Mineralogical variability of the Permian Roseneath and Murteree Shales from the Cooper Basin, Australia: Implications for shale properties and hydrocarbon extraction

Quaid Khan Jadoon[1], Eric M.Roberts[1], Robert A. Henderson[1], Thomas G. Blenkinsop[2], Raphael A.J. Wust[3]*

[1]Department of Geosciences, College of Science, Technology & Engineering, James Cook University, Townsville, Queensland 4811, Australia

[2]School of Earth and Ocean Science Cardiff University Main building, Park Place Cardiff CF10 3AT United Kingdom

[3]Trican Geological solutions Ltd, 621-37th Avenue NE Calgary, Alberta, Canada T2E2M1

Corresponding Author: quaid.jadoon@my.jcu.edu.au

Abstract

Brittleness and plasticity indices in hydrocarbon reservoirs are calculated to understand how rocks behave under stress, and for assessing the fracturing performance of clay-rich shale reservoirs and assessing borehole stability. Evaluating shale plasticity/brittleness requires careful analysis of clay mineral composition in target shales and the development of fracking strategies for optimal shale stimulation. Here we report on the mineralogical variability of two Permian lacustrine shale units, the Roseneath and Murteree shales in the Cooper Basin, Australia, that are considered to have potential as unconventional hydrocarbon producers. The study involved a combination of X-ray diffraction, scanning electron microscopy and petrophysical modelling of the Roseneath and Murteree shales in order to obtain a better understanding of the compositions and microfabrics of these two units. This is part of a larger investigation of the shale gas potential of these two units in the Cooper Basin, and the results presented here may ultimately lead to improved reservoir stimulation techniques in both units. Core data has been integrated with wireline logging data to better identify brittle and plastic zones within the Roseneath and Murteree shales. Mineralogical analysis shows that both units are composed mainly of detrital quartz and clay/mica minerals with siderite cement. The clay mineral composition is dominated by illite/mica, and kaolinite in both units. However, based on the relative mