, Ce, Pr and Nd), middle rare earth elements (MREEs - Sm, Eu, Gd, Tb and Dy) and heavy rare earth elements (HREEs - Ho, Er, Tm, Yb and Lu). Depths quoted in the report are in metres and are measured depths (MD) unless otherwise stated. The single depth given for a cuttings sample collected over an interval from x metres (MD) down to y metres (MD) is the deepest depth (i.e., the y depth).

Data Validity (Post-analysis)

The success of a chemostratigraphic study is dependent on good quality geochemical data from representative samples. The samples analysed in this study are mainly from cuttings, which are collected over a specific interval. The geochemical data of cuttings samples thus reflects the 'average' geochemistry of the interval. Cuttings need to be assessed for quality as this can be variable due to cavings, contamination by drilling muds and additives, and lag calculation issues.

A synthetic chemical gamma log 'ChemGR' has been created for each well over the study interval based on the K, Th and U data acquired from the ICP-OES-MS analysis of the samples. A ChemGR value for each sample is calculated using the following equation, (Ellis & Singer, 2007):

$$\text{ChemGR} = (\text{K}_2\text{O} \times 13.55) + (\text{Th} \times 3.93) + (\text{U} \times 8.08)$$

The ChemGR profile for each study interval is superimposed onto the wireline gamma logs and

where a shift was required an unshifted and shifted ChemGR is shown on Figure 3. ChemGR to Gamma Ray (GR) comparison. **(Figure 3)**. Core to log depth shifts for several legacy wells were available from the Oolithica Report (Laker N., 2000) and a core GR was available for Mondarra-7 to facilitate depth shifts. Core to log shifts for wells Lockyer-1, Apium-1 and Jingemia-4 were derived from using the ChemGR to devise the optimal match with the wireline data.

A significant depth shift was required for the Warradong-1 cuttings samples to match the top and bottom of the clean Wagina sand succession, however internally there was insufficient character in the ChemGR to confidently confirm this was appropriate throughout the Wagina Sandstone. In addition, there remains a poor ChemGR-GR match in the upper Wagina and Dongara sandstone despite repeated re-evaluation of the samples. In North Erregulla-1 the Wagina sands were very clean, and this was reflected in the consistent very low ChemGR values, and a match was based on the recognition of a few prominent shale interbeds. In Erregulla-1 the discrepancy of the values for the wireline GR and ChemGR increases with depth and a confident match could not be made. All sample depth shifts are included in the supplementary data spreadsheet.

Various elemental indicators are utilised to highlight artificial sample contamination. Baryte and calcium carbonate are common drilling additives and their residual presence in the samples can be assessed by reviewing the Ba and Ca abundance respectively. Ca is a common rock forming mineral and the DT curve can be used to assess whether this is an in-situ component as cemented zones are likely to produce a fast sonic response. There are also stratigraphic intervals that are known to be carbonate-rich. Low totals (of major elements) are associated with the carbonate content as it is not possible to analyse for elements C and O. As there are no coals in the study interval then other low total zones may relate to baryte or other drilling contaminants containing elements C and / or O.

The Ba content does not exceed 10000 ppm (1%) in any of the study wells, indicating that contamination by drilling additives was minor. Well Tarantula-1/ST1 has some of the highest Ba values in the clean uncemented sands indicating that these were highly porous intervals. Lower totals are generally restricted to carbonate-rich or clay-prone intervals, indicating their hydrous nature. The lower totals zone in the Wagina Sandstone in Lockyer-1 is more difficult to explain given the clean nature of the sand, but as these are not less than 87%, this is not considered a serious issue.

There was also evidence for drill bit contamination in the cuttings of several wells. Mo may be present in the study interval at levels greater than a few ppm if it's associated with other redox sensitive elements, such as elements U and V. This is generally not observed, rather the Mo has a strong positive correlation with Cr **(Figure 4)** indicating the presence of metallic alloys, that are non-magnetic as haven't been removed with standard sample clean up techniques. Where Mo/Cr exceeds 0.1 (for cuttings) and Mo >5 ppm then a flag has been created to highlight these zones, principally located in wells Tarantula-1/ST1, Lockyer-1, Apium-1, and Hovea-3/ST1. For the latter two wells it should be noted that these zones are in similar stratigraphic positions and in the case

of Hovea-3/ST1 immediately below a large, cored interval. In East Heaton-1 (**Figure 5**) the contaminated samples are also associated with an increase in U and S abundance in a clay-prone interval. It may be in this case that the high Mo may (in part) be related the presence of pyrite, potentially indicating deposition in anoxic environment, and may be associated with increased TOC.

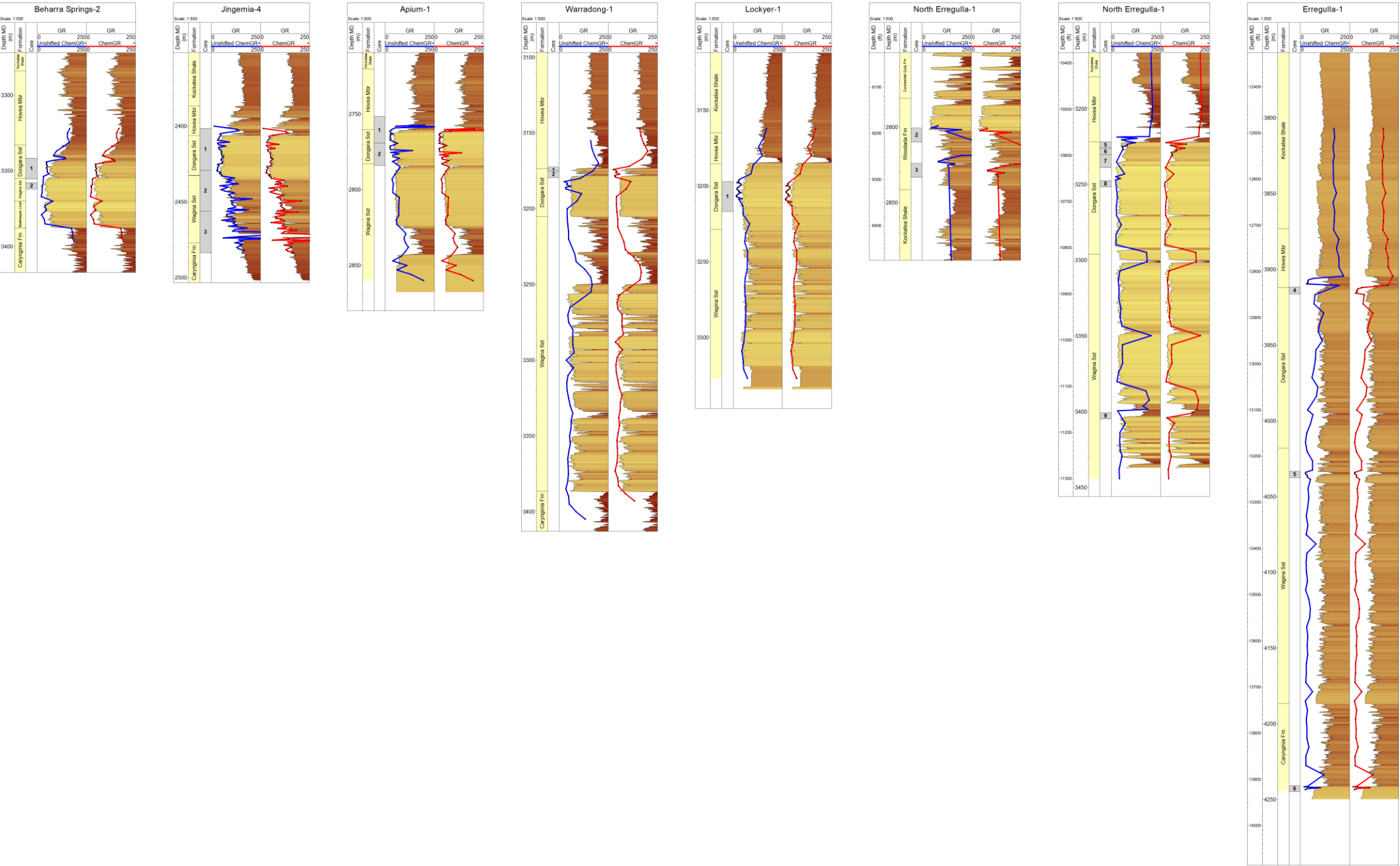


Figure 3. ChemGR to Gamma Ray (GR) comparison.

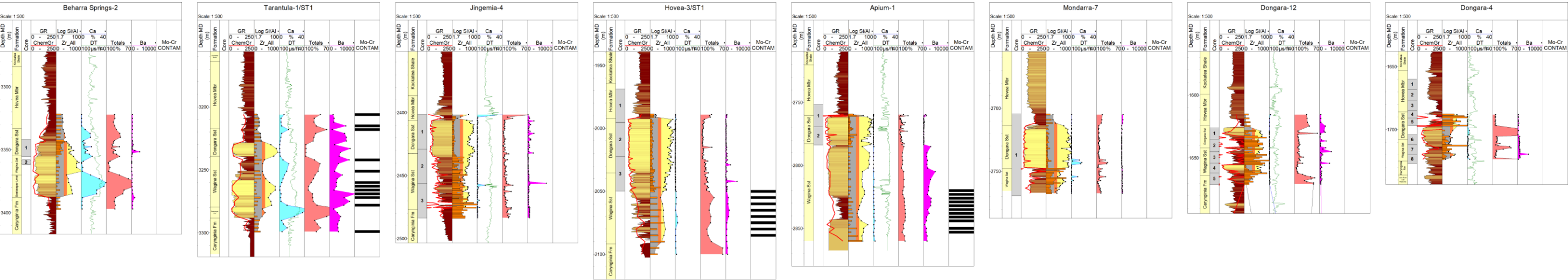
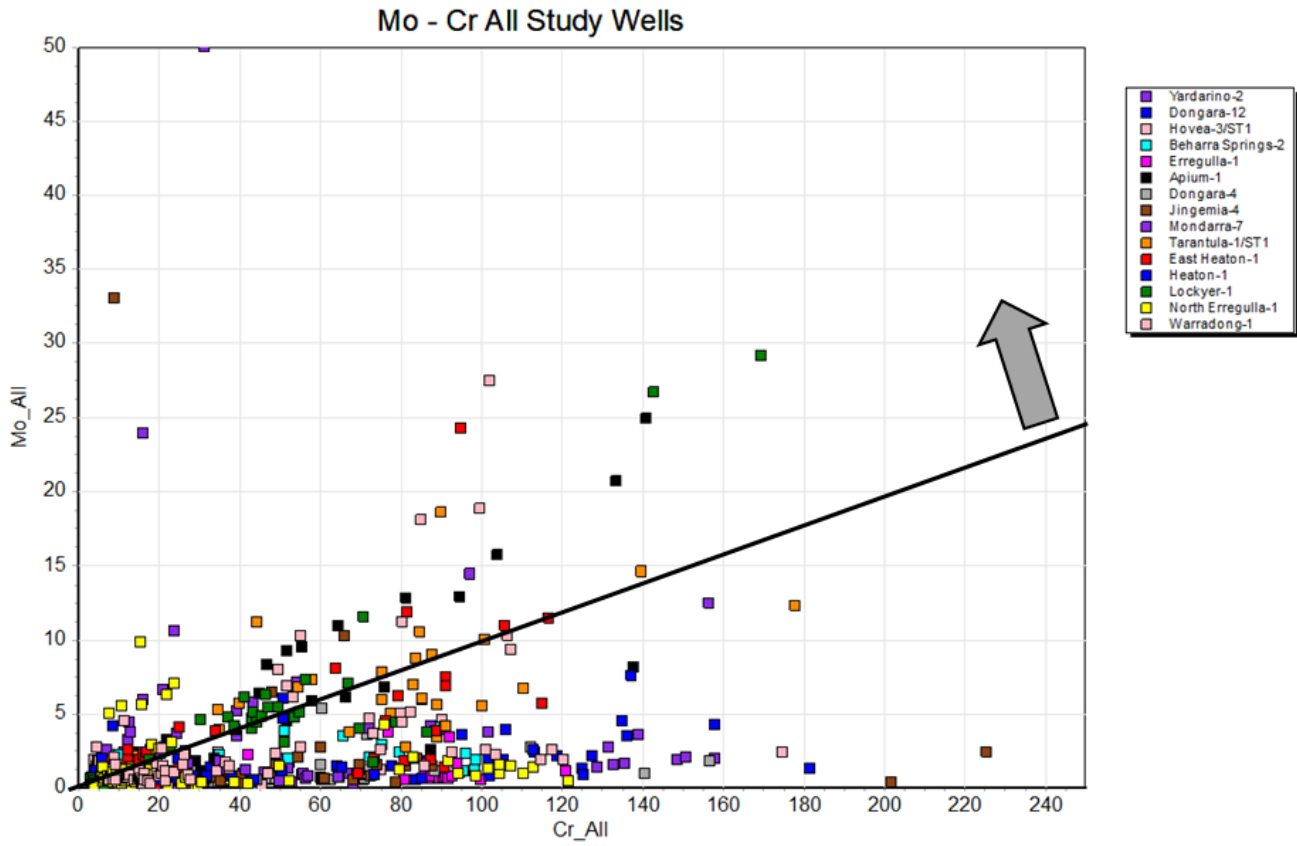


Figure 4. Sample QC (west).



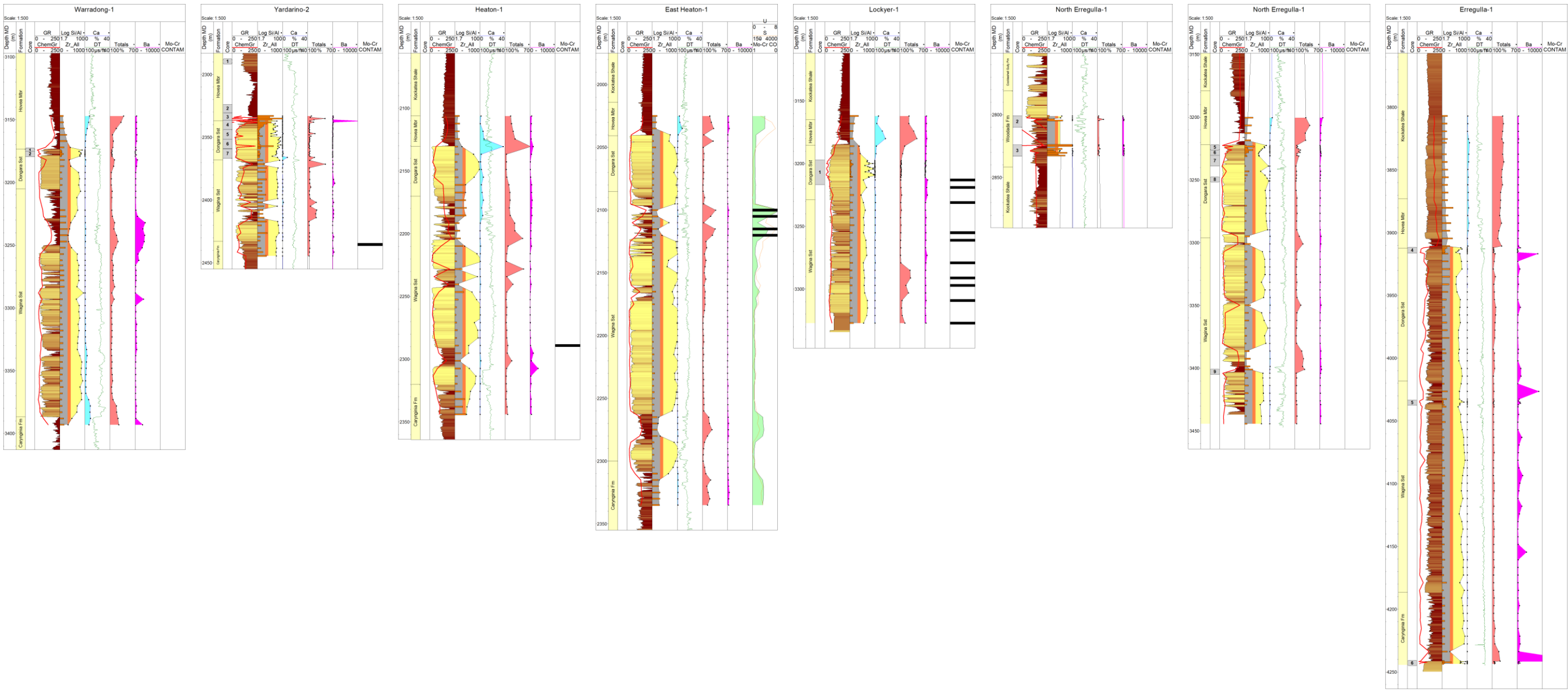


Figure 5. Sample QC (east).

CONTROLS ON GEOCHEMISTRY

When carrying out a chemostratigraphic evaluation it is important to acknowledge that the correlation represents changes in bulk, whole rock, composition. However, manifested within the dataset will be expressions of sediment provenance, transportation, environment of deposition and diagenetic processes. Changes in lithology and mineralogy and how these changes are expressed in the geochemistry are discussed below.

Geochemistry & Lithology

The impact exerted by differences in lithology on the bulk geochemistry must be considered prior to interpretation. Lithology is mainly controlled by mineralogical variations, and these are strongly reflected in changes in geochemistry. Comparisons between the geochemistry from samples of similar lithology can be important for reducing the discrepancies introduced when lithological variation is present.

Chemostrat usually assesses the average lithology of a sample using Si/Al value and Ca concentration. Si/Al value provides an idea of quartz abundance (Si) relative to clay abundance (Al) in clastic rocks, and so can be approximately equated with lithology. Ca concentrations are associated with carbonate minerals. Using the Si/Al value and Ca concentrations, analysed samples can be assigned to categories of geochemical lithotypes, termed 'ChemLith' (**Figure 6 top**). The definitions of the lithotypes are listed below:

- mudstone lithotype: Si/Al values < 4
- siltstone lithotype: Si/Al values 4 - 6
- argillaceous sandstone lithotype: Si/Al values 6 - 10
- sandstone lithotype: Si/Al values > 10
- hot sands lithotype: Si/Al values > 10, ChemGR >100
- limestone lithotype: CaCO₃ concentrations greater than 50%

Additional qualifications can be introduced if a sample has 10% or more of a particular element. For example, samples with more than 10% CaCO₃ are classified as calcareous e.g., calcareous sandstone. A sample with more than 50% CaCO₃ (50% CaCO₃ = CaO 28%) is classified as a limestone and the Si/Al value is then used to qualify this classification e.g., argillaceous, silty, or sandy limestone.

An alternate classification (Herron, 1988) attempts to differentiate between sands that contain lithic clasts or feldspar framework grains. The Herron sandstone classification plot is predominantly used to categorise the sands, but also the sand from wacke/shale. The Herron plot for each sample (coloured by lithostratigraphic formation) is included on **Figure 6 (bottom)** and the percentage of lithology for each well is included as **Figure 7**. The Fe₂O₃/K₂O value separates lithic sands from feldspathic sands, and the SiO₂/Al₂O₃ value separates Si-rich quartz arenites from Al-rich shales.

There are issues associated with both lithology classification schemes. For example, the Herron

plot relies on K to determine feldspar abundance and so will not accurately define the arkosic nature of rocks with a significant plagioclase feldspar content. The ChemLith classification attempts to define a grainsize based on interpreted mineralogy which may lead to errors in the cases such as fine-grained quartz-rich siltstone, which would be classified as sandstone. Similarly, a lithic- or feldspar-rich sandstone would cause the ChemLith classification to indicate argillaceous sandstone or even siltstone based on increased Al contents, which would be incorrect. Neither of these schemes can characterise metamorphic or igneous rocks that may occur as basement.

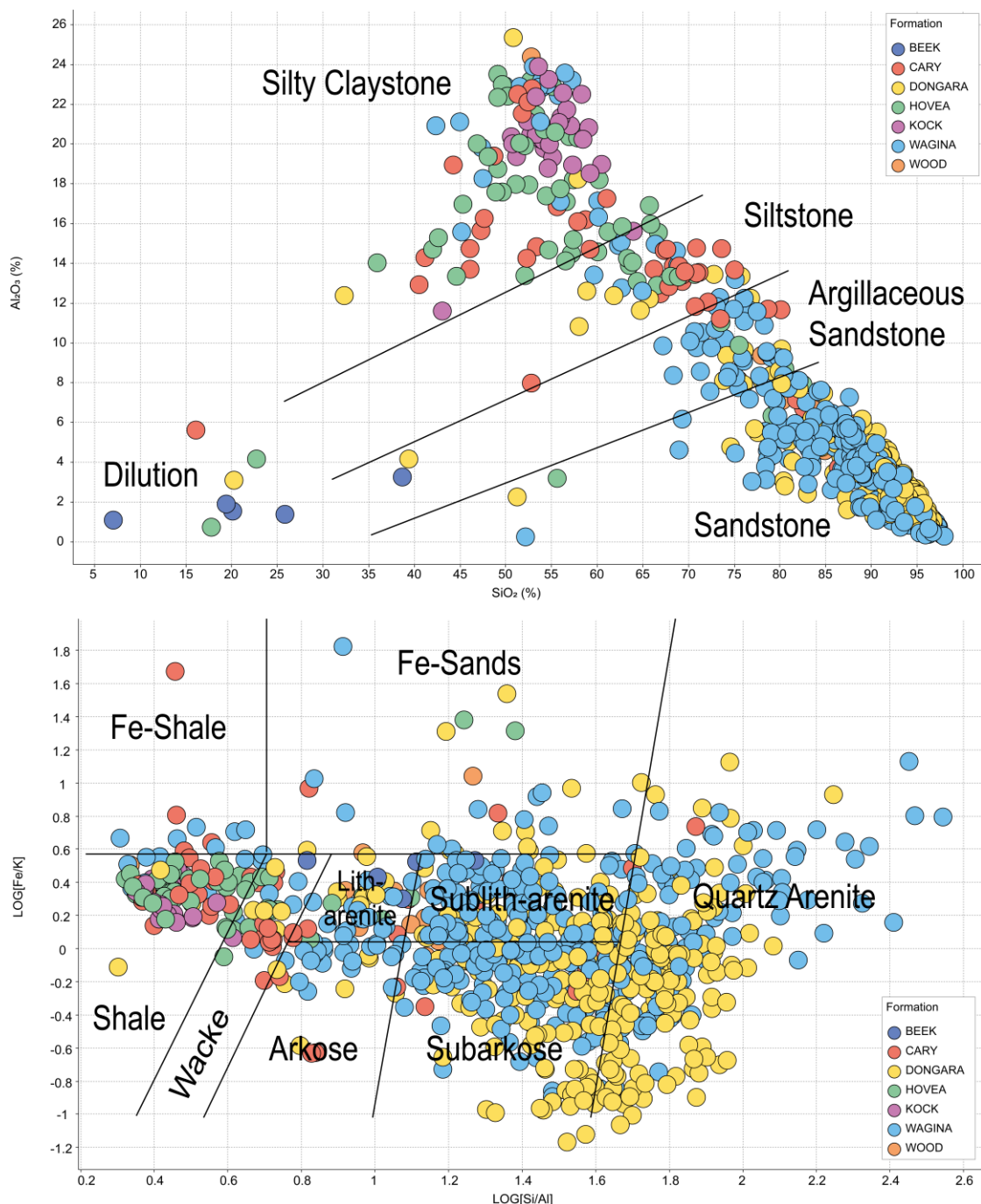


Figure 6. Lithological classification diagrams (*top*) Si-Al ChemLith plot, (*bottom*) Si/Al – Fe/K plot (**Herron, 1988**).

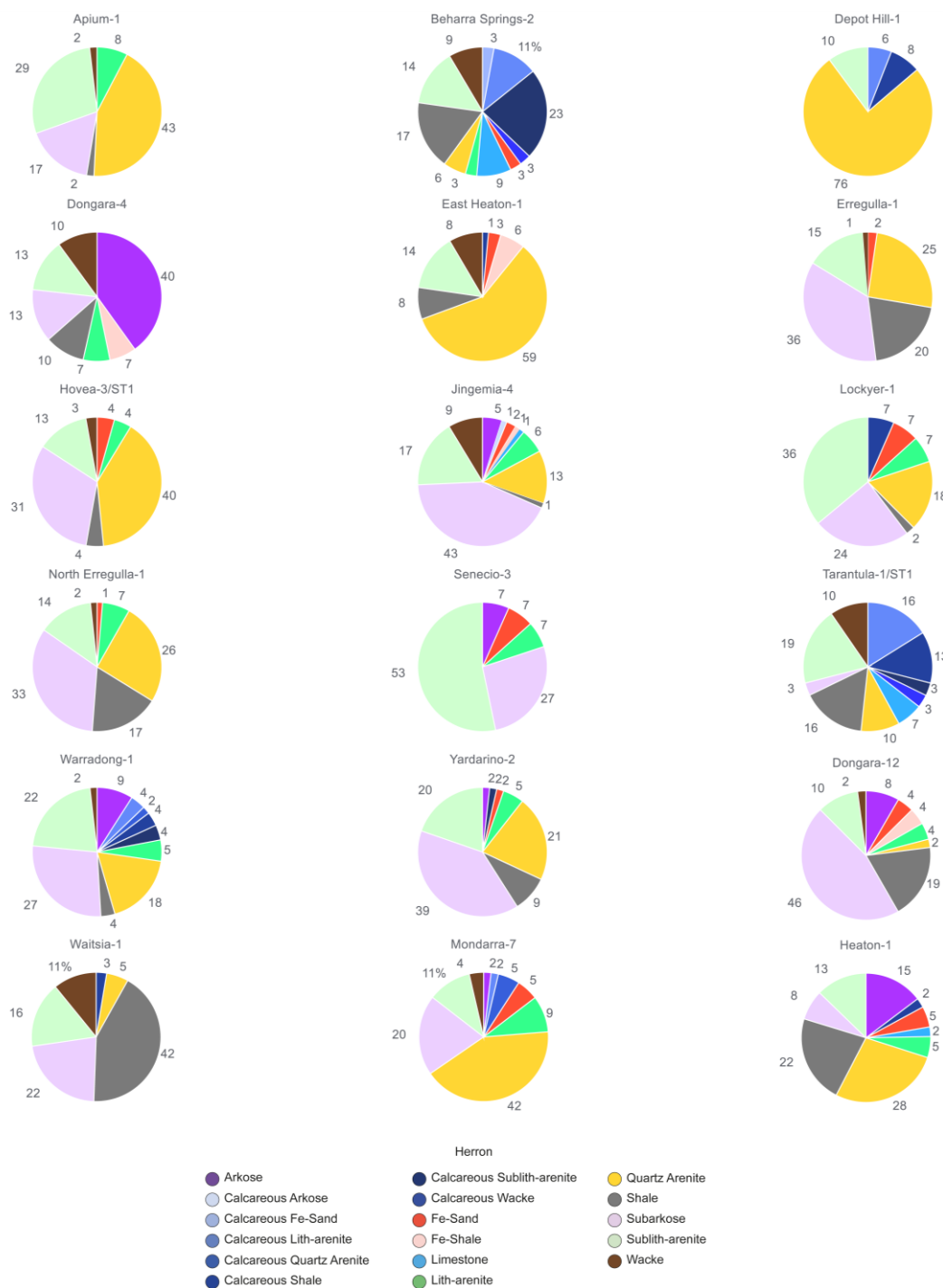


Figure 7. Lithology distribution by well.

The Herron (1988) and Si/Al ChemLith classifications shown within **Figure 6** shows that the Dongara and Wagina sandstones are predominantly classified as arkosic/lithic arenite to quartz arenite and argillaceous sandstone to sandstone, respectively. Distribution of the lithologies by well, shown within **Figure 7** and **Figure 8**, demonstrate that high abundances of quartz arenite are seen within the wells Apium-1, Depot Hill-1, East Heaton-1, Hovea-3/ST1, Mondarra-7, North Erregulla-1, and Yardarino-2 wells. Dongara-4, Dongara-12, Hovea-3/ST1, Jingemia-4, North Erregulla-1 and Yardarino-2 contain considerable abundance of arkose and sub-arkose, while

high proportions of lithic arenite, and sub lithic-arenite, are recorded within Apium-1, Lockyer-1, and Senecio-3 (**Figure 7**). The highest proportions of shale and wacke classified sediments are noted from the Waitsia-1 well, and the highest abundance of carbonate-rich lithologies are noted within Beharra Springs-2 and Tarantula-1/ST1.



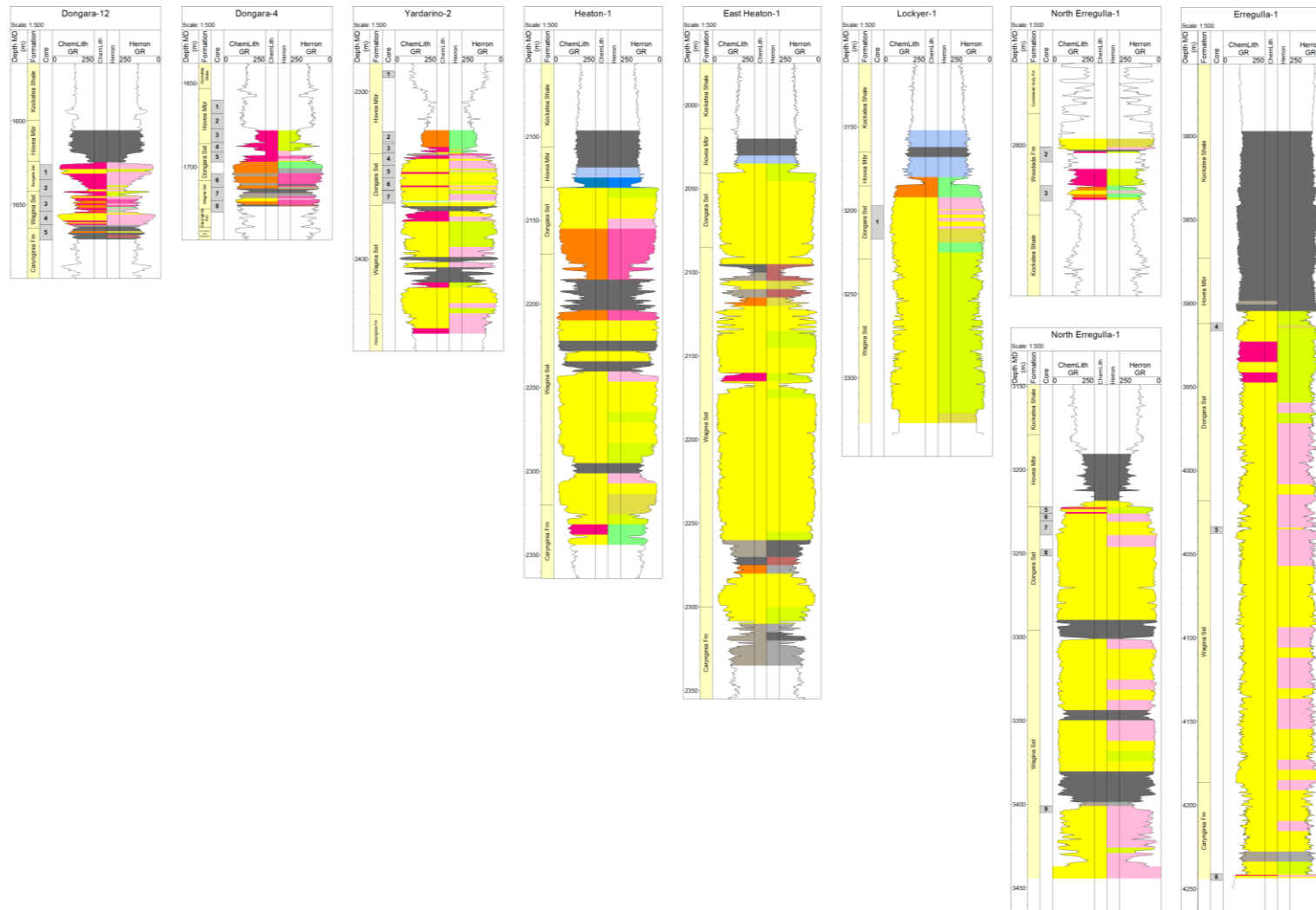


Figure 8. Lithology well plots for both Herron and ChemLith classifications.

Geochemistry & Mineralogy

Chemostratigraphic interpretation relies on the characterisation of sedimentary strata using bulk, whole rock, geochemical data. However, for the range of elements analysed for only a limited number of 'fingerprint' elements that are required to characterise the sedimentary succession. However, it is important to establish the mineralogical-elemental affinities and identify elements associated to framework grains and those linked to authigenic cements, the geochemical characterisation of sedimentary rocks should be based on element data associated solely with detrital minerals. Furthermore, key elements have been combined into key element ratios, the changing up-sequence values of which add further detail to the geochemical characterisation of the rocks.

Ideally, the geochemical data is compared to equivalent mineralogical analysis, such as X-ray diffraction (XRD) or petrography. In this study no new mineralogical analysis has been undertaken, however, a considerable amount of legacy data as well as HyLogger spectral data is available and has been utilised where possible.

Published Mineralogy

A significant amount of petrology work has been conducted although this has been undertaken by multiple authors with different focuses over many years, thus is not always directly comparable. The most detailed and complete thin section data was undertaken on Beharra Springs-2, Dongara-4, Dongara-12, Erregulla-1, North Erregulla-1, and Warradong-1 for the Oolithica Report (Laker N., 2000). Evaluation of Jingemia-4 (Philips, 2005), and Hovea-3/ST1 (Baker, 2003) were included as part of their respective well completion reports. Apium-1 was assessed as part of a structural geology thesis by (Olierook., 2011), and Dongara-4 and Yarrarino-2 were reviewed by (Rasmussen, 1993) as part of his thesis on diagenesis and heavy minerals in the Perth Basin. These sources have been used to provide the petrological data and the conclusions are summarised below.

As indicated by the Herron classification the Wagina Sandstone comprises a range of lithologies, namely sublitharenites, subarkose, greywacke and quartz arenites. Grain size and sorting is highly variable and can be calcite cemented which is often ferroan. Relatively high concentrations of accessory minerals and micas within the Wagina Sandstone have influenced the gamma ray logs at selected intervals. High percentages of biotite, which is chemically less stable than muscovite, might indicate short distances of sediment transport from an igneous and/or metamorphic terrane. This hypothesis is consistent with preservation of coarse sand size feldspars within the sequence. K-feldspars with perthite and tartan twinning typical of orthoclase and microcline are more abundant than plagioclase. This fact might suggest the source was either granite and/or acid gneiss. Mixing of igneous and metamorphic sediment sources is also apparent from the lithic fraction. Metamorphic lithics of quartzite, micaceous schist, shale and pyrophyllite were identified. Igneous lithics (granitic) are typically less abundant. Chert and chalcedonic lithics were probably of sedimentary origin and could have been reworked from the Beekeeper

Formation. Mudstone lithics may have been locally introduced as either rip-up clasts or due to bioturbation.

Based on core descriptions, a series of depositional environments was recognised at Jingemia-4 ranging from inner neritic (shelf) through lower to upper shoreface. In the Beharra Springs Field, the Wagina Sandstone consists of thin sharp-based sandstones with burrowed tops and may have been deposited further seawards below storm wave base as outer shelf turbidites. To the south of the Beharra Springs Field the Wagina Sandstone grades into a carbonate province deposited in an outer shelf environment remote from clastic input represented by the Beekeeper Formation.

Average grain size in the Dongara Sandstone is coarser and grains are better rounded than the Wagina Sandstone. Lithology is dominated by quartzarenites with rare moderately-well sorted subarkose and moderately sorted sublitharenite, consistent with the Herron classification. As for the Wagina Sandstone, it is possible that sandstones in the Dongara originally contained more feldspars. Two to five percent feldspar could be added to the detrital mineralogy based on the percentage of kaolin replacing feldspars for all samples except the cleanest quartz arenites. If two to five percent feldspar was present at the time of deposition in the other sandstones then lithologically they were subarkoses. Based on the core from Jingemia-4, the Dongara Sandstone represents a barrier bar / strandline complex with a nearby tidal inlet (Philips, 2005).

Overall, differences between the detrital mineralogy of the Wagina Sandstone and the Dongara Sandstone may in part be attributed to the change in grain size and hydraulic regime rather than sediment provenance. Feldspars in the Dongara Sandstone, which are dominated by K-feldspars with perthite and tartan twinning, and rare plagioclase, are very similar to those described from the Wagina Sandstone. Rare accessory minerals of zircon, monazite, garnet, rutile, tourmaline and opaques recognised in the Dongara Sandstone are consistent with the Wagina assemblage.

Reservoir Quality Data

There are 452 routine core analysis (RCA) data available for the study wells from the Dongara and Wagina sandstones. The data is plotted on the porosity-permeability plot (**Figure 9**) and shows that both the Dongara and Wagina sandstones plot on a positive trend, with the decreasing porosity and permeability following the compaction and/or cementation trends suggested by (Cade, et al., 1994). Furthermore, **Figure 9** demonstrates that the best permeability is seen within the samples from the Dongara Sandstone, as they exhibit higher permeability than samples with equivalent porosity from the Wagina Sandstone. However, higher porosities (>18%) are generally recorded within Wagina Sandstone RCA data.

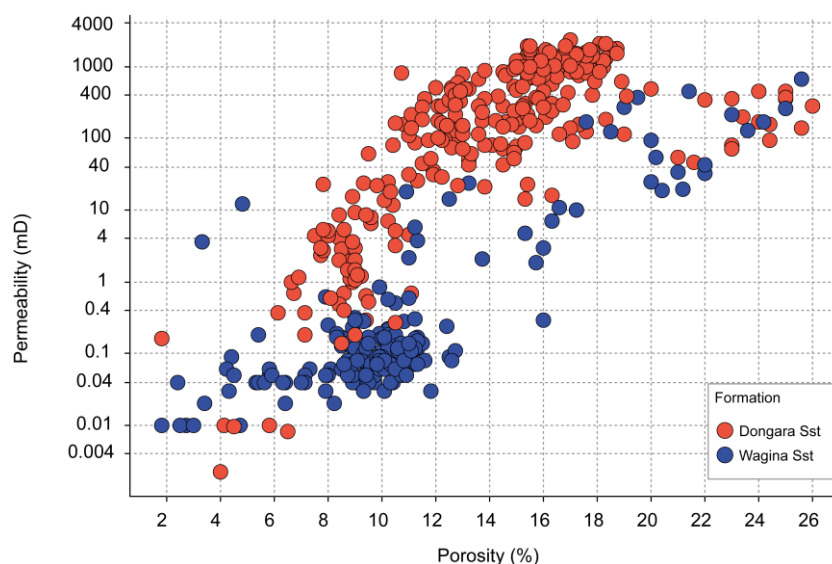


Figure 9. RCA data of available Dongara and Wagina Sandstone cores.

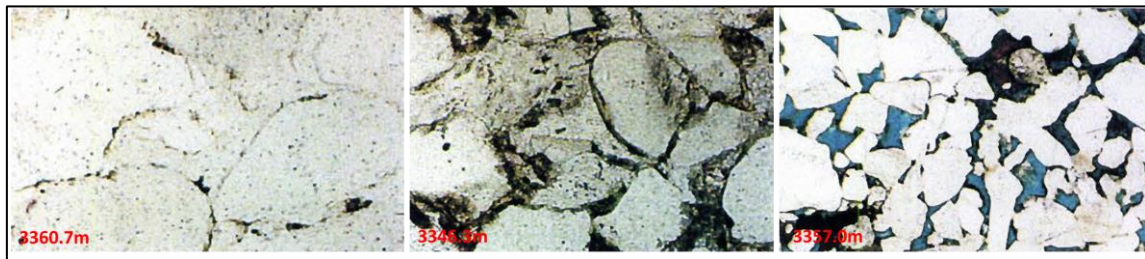
Reservoir quality in the Wagina Sandstone is limited because primary intergranular pores (and hence permeability) are generally not well preserved. The percentage of intergranular pores in the Wagina Sandstone has been limited by the abundance of ductile micas and detrital clay matrix favouring early compaction, the abundance of pore filling quartz overgrowths, kaolin squeezed into intergranular pores and locally pore filling carbonate spar. Dissolution pores are dominant in the Wagina Sandstone however these are unlikely to be interconnected hence permeability is limited. Secondary dissolution pores are grain sized due to the corrosion of labile grains, honeycomb where feldspars are partially dissolved, and rarely intragranular when lithics are partially dissolved. Isolated samples where chlorite rims are best developed do have intergranular pores, but these are confined to specific coarser grained laminae. Micropores associated with kaolin in the Wagina also contribute to total porosity they are unlikely to influence effective porosity.

Primary intergranular pores are typically more abundant in the Dongara Sandstone than the Wagina Sandstone therefore permeability has been preserved. Intergranular pores in the Dongara Sandstone tend to be better preserved where sandstones are moderately to well sorted and there is no detrital clay. Therefore, reservoir quality was probably controlled by the hydraulic regime of the depositional environment. As with the Wagina Sandstone, ineffective clay micropores and dissolution pores of various types are also recognised. Fracturing of fresh, sericitised and corroded feldspars (0-2%) has also contributed to total porosity.

Authigenic kaolinite is an abundant pore filling cement occurring as aggregates of booklets, and multiple phases of kaolinisation have been recognised. It is associated with the early dissolution of feldspar and lithic grains and predominantly occurs within early grain dissolution pores, or locally as an in-situ grain replacement. Kaolinite formation is thought to be associated with low salinity pore waters, which are characterised by low cation concentrations. Its development is therefore favoured by areas of the basin which were characterised by meteoric pore waters. Kaolinite alteration will result in illite cementation at depths greater than approximately 3 km.

Pervasive quartz cementation is inferred to form greater than 2 km depth. Two factors that are key to inhibiting the nucleation of quartz overgrowths are either the development of (continuous) chlorite grain coatings (or grains that do not favour quartz nucleation), and/or early hydrocarbon emplacement. Two phases of chlorite grain coatings are recognised: early syn-depositional chlorite, and later clay development following compaction after significant quartz cementation.

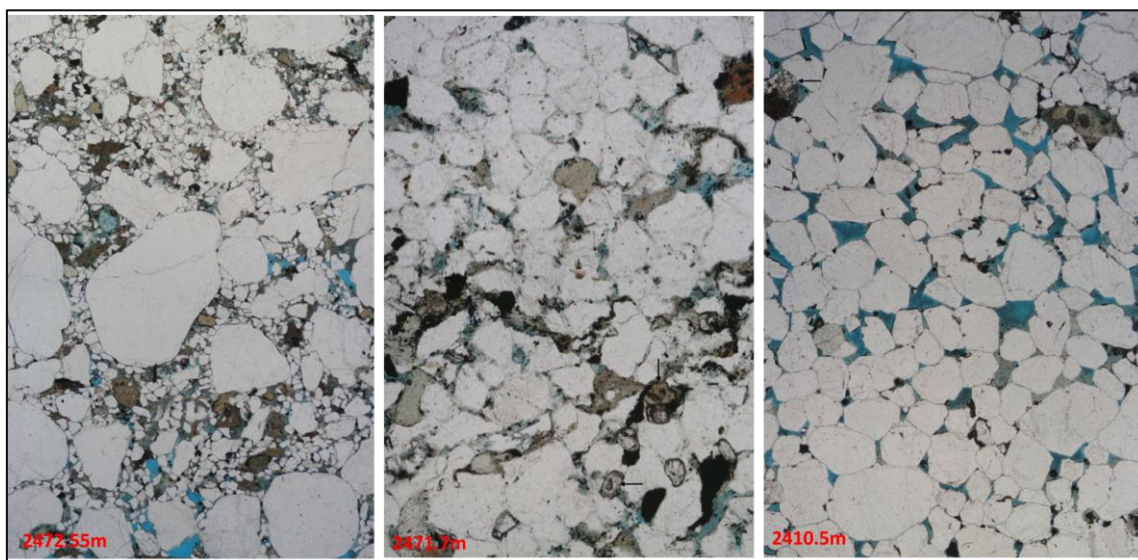
Well-developed grain coating chlorite is generally not observed in the Dongara and Wagina sandstones, ascribed this to pervasive early meteoric flushing from the northwest. In Beharra Springs-2 (**Figure 10**) however, effective chlorite (and illite-smectite) grain coats are recognised, although in some of the chlorite coated sands calcite cement has nucleated on bioclasts.



Left: Quartz cements around patchy grain coats. **Middle:** calcite cements within chlorite grain coated sands. **Right:** Porosity preserved due to grain coated sands (**Laker N., 2000**).

Figure 10. Petrography Summary of Beharra Springs-2.

The impact of both lithics and texture on rock quality is highlighted in Jingemia-4 (**Figure 11**) where only the cleanest and best sorted sands are effective. Sublitharenites of the Wagina Sandstone in Jingemia-4 (left and middle, **Figure 11**) typically have a poor textural maturity, comprising a coarse fraction of monocrystalline quartz, K-feldspar and lithics, and a fine fraction which also includes altered biotite and accessory minerals zircon, monazite, rutile, and garnet. Chlorite rims are locally recognised, however syntaxial quartz overgrowths have filled intergranular pores where rims are not well developed, and fine sand is dominant. In contrast, quartz arenites of the Dongara Sandstone in Jingemia-1 (right, **Figure 11**) is dominated by well sorted coarse sands with minor corroded feldspars and lithics. Syntaxial quartz overgrowths and pore filling and grain replacing kaolin booklets are the dominant authigenic minerals.



Left: bimodal grain size with high lithics in the finer grained fraction (Wagina). **Middle:** Cemented sandstone with significant lithic content (Wagina). **Right:** Clean sand and preserved intergranular pores despite quartz cementation (Dongara) (Philips, 2005).

Figure 11. Petrography Summary of Jingemia-4.

Principal Component Analysis (PCA)

Within the absence of comparable elemental and mineralogical datasets the statistical testing of Principal Component Analysis (PCA) is used to test the element-to-element relationships, from these a mineralogical affinity is deduced. PCA has previously been utilised in many chemostratigraphic studies as a cluster analysis tool and can reduce the inherent variability present in any geochemical dataset to a smaller number of derived variables termed principal components (PC). From this, one is then able to determine which elements have similar distributions, these new element associations subsequently being used to highlight specific characteristics of a dataset. Principal components 1, 2, 3 and 4 (PC1 to PC4) typically account for around 80% of the total variance in any one dataset. The principal component (PC) score assigned to each sample is derived from the eigenvectors (EV) - when the eigenvector values are plotted against each other, the closer the variables (elements) plot to one another, the more closely associated they are in the sedimentary rock, thereby providing a means by which to recognise any relationships between the elements and minerals (Pearce, et al., 1999). The PCA analysis carried out on the geochemical dataset had been carried out using the centre logged ratio (clr) transformation (Pawlowsky-Glahn, et al., 2011).

PCA results are best represented in a biplot (**Figure 12.**), a valid interpretation of which is achieved by considering the following:

- the length of a ray (of a component or element): the length of a ray reflects the degree of

variability of a component (element), such that a long ray denotes a component with a high degree of variability within the geochemical dataset, whereas a short ray signifies a component with a low degree of variability within the dataset.

- the angle between two rays: small inter-ray angles correspond to high proportionality for the elements involved, whilst an angle of 90° suggests there is no correlation between the processes controlling the variation of each of the two elements, an angle of 120° points to the existence of three independent processes and/or mixing between the elements and an angle of 180° reflects inverse proportionality between the processes controlling the variation of each of the two groups of elements.

Based on the PCA analysis eight elemental groups have been recognised (**Figure 12**), their descriptions are as follows:

- *Quartz, characterised by negative PC1 (1st) and PC2 (2nd) values. This association only contains the element Si. Si is almost exclusively associated quartz, and within the context of this study is used in that way. Si will also have minor associations with other siliciclastic minerals, included but not limited to mica, clay minerals, and feldspars.*
- *Zircon, characterised by negative PC1 (1st) and positive PC2 (2nd). This elemental association contains the elements Zr, Hf, Th and U. Zr and Hf are exclusively associated with the heavy mineral zircon; Hf is often substituted into the zircon crystal structure. Other elements that may associate with zircon include elements such as Th and U, by elemental substitutions.*
- *Ti-oxides, this group is characterised by negative PC1 (1st) and positive PC2 (2nd). This elemental association contains the elements Ti and Nb. Ti and Nb are both usually associated with Ti-oxide heavy minerals such as rutile and/or anatase. The close association to the Zr group implies a similar grainsize fraction. Automated Raman or optical heavy mineral analysis would be recommended to confirm this elemental association.*
- *K-feldspar/illite, this group is characterised positive PC1 (1st) and negative PC2 (2nd). This elemental association contains the elements K, Rb and Al. K-feldspar is preferentially enriched in K relative to Rb, while illite contain a greater proportion of Rb. High K/Rb ratios distinguish between K-feldspar and illite.*
- *Kaolinite, this group is characterised positive PC1 (1st) and negative PC2 (2nd). This elemental association contains the elements Ga and Al. Ga is predominantly associated with kaolinite. Kaolinite may form because of enhanced geochemical weathering, particularly within humid and tropical areas with subaerial exposure.*
- *Smectite, this group is characterised positive PC1 (1st) and negative PC2 (2nd). This elemental association only contains the element Cs, which is a predominant indicator of smectite. Cs is most abundant within marine conditions and Cs rich smectite are often inferred as indicators of a marine environment.*
- *Chlorite/Chamosite/Glaucanite. This group is characterised by positive PC1 (1st) and*

positive PC2 (2nd). This elemental association contains the elements Cr, Sc, P and Fe. While an elemental association such as this would typically be attributed to the occurrence of mafic volcanism, which is typical of a rifting tectonic setting. However, the likely association of this group is the occurrence of chamosite (a Fe-chlorite) and glauconite, both have been identified within petrographic studies. It could be suggested that there is potential reworking of mafic volcanic products to supply the high proportion of Fe recognised within some of the fine-grained sediment. Furthermore, the PCA analysis of the data supports the evidence of (Laker N., 2000) as the chlorites were recognised as Fe-rich.

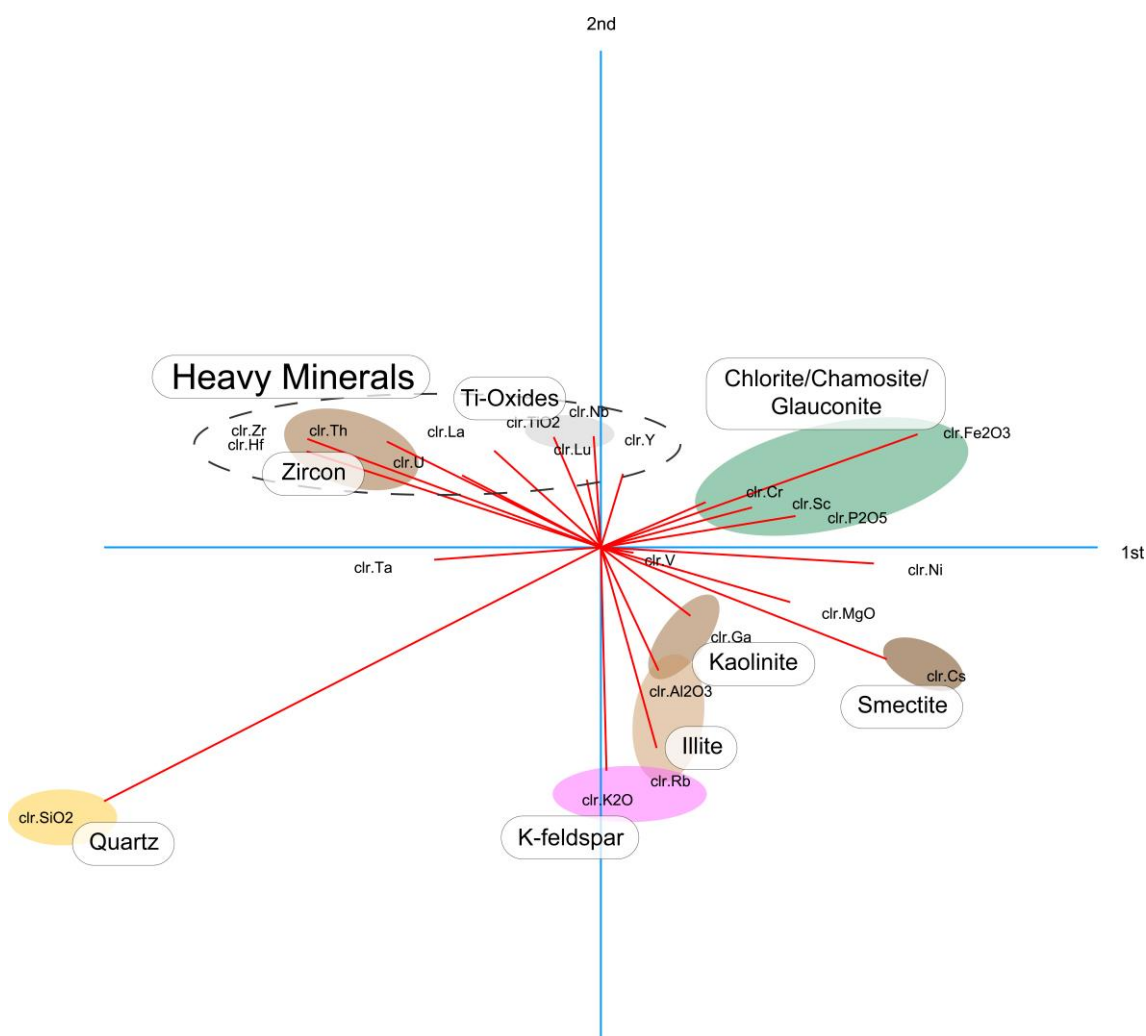


Figure 12. PCA Biplot (PC1-PC2).

Key Ratios

Following a review of the published data and the statistical testing of the elemental datasets the following 'key ratios & elements' are selected and reflect the geochemical variation over the study interval (**Table 2**). These elements are usually related to provenance, climatic, and organic matter changes as they typically have the best correlation potential over a greater distance. The key elements are presented as elemental ratio profiles as this normalises out the effect of changes in

grainsize on the data. In this case several ratios use REE as rare earth phosphates (monazite, xenotime) are known to locally have a high abundance in the study interval.

Table 2. Key ratios and elements

Ratio/Element	Interpretation
Si/Zr & Si/Al	Si/Zr and Si/Al are both primarily a function of grain size, and therefore are attributed to geological process – particularly the energy within the environment of deposition. Higher Si/Al values are typical of sandstones, and therefore a higher environment energy, such as a shoreface or channel. Si/Zr reflects the abundance of quartz to the heavy mineral zircon; zircon and silt-fine sand sort within a similar manner, higher values reflect the accumulation of quartz over zircon implying coarser grain sizes.
Ca	Principally attributed to calcite, although can be present in clays and feldspars in lesser abundances.
Na	Plagioclase feldspar or NaCl contamination.
Mo	Mo is enriched in anoxic marine environments. Mo has affinities with pyrite, as well as heavy minerals and clay minerals.
Mn	Mn substitutes for Ca, Fe, Mg and Sr in a range of minerals that include clay minerals, mica, mafic minerals such as pyroxene and carbonate minerals like calcite, siderite, dolomite and ankerite.
Ti/Nb	Both elements will be present in Ti-bearing heavy minerals, clays & micas. Changes in this ratio are linked to changes in sediment provenance.
Ti/Cr	Both elements will be present in clay minerals, micas & heavy minerals. This ratio relates to changes in the assemblages of heavy & clay mineral and may be linked to sediment provenance.
Nb/Y	Likely related to heavy minerals and clays and changes may be linked to changes in sediment provenance. Y is relatively immobile and is found in heavy minerals, e.g., zircon and garnet, and can also be found in bone phosphate, where it is associated with P, Sr, the REE's, U and Th.
Nb/Th	Nb and Th are both associated with heavy minerals by substituting into the crystal lattice of Ti-oxides and zircons, or phosphatic heavy minerals, respectively. Minor amounts of Nb are also linked with biotite and chloritic clay minerals. High values are indicative of abundant Ti-oxide heavy minerals, while low values are indicative of zircon or in this case RE phosphates. Changes may be linked to changes in sediment provenance.

V/Sc	V is associated with clay minerals (chiefly illite and chlorite) and Sc is found in trace amounts in feldspar, clay minerals and mica, and in kaolinitic silty claystones, high Sc levels are often associated with Al, Ga and the LREEs. This ratio principally relates to changes in the assemblages of clay minerals and may be linked to sediment provenance.
V/La	Both elements will be present in clay minerals and La is also present in heavy minerals, notable monazite. Changes may be linked to changes in sediment provenance and higher values could suggest a more chlorite-rich interval or indicate anoxic deposition if associated with other paleoredox indications.
V/Al	V is associated with clay minerals (chiefly illite and chlorite) and organic matter as V is also sensitive to redox conditions. Normalising to Al will highlight V enrichment in the clays.
V/Ti	Both elements will be present in clay minerals (especially illite and chlorite) and Ti will also occur in a variety of heavy minerals. This ratio is primarily used to highlight changes in clay assemblage in sandstone, notably the presence of chlorite associated with porosity.
Cr/U	Cr is linked to heavy minerals and can also be associated with chloritic clay minerals and biotite. In Package 3 (Kingia Sandstone) higher values of this ratio have been linked to the enrichment of chlorite, and enhanced porosity preservation in the Waitsia wells.
P/Cs	Phosphate is typically an indicator of biogenic activity. High P values relative to Al, may reflect biogenic activity, but high values with other heavy mineral associated elements may reflect the occurrence of P-bearing heavy minerals. Ratio to Cs indicates enrichment relative to background clay composition.
Rb/Cs	Rb is associated with K-feldspar and especially illite, while Cs is primarily attributed to marine smectite. The ratio will highlight subtle changes in clay composition
K/Al	K is associated with the occurrence of K-feldspar and illite. High K/Al values (>0.35), in conjunction with high K/Rb values are indicative of K-feldspar abundance.
K/Rb	K and Rb are both associated with K-feldspar and illite, with the latter being preferentially enriched in Rb. High values are indicative of the K being present in K-feldspar, while lower values demonstrate relative illite abundance
K/Na	Ka typically reflects the abundance of K feldspar (+illite/mica), while the Na is typically associated with the abundance of plagioclase. This ratio examines the changes in feldspar population.

Ga/Rb	This ratio typically represents a kaolinite/illite ratio. Ga is preferentially enriched in kaolinite, while the Rb is enriched in illite. Changes in this ratio reflects a change in the clay mineral type. May also have implications within a climatic interpretation as kaolinite typically forms under enhanced tropical weathering of subaerially exposed sediment.
Fe/Al & Mg/Al	Fe is primarily associated with clay minerals, most likely chlorite. Both Fe and Mg may also be associated with carbonates, siderite and dolomite, or mafic minerals, such as pyroxene. Locally, Fe may be associated with S indicating the presence of pyrite or jarosite. Normalising to Al will highlight the enrichment in non-clay phases.
La/Al	La is present in clay minerals and heavy minerals. Monazite is known to be prevalent in the Dongara-Wagina and is concentrated in LREE. Normalising to Al will highlight the heavy mineral enrichment.
Th/Dy	Likely related to heavy minerals and clays and changes may be linked to changes in sediment provenance. Th is known to be the primary radioactive component in the Dongara-Wagina, and this is concentrated in the RE phosphates (monazite and xenotime).
Cs/Ce	Lower values reflect changes in clay composition and in this case likely reflect the occurrence of heavy mineral (especially RE phosphate) rich sediments. High ratio values possibly may indicate marine flooding events, with abundant smectite.

CHEMOSTRATIGRAPHY

Chemostratigraphy is based on the geochemistry of sedimentary rocks typically being variable and sensitive to subtle changes in the mineralogy of the rocks. Apparently uniform successions often have differences in the geochemistry of their component minerals or in the abundance and proportions of accessory minerals, such as heavy minerals and clay minerals, some of which have very distinctive trace element contents.

The technique involves the zonation and correlation of units of rock with similar geochemical characteristics. These may be used on various scales, analogous to a lithostratigraphic hierarchical scheme. The hierarchical zonation scheme used for this study has resulted in the identification of chemostratigraphic packages that are divided into units.

Package: a chemostratigraphic division having distinct geochemical characteristics that are of significant magnitude and believed to have the ability to be correlated regionally.

Unit: a chemostratigraphic division within a package which may only correlate on a local- or field-scale.

Chemostratigraphic divisions correspond to intervals of sedimentary rocks that have similar geochemical compositions. These divisions are not equivalent to small-scale features such as sand bodies. Chemostratigraphy has the potential to recognise regional changes in provenance regardless of lithology.

Chemostratigraphic zonation

Chemostratigraphy is a stratigraphic technique involving the characterisation, and correlation of sedimentary strata based on the stratigraphic variations in inorganic geochemistry (Pearce et al. 2005; Ratcliffe et al. 2006). These geochemical variations reflect changes in the mineralogy of the sedimentary rocks, which are linked to either change in provenance, climate, depositional environment, and diagenesis; geochemical variations linked to changes in provenance and climate are the most significant with respect to chemostratigraphy. For example, Hildred et al. (2010) demonstrated the homotaxial nature of a two-valley system using changes in the concentrations of provenance-related elements, whereas Ratcliffe et al. (2010) described how elements whose concentrations are influenced by climate changes can be used for chemostratigraphic purposes.

The interpretation has been based on the existing chemostratigraphic framework of the onshore North Perth Basin. The Wagina Sandstone has been assigned to Package 6 and the Dongara Sandstone, Package 7, and have been subdivided into seven and five units respectively. **Table 3** lists the chemostratigraphic zonation depths and the interpretation is summarised in the correlation. Each datapoint in the supplementary data is assigned a chemostratigraphic interpretation.

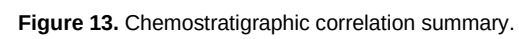
Table 3. Chemostratigraphic zonation depths

All depths are in metres and as measured depths

Package	Unit	Apium-1		Beharra Springs-2		Dongara-12		Dongara-4	
		Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth
P7	7_5	2760.3	2764						
	7_4	2764	2770.6						
	7_3	2770.6	2777						
	7_2	2777	2781.6						
	7_1	2781.6	2784.2						
P6	6_6	2784.2	2803.3			1630.8	1644.1	1688.3	1700.7
	6_5	2803.3	2828.4			1644.1	1655.3	1700.7	1719
	6_4	2828.4	2844.5	3332.8	3340.7	1655.3	1660	1719	1723.5
	6_3	2844.5	2860	3340.7	3347	1660	1663.9		
	6_2			3347	3353.6				
	6_1			3353.6	3365.1				
	6_0			3365.1	3387.88				
Package	Unit	East Heaton-1		Erregulla-1		Heaton-1		Hovea-3/ST1	
		Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth
P7	7_5	2040.7	2066.9			2130.2	2145	1992.2	1998.1
	7_4							1998.1	2006.4
	7_3							2006.4	2016.8
	7_2							2016.8	2023.8
	7_1							2023.8	2033.0
P6	6_6	2066.9	2092.7	3912.1	3993.1	2145.0	2186.6		
	6_5	2092.7	2122.9	3993.1	4061.2	2186.6	2228.3	2033.0	2037.7
	6_4	2122.9	2169.1	4061.2	4127.0	2228.3	2256.0	2037.7	2047.3

	6_3	2169.1	2260.2	4127.0	4185.4	2256.0	2290.1	2047.3	2091.7
	6_2	2260.2	2284.4	4185.4	4243.4	2290.1	2305.7		
	6_1	2284.4	2313.5			2305.7	2328.0		
	6_0								
Package	Unit	Jingemia-4		Lockyer-1		Mondarra-7		North Erregulla-1	
		Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth
P7	7_5	2406.2	2407.1	3185.3	3247.6	2713.7	2717.0	3221.9	3244.9
	7_4	2407.1	2413.0			2717.0	2722.9		
	7_3	2413.0	2420.5			2722.9	2731.7		
	7_2	2420.5	2426.6			2731.7	2740.1		
	7_1	2426.6	2433.7			2740.1	2747.6		
P6	6_6	2433.7	2442.0	3247.6	3327.0	2747.6	2762.3	3244.9	3293.0
	6_5	2442.0	2455.4			2762.3	2767.3	3293.0	3349.2
	6_4	2455.4	2464.5					3349.2	3417.4
	6_3	2464.5	2475.0					3417.4	3444.3
	6_2								
	6_1								
	6_0								
Package	Unit	Tarantula-1/ST1		Warradong-1		Yardarino-2			
		Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth	Top Depth	Base Depth
P7	7_5			3173.4	3205.2	2337.0	2340.2		
	7_4					2340.2	2348.9		
	7_3					2348.9	2359.2		
	7_2					2359.2	2365.5		
	7_1					2365.5	2369.3		
P6	6_6			3205.2	3250.2	2369.3	2385.9		
	6_5			3250.2	3288.3	2385.9	2407.4		

	6_4	3209.0	3216.4	3288.3	3343.3	2407.4	2415.8		
	6_3	3216.4	3228.8	3343.3	3372.8	2415.8	2428.7		
	6_2	3228.8	3258.0	3372.8	3386.0	2428.7	2432.9		
	6_1	3258.0	3275.1						
	6_0	3275.1	3288.2						



Chemostratigraphic definitions

Table 4. Geochemical differentiation of chemostratigraphic units

Unit	Lithostrat (approx.)	Definition
Units 6_0	Wagina Sandstone	Calcareous sand/siltstone - limestone and associated Mg-Fe enrichment, high La/Al, low Cs/Ce. Top is defined by sharp decrease in carbonate content.
Unit 6_1	Wagina Sandstone	Arenaceous interval with Nb enrichment at base.
Unit 6_2	Wagina Sandstone	Similar to Unit 6_0
Unit 6_3	Wagina Sandstone	Base is defined by a zone of Nb and Mn enrichment. High La/Al, low Cs/Ce, high V/Al & V/Sc. Top increase in Cs/Ce and decrease
Unit 6_4	Wagina Sandstone	Low Ti/Nb and low V/Al, although can be high at top. Low La/Al, high Cs/Ce, high V/La & low Th/Dy. Top decrease in Ti/Nb.
Unit 6_5	Wagina Sandstone	High Rb/Cs and high Ti/Cr & Ti/Nb.
Unit 6_6	Wagina Sandstone	Decreasing Rb/Cs Higher Ti/Cr & Ti/Nb. Low V/Sc & high La/Al
Unit 7_1	Dongara Sandstone	High V/Al, decrease in Ti/Cr
Unit 7_2	Dongara Sandstone	High V/Sc, low V/Al, low Ti/Cr
Unit 7_3	Dongara Sandstone	High Th/Dy, increasing V/Al
Unit 7_4	Dongara Sandstone	Decreasing Rb/Cs, high V/Sc at the top
Unit 7_5	Dongara Sandstone	Low P/Cs, high Cs/Ce. Often heavy mineral rich.

DISCUSSION

HyLogger Data

The HyLogger spectral scanner is a rapid non-destructive spectroscopic logging and imaging system that uses continuous visible and infrared spectroscopy and digital imaging to examine cores, samples, and cuttings. HyLogging is an automated technology designed by CSIRO to determine drillcore mineralogy using rapid reflectance spectroscopy at 400–2500 and 6000 – 14 500 nm wavelength regions (DMIRS, 2021). Many of the study wells (core and cuttings) were analysed for the GSWA Perth Basin reservoir quality study (Copp, et al., 2021), the data for which is open file. The raw data was evaluated using The Spectral Geologist software and exported for this study. Generally, the SWIR is good for identifying the hydrous minerals (clays, micas, sulphates) and carbonate minerals. Dark coloured mudstones absorb and scatter the IR resulting in 'aspectral' mudstones in SWIR. The TIR is used for quartz, feldspars, carbonates, some silicate minerals (including clays & micas). Data are given as relative abundance for each of the spectral regions. Variations in illite composition are typically interpreted as muscovite, phengite and muscoviticillite. Chlorite is reported as either Fe or Mg-dominant.

Figure 14 shows the HyLogger data for Jingemia-4 plotted with the petrology data, RCA data and selected elements and ratios.

The (Wagina) sands in Package 6 are generally considered clean although do exhibit a variable amount of clay, whereas Si levels are consistently very high in Package 6 and thin-section analysis indicates the presence of authigenic quartz. HyLogger has recognised the presence of K-feldspar, most noticeably in Unit 6_3 where the highest K/Al values were observed. High levels of microcline are indicated by the HyLogger in Package 5 (Carynginia Formation) and orthoclase in Package 8 (Hovea Member). Plagioclase is only rarely reported in the HyLogger data, and this is predominantly identified in Package 8, consistent with the petrology thin section analysis (Philips, 2005) and low Na levels throughout the study interval. The HyLogger data indicates the dominant clay is kaolinitic, confirmed by the thin section analysis, however the Wagina Sandstone also has an illitic component, as confirmed by the elevated Rb.

Chlorite is reported from the thin section analysis of the Wagina Sandstone, most notably in units 6_3 and 6_4 and this is also observed in the HyLogger data which also indicates localised presence in units 6_5 and 6_6. There is excellent corroboration with Cr, Mg and Fe enrichment. The chlorite zone at the top of Unit 6_4 and at the base of Package 6 appear to contain calcite and siderite cement, reflected in the poor reservoir quality, and have lithics reported. The chlorite indicated in units 6_5 and 6_6 doesn't appear to have a positive effect on the reservoir quality which is universally poor in the Wagina Sandstone in Jingemia-4.

The top of Package 6 is reported to be a faulted contact (Philips, 2005) and a prominent spike in several elements may support this.

K-feldspar is reported in the thin-section analysis of all Package 7 samples and the K/Al values

indicate K-feldspar is locally present although decreasing toward the top of the package and not in sufficient quantities to be recognised by the HyLogger. There is an enrichment of Mn, Mg and Fe in Unit 7_3, and a minor increase in P towards the top of the unit. This would indicate the presence of minor siderite. A minor increase in P is also observed at the top of Unit 7_4 and this may indicate the preservation of biogenic phosphate associated with hiatal surfaces. Reservoir quality is good to excellent throughout Package 7 in Jingemia-4. The reduced permeability observed in Unit 7_2 reflects a minor increase in clay content (**Figure 14**, far right track), in this case pore filling kaolinite which does not impact the GR response.

Package 7 is directly overlain by a high GR likely source interval characterised by high Mo, immediately overlain by a sideritic limestone, characteristic of Package 8 (Hovea Member).

Many similar observations can be made on other wells (**Figure 15**). In Hovea-3/ST1 Unit 6_4 chlorite is indicated (from HyLogger and elemental data) but no significant carbonate is present, the RCA data suggests this may be fair quality reservoir. The petrology description for the sample at 2044.13 mMD (Baker, 2003) confirms that chlorite is present, however the grain rims are poorly developed, and primary intergranular pores are filled by quartz overgrowths. The porosity observed comprises secondary grain dissolution pores in which chlorite occurs as a remnant of labile grains.

As observed in Jingemia-4 chlorite is evident in Mondarra-7 at two levels in Unit 6_6 associated with iron-rich carbonates, and a clay-prone level in Unit 6_5, however the miniperm data indicates that no reservoirs are present in Unit 6. Unit 7_1 is (ferroan) carbonate cemented and above this the HyLogger data indicates a change to a mixed illitic-kaolinitic assemblage. Minor Cr enrichment in units 7_3 and 7_4 appear to have a positive impact on the reservoir quality, as evident by correlation of the Cr/Al curve and the miniperm data (far right track), although no chlorite is indicated by the HyLogger data. This change in clay assemblage compared to other wells may represent early hydrocarbon influx retarding diagenetic alteration.

No chlorite is interpreted from any of the datasets in the study interval in the Dongara wells, predominantly comprising Package 6 (Wagina) lithic rich 'hot' sands. This is the shallowest intersection of the study interval, and porosity comprises predominantly of oversized intergranular pores not yet occluded by authigenic quartz (Laker N., 2000).

Similarly, clean sands in upper Package 6 (units 6_6 and 6_5) and Package 7 in Apium-1 have no indication from any of the datasets for the presence of chlorite. The Fe enrichment observed at sample 2769.5 m occurs at an inflection in the sonic and increase in reservoir quality and may represent a fault zone. There is however evidence from the HyLogger and elemental Mg and Fe data for the presence of chlorite in Unit 6_3, just above TD, although porosity logs don't extend that far.

Unit 6_5 and 6_6 sands in Yardarino-2 display prominent Cr enrichment however no HyLogger is available to confirm the presence of chlorite. The (lithic rich) base of the Package 7 sands in

Yardarino-2 also appears to be locally carbonate cemented, however the RCA data indicates that the remainder predominantly comprises of good quality sands. Unit 7_3 is also characterised by a Cr enrichment which the HyLogger data ascribes to the presence of hematite, although there is only minor Fe enrichment.

The presence of (Mg-rich) chlorite is confirmed by thin-section analysis, elemental and HyLogger data in the (increasingly argillaceous) sands of units 6_1, 6_2, 6_3 in Beharra Springs-2. These sands appear to be more plagioclase rich than observed in wells to the north as indicated by all datasets. Reservoir quality, however, will no doubt be impacted by the presence of pervasive carbonate cements.

No HyLogger data is available for wells on the Allanoooka Terrace where many of the Package 6 sands exhibit local Cr enrichment, however it's not clear if this has a positive impact on reservoir quality. Detailed evaluation of the reservoir quality from sands in the Dandaragan Trough is problematic given the generally limited nature of the samples. However, sands in units 6_3 - 6_6 are often very clean with limited evidence for significant chlorite development from the HyLogger and elemental datasets, and the minor carbonate cements appear ferroan. The limited thin-section analysis available indicates pervasive authigenic quartz and there is likely to be significant illite cementation given the depths.

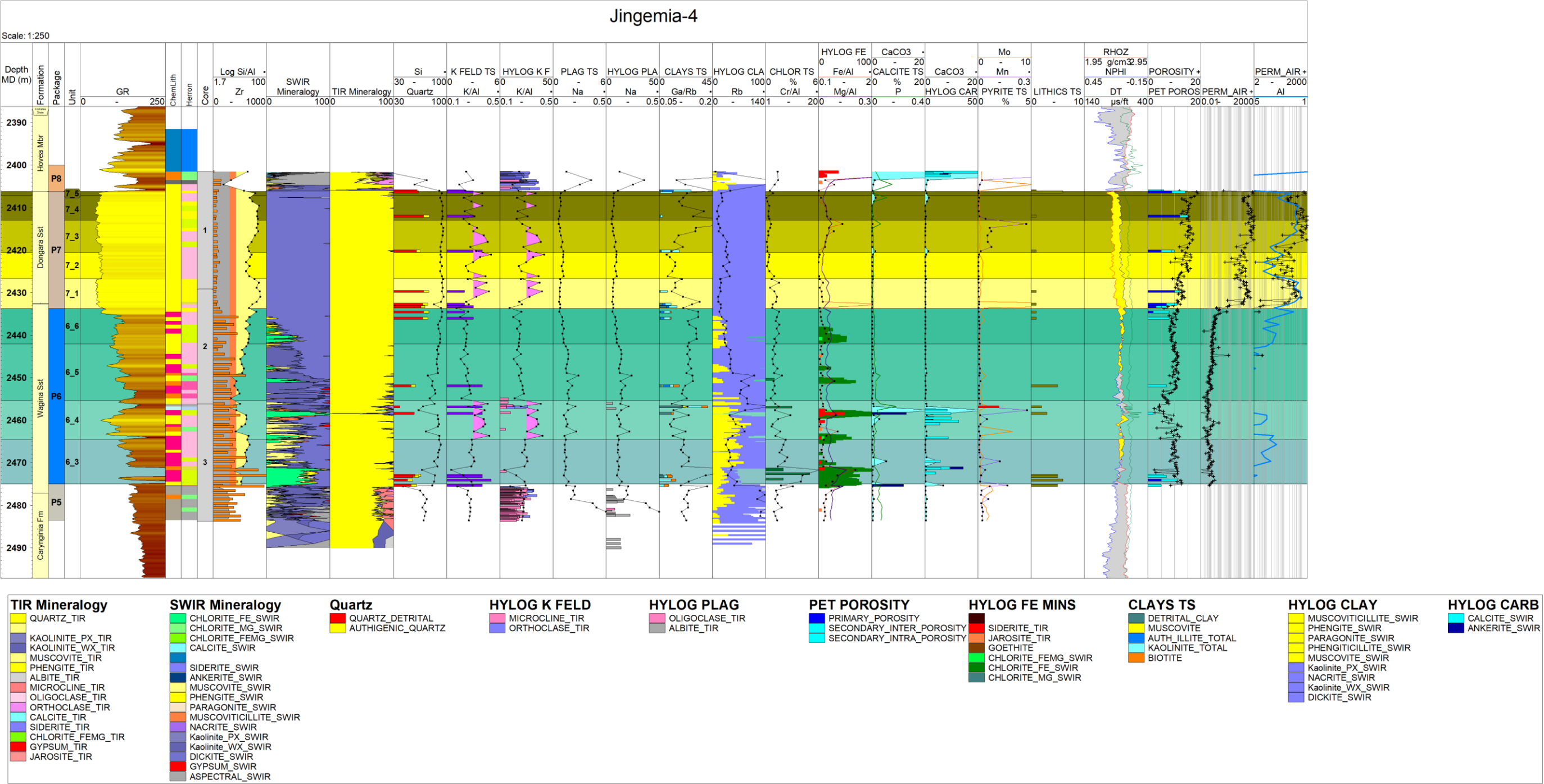


Figure 14. HyLogger, petrology and selected elements and ratios for Jingemia-4.

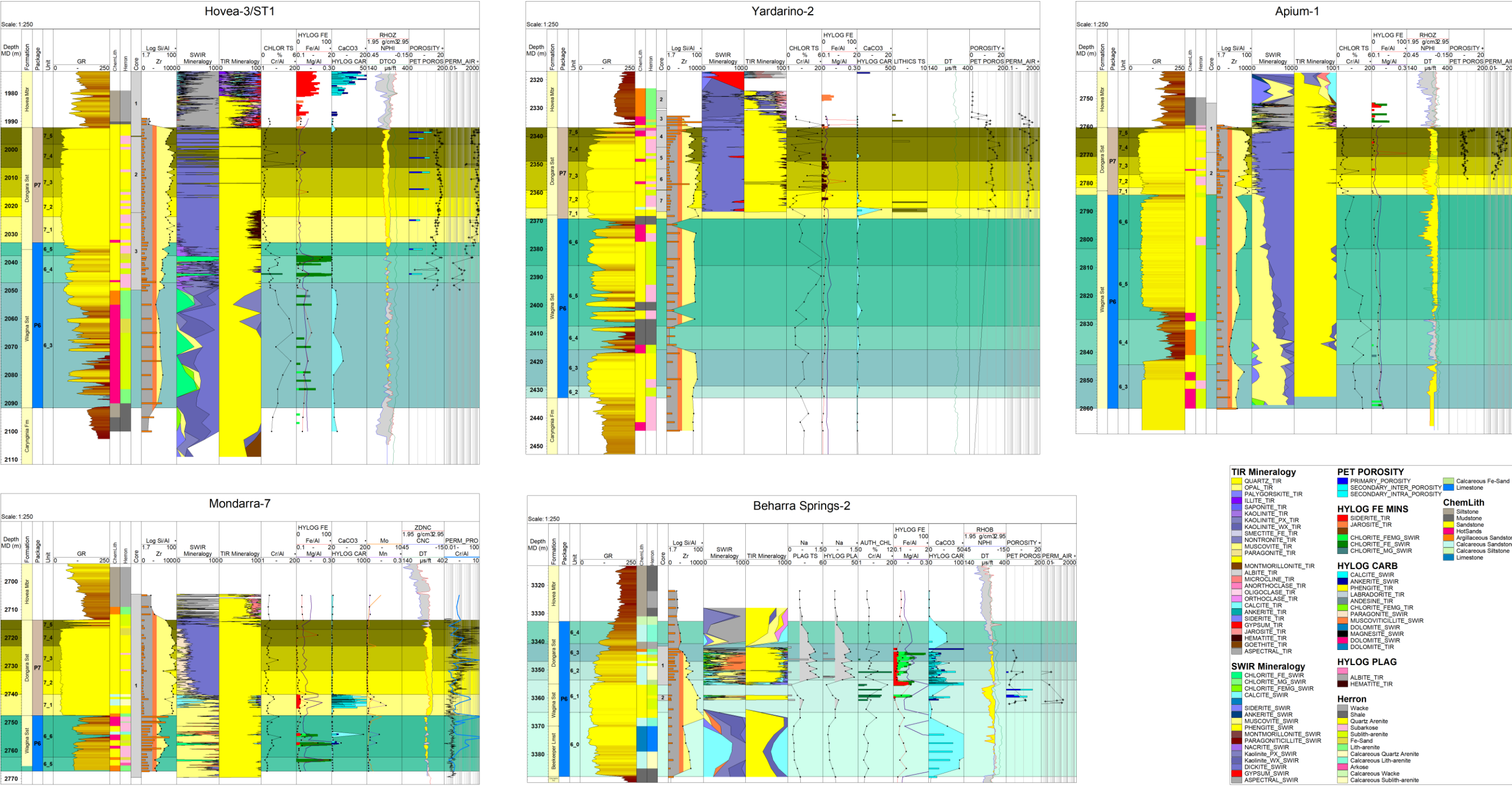


Figure 15. HyLogger, petrology and selected elements and ratios, multiple wells.

Heavy Minerals

Heavy minerals are widely reported throughout the Wagina succession (Laker N., 2000; Rasmussen, 1992) in the North Perth Basin, particularly in the Mondarra-Yardarino-Dongara area. Ramen heavy mineral analysis (Chemostrat Australia, 2021) conducted on samples from the Dongara and Wagina formations in Senecio-3 and Depot Hill-1 shows that the heavy mineral assemblage is dominated by rutile with subordinate zircon. This has also confirmed the presence of abundant monazite (and xenotime) rare earth phosphates (**Figure 16**).

Heavy mineral concentrations (particularly monazite) produce a characteristic high GR response and may form because of storms winnowing sands around fair-weather wave base (Ferdinando, et al., 2021). Monazite comprises principally Ce phosphate but also contains a wide range of REE. Th is common (4-13%) and is responsible for most of the radioactivity although other radioactive constituents include uranium and some isotopes of the REE's. Monazite generally forms in granitic rocks and pegmatites and is moderately resistant to weathering. Whilst zircon is also common, zircon grains from the Permo-Triassic sandstones and basement rocks are compositionally similar with little or no Th or U (Rasmussen, 1992).

Investigation of the enrichment of the Ce (as a proxy for the presence of monazite) in the study wells (**Figure 17**) shows that this is relatively abundant in Package 6, most notably in Unit 6_6, although there are particular units (e.g., Unit 6_4) where this is not case. This results in widespread ChemLith recognition of 'hot' sands (clean sands with ChemGR >100), within Package 6, especially on the Dongara Terrace and Waitsia area. Enrichment can be indicated in the cleanest Package 6 sands, for example on the Allanooka Terrace, however the absolute abundance is insufficient to significantly impact the GR response. Wells in the Dandaragan Trough appear to have only sporadic development of Ce enrichment and very few 'hot' sand samples have been recognised. It's likely that heavy mineral concentration diminishes eastwards due to distance from source area (Northampton Complex) and/or dilution in an expanded section. In most cases, Ce enrichment is accompanied by a commensurate enrichment in Ti and increase in the absolute abundance of Zr (indicating the presence of zircons). Thus, the principal heavy mineral components appear to be present throughout the study interval and are hydraulically sorting together.

In the clean sands of Package 7 (Dongara Sandstones) localised heavy mineral development is indicated but very few are classified as 'hot' sands. Where there is high sample density (from core) a stacking pattern of heavy mineral enrichment is evident, identifying the presence of multiple heavy mineral-rich horizons.

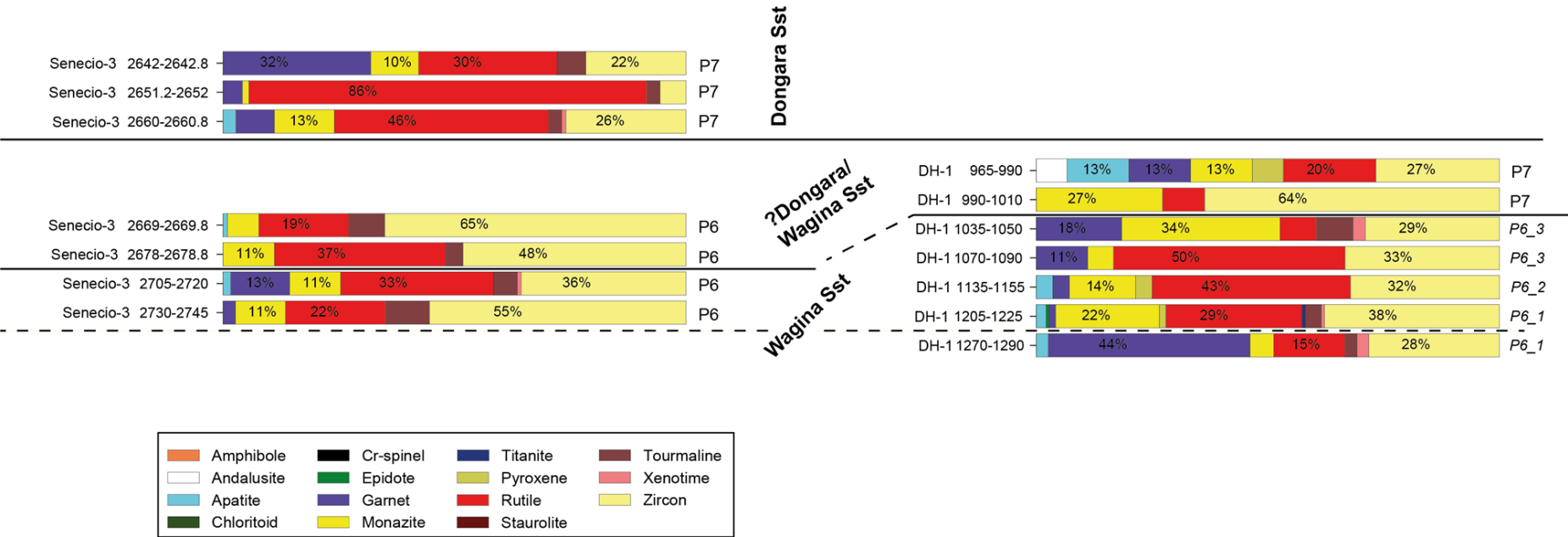
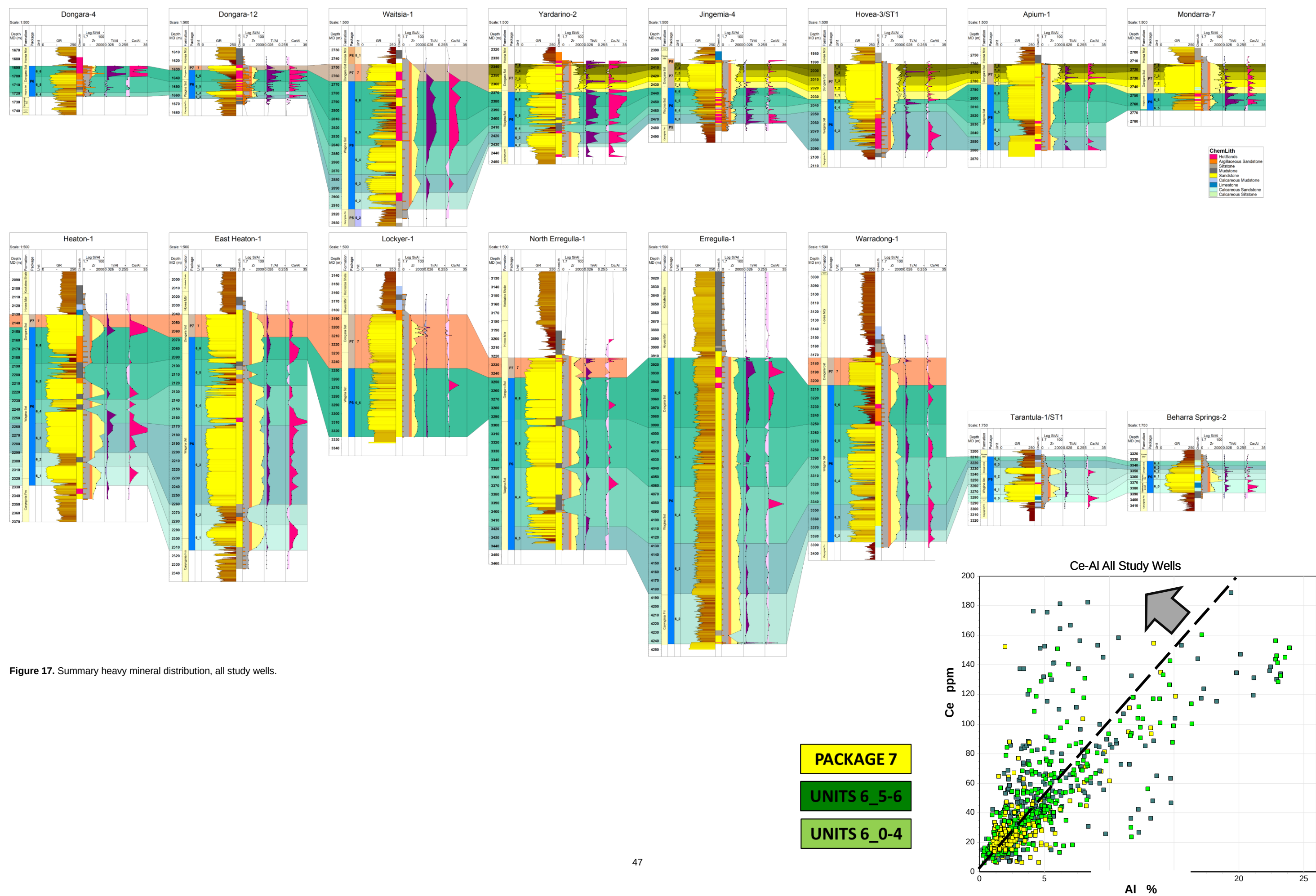


Figure 16. Raman heavy mineral summary, Senecio-3, and Depot Hill-1.



Reservoir Quality

The Dongara and Wagina sandstones represent the most significant historical Permian reservoirs in the onshore North Perth Basin. The RCA data discussed previously (see **Reservoir Quality Data**) differentiates between the Dongara and Wagina sandstones; the Dongara Sandstone is characterised by higher permeability than the Wagina Sandstone at the same porosity values. While the Wagina Sandstone demonstrated higher porosities, and generally lower permeabilities.

The addition of the geochemical dataset allows the RCA data to be replotted using the geochemical classifications made using the Herron (1988) classification (see **Geochemistry & Lithology**). In **Figure 18** the RCA data points are coloured by their respective geochemical classifications according to Herron (1988), while the symbol corresponds to the lithostratigraphy. Generally, samples from the Dongara Sandstone, which are classified as quartz arenite, are characterised by higher permeability. In contrast, Wagina Sandstone samples are plotting with higher porosity and generally correspond to sublitharenite, litharenite, subarkose, and arkose. This difference could reflect the occurrences of secondary porosity generated from the alteration of unstable mineral phases – the alteration products also limiting the permeability. The generation of secondary porosity is recognised as key to the reservoir quality of the Dongara and Wagina sandstones which is generated through the alteration of lithic clasts and feldspar (Laker N., 2000).

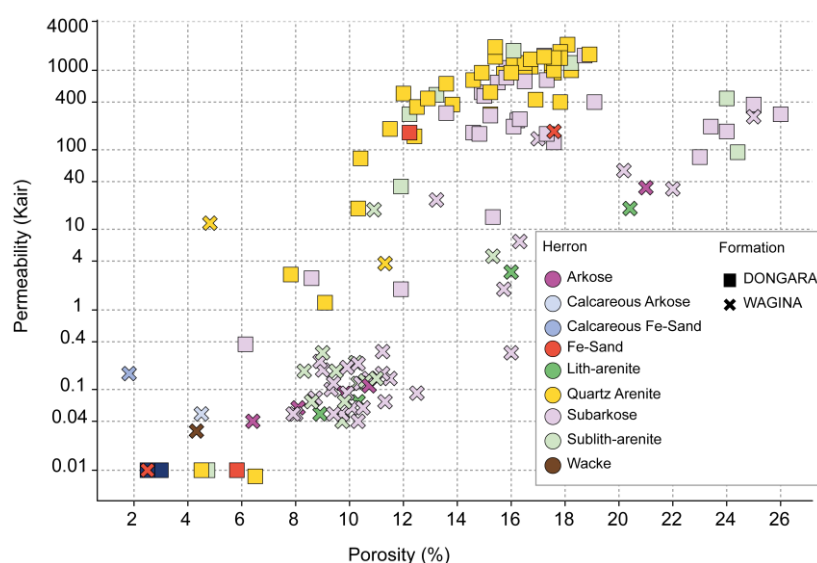


Figure 18. RCA data of geochemically analysed samples.

The Oolithica report (Laker N., 2000) identified the predominant limitation of reservoir quality as quartz overgrowths, which geochemically are modelled by the Si/Zr ratio. Typically, zircons, represented by Zr, are hydrodynamically sorted with quartz, represented by Si. Within coarse sediment or sediment with extensive quartz overgrowth, the sediment is enriched in Si with respect to Zr causing the Si/Al values to be high. This ratio may also be displayed as a binary between Zr and Si; detrital material plots on a positive correlation, while quartz cemented or

coarse-grained sediment plots within the top left portion of the plot. Within **Figure 19** the size of the marker has been set to be proportional to the porosity (top) and permeability (below). Sediments with the greatest porosity (i.e., the largest markers) are the arkosic and lithic rich sediments – reflecting the secondary porosity. The greatest permeability is shown within the quartz arenites it is therefore likely that the Si/Zr is reflecting coarse grain size rather than quartz overgrowths. Coarser grained sediments are characterised by larger pore throat, which promote permeability.

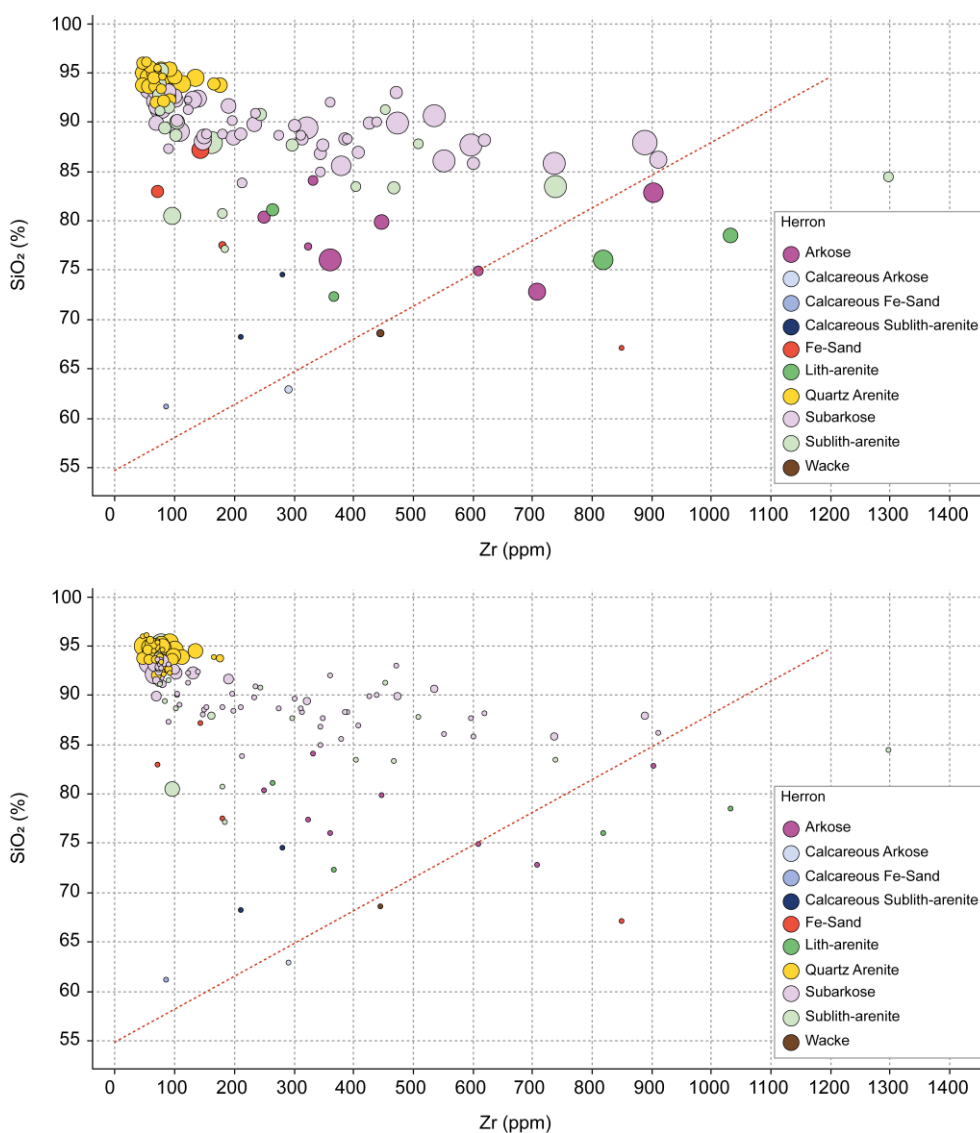


Figure 19. Si-Zr plot with samples classified using the Herron (1988) scheme (top) marker size reflects porosity, (bottom) marker size reflects permeability.

Chemostratigraphic Zonation & Correlation

Dongara Terrace (Figure 20)

Includes two wells with cored Package 7 (Dongara Sandstone) section allowing for detailed subdivision and correlation of five units which expand slightly from Jingemia-4 into Hovea-3/ST1. Upper Package 6 (Wagina Sandstone) units not interpreted to present in Hovea-3/ST1, represents the clearest example of erosion at the Package 6 – 7 contact. Consequently, there appears that there is an expanded Unit 6_3 in Hovea-3/ST1 that, as discussed previously, is also characterised by high Mo and Cr, most likely considered a result of drill bit contamination.

Only the top sand in Dongara-12 is interpreted to represent Package 7 and correlation at unit scale is not feasible. Much of the elemental signal is dominated by heavy minerals but it's possible to confidently identify many of the trends observed in Jingemia-4 such as the Ti/Nb shift at the base of Unit 6_5.

Elegans Trough – Waitsia (Figure 21)

The same Package 7 units are interpreted in cored wells Mondarra-7, Apium-1, and Yardarino-2. Mondarra-7 is interpreted to TD in upper Package 6 whereas Apium-1 extends to Unit 6_3. Waitsia-1 relies on a coarse legacy elemental dataset but shows an expanded heavy mineral-rich units 6_5 and 6_6. A characteristically zone of low heavy mineral abundance is observed in the Yardarino-2 in Unit 6_4 and toward the base of Unit 6_5, however Unit 6_3 seems to have a higher abundance of heavy minerals than observed further south.

Allanooka Terrace (Figure 22)

Wells are interpreted to penetrate Unit 6_1, in this case, an Nb enriched clean sand in Heaton-1 and East Heaton-1. The Heaton wells are only 4 km apart however the upper Package 6 units are not easy in to correlate with confidence but Unit 6_3 is interpreted to expand in East Heaton-1 and Depot Hill-1, although in the latter there is only a coarse legacy elemental dataset, and a tentative correlation is provided. Package 7 is interpreted in all the wells on the Allanooka Terrace.

Dandaragan Trough (Figure 23)

Correlation is particularly difficult clean nature of the sands and lack of clay signal from the cuttings samples. The geochemical signal from Lockyer-1 appears extremely muted, especially when compared to the data from the cored interval. The most consistent trends are from Erregulla-1 and allow correlation to wells further to the west. No Package 7 is interpreted in Erregulla-1 however as the section above the top Package 6 is all clay-prone. It is noted there is not a clear Hovea Member signal, and it may be that the intervening zone below the prominent Ti/Nb shift is a distal lateral equivalent. No wells are interpreted to penetrate the earliest Package 6 units

Beharra Springs Terrace (Figure 24)

The earliest Package 6 units recognised in the study area comprise sideritic calcareous sandstones on the Beharra Terrace, believed to be the lateral equivalents of the Beekeeper Formation. A prominent Nb enrichment is observed above Unit 6_0 at the base of a sand-prone interval which includes the Beharra Springs reservoir, not interpreted in Warradong-1. Confident interpretation of Package 6 units above this in Tarantula-1/ST and Beharra Springs-1 this is problematic given their condensed nature, but the low Ti/Nb value strongly indicates that Unit 6_5 has not been sampled.

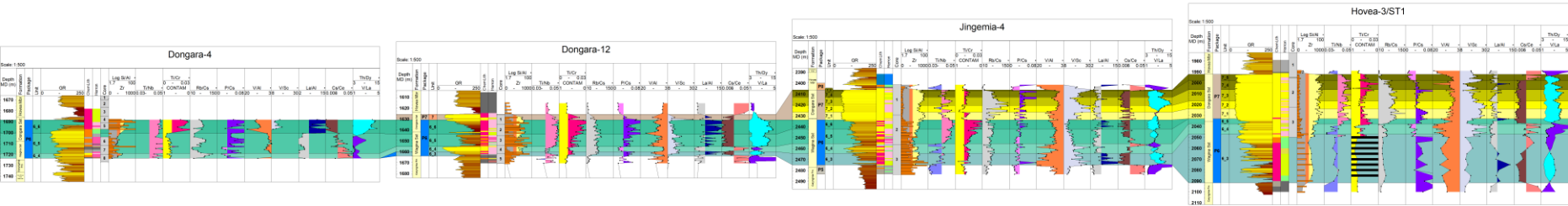
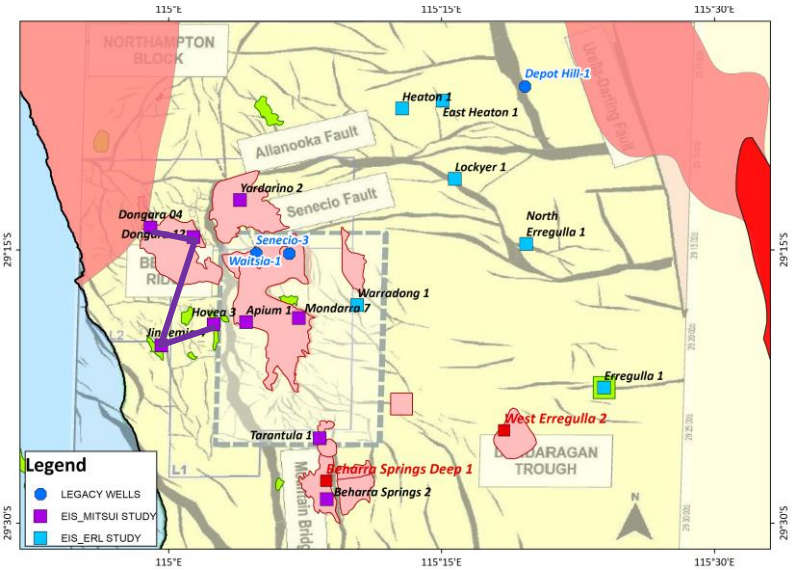
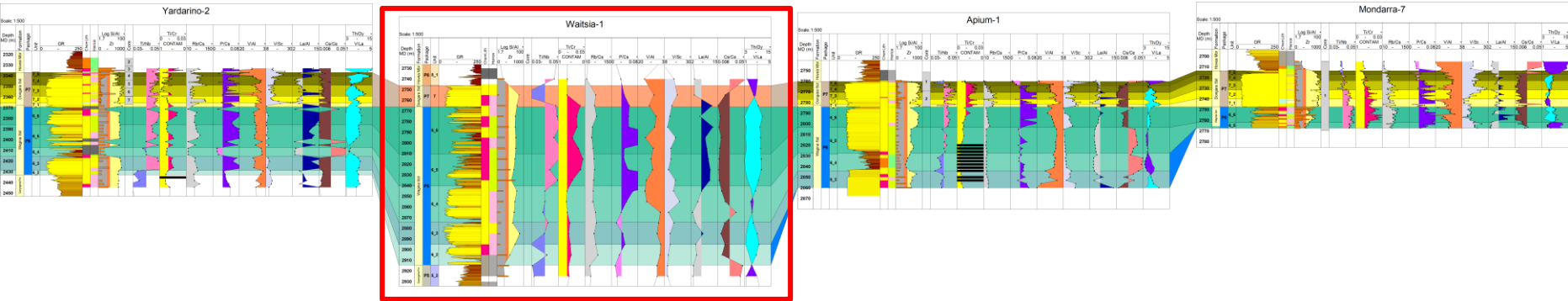


Figure 20. Chemostratigraphic correlation, Dongara Terrace (1:500).





LEGACY DATA ONLY (Chemostrat Australia, 2019)

Figure 21. Chemostratigraphic correlation, Elegans Trough – Waitsia (1:500).

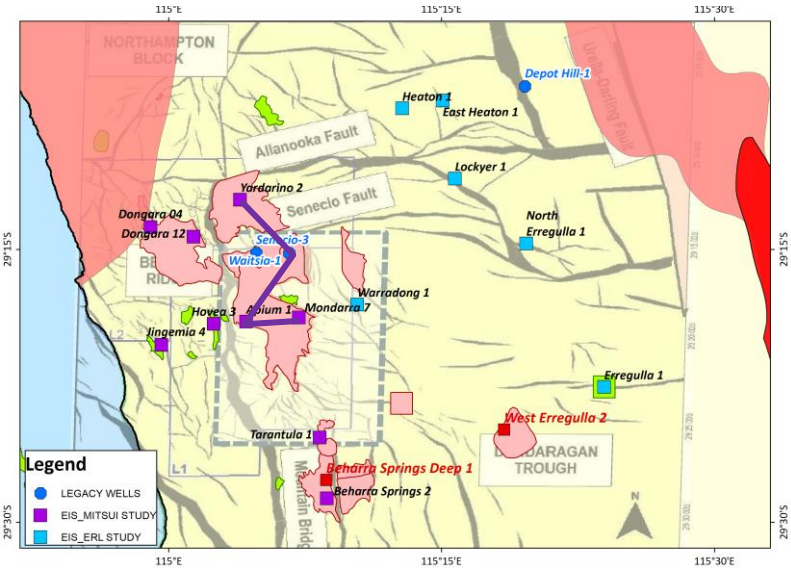
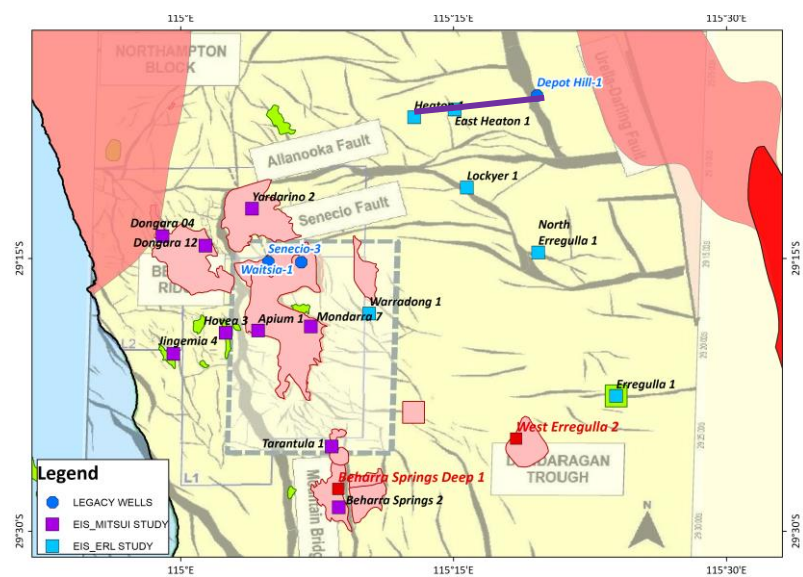




Figure 22. Chemostratigraphic correlation, Allanooka Terrace (1:750).



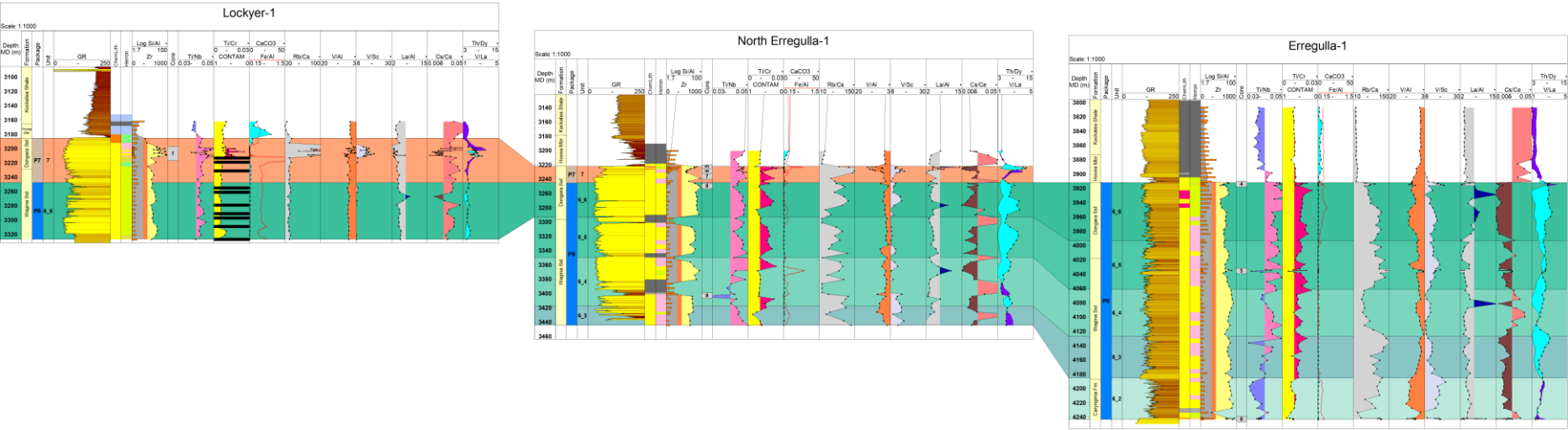
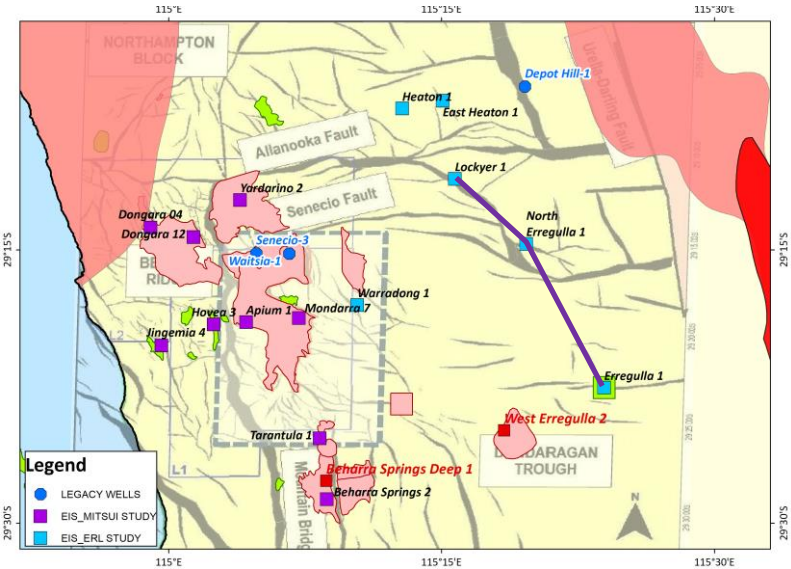
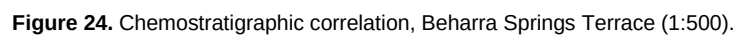


Figure 23. Chemostratigraphic correlation, Dandaragan Trough (1:1000).





CONCLUSIONS

Following the completion of the chemostratigraphic evaluation of the Late Permian Dongara – Wagina succession, onshore North Perth Basin, Chemostrat Australia Pty Ltd make the following conclusions:

- Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) analysis of 402 newly collected cuttings and 410 core samples from 15 wells has allowed for a regional chemostratigraphic correlation and geochemical evaluation of mineralogy.
- Cuttings and core to log shifts were applied based on ChemGR and previously released calculations. A few wells, notably Warradong-1, exhibit caving contamination that could not easily be excluded. There is evidence for drill bit contamination resulting in anomalous Mo and Cr values, most notably in Unit 6_3 in Hovea-3/ST1 and Apium-1.
- The interpretation has been based on the existing chemostratigraphic framework of the onshore North Perth Basin, whereby the Wagina Sandstone has been assigned to Package 6 and the Dongara Sandstone, Package 7. For this study the packages have been subdivided into seven and five units respectively.
- The earliest units recognised are sideritic calcareous sandstones on the Beharra Terrace, believed to be the lateral equivalents of the Beekeeper Formation. Subdivision of the overlying Package 6 sand-prone units is based principally on the recognition of a consistent Ti/Nb shift and fluctuations in the abundance of heavy minerals. There is a considerably expanded section in the Dandaragan Trough wells, although the precise interpretation is complicated by the generally clean nature the samples.
- Missing Package 6 units at base of Package 7 is only recognised at Hovea-3/ST1. There is no evidence from the geochemical data for significant provenance change at the transition.
- The subdivision of Package 7 is based on variability in detrital components and clay composition, and heavy mineral abundance from cored intersections on the Dongara Terrace. Package 7 is also recognised on the Allanooka Terrace and the northern Dandaragan Trough; however, it is not interpreted in Erregulla-1.
- Elemental data can be used to highlight the spatial and stratigraphic distribution of heavy mineral abundance, notably the presence of Ti oxides and RE phosphates, the latter of which contain high concentrations of Th and can impact the GR response. Overall, this decreases to the southeast, due to either dilution and / or distance from source.
- Elemental data, integrated with HyLogger and thin section (where available) demonstrates the nature and distribution of diagenetic and detrital mineralogy.

- The data shows the distribution of the chlorite responsible for inhibition of quartz cement in the Package 6 (Wagina Sandstone) reservoir for the Beharra Springs Field. Chlorite-bearing zones are also recognised in other wells, notably in units 6_2 and 6_3. These can have significant associated carbonate cements however, and the sediment immaturity means that the porosity can be ineffective.
- The best reservoir quality is observed the coarse sands of Package 7, although permeability is sensitive to the presence of clays, likely kaolinite booklets. Minor Cr enrichment is locally observed that can have a positive correlation with reservoir quality, for example Mondarra-7 where chlorite may have been preserved as a result of early hydrocarbon emplacement.
- There is little evidence for the presence of chlorite in Package 6 and 7 reservoirs to the south and east where deep burial appears to have resulted in significant quartz and / or illite cementation.

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Appendix 1: Elements & Chemical Symbols

Symbol	Atomic Mass	Element	Analysis	Symbol	Atomic Mass	Element	Analysis
Al	27	Aluminium	OES	Nd	144	Neodymium	MS
Ba	137	Barium	MS	Ni	59	Nickel	MS
Be	9	Beryllium	MS	P	31	Phosphorus	OES
Bi	209	Bismuth	MS	Pb	207	Lead	MS
Ca	40	Calcium	OES	Pr	141	Praseodymium	MS
Ce	140	Cerium	MS	Rb	86	Rubidium	MS
Co	59	Cobalt	MS	S	32	Sulphur	OES
Cr	52	Chromium	MS	Sc	45	Scandium	OES
Cs	133	Caesium	MS	Si	28	Silica	OES
Cu	64	Copper	MS	Sm	150	Samarium	MS
Dy	163	Dysprosium	MS	Sn	119	Tin	MS
Er	167	Erbium	MS	Sr	88	Strontium	MS
Eu	152	Europium	MS	Ta	181	Tantalum	MS
Fe	56	Iron	OES	Tb	159	Terbium	MS
Ga	70	Gallium	MS	Th	232	Thorium	MS
Gd	157	Gadolinium	MS	Ti	48	Titanium	MS
Hf	179	Hafnium	MS	Tl	204	Thallium	MS
Ho	165	Holmium	MS	Tm	169	Thulium	MS
K	39	Potassium	OES	U	238	Uranium	MS
La	139	Lanthanum	MS	V	51	Vanadium	MS
Lu	175	Lutetium	MS	W	184	Tungsten	MS
Mg	24	Magnesium	OES	Y	89	Yttrium	MS
Mn	55	Manganese	OES	Yb	173	Ytterbium	MS
Mo	42	Molybdenum	MS	Zn	65	Zinc	MS
Na	23	Sodium	MS	Zr	91	Zirconium	MS
Nb	93	Niobium	MS				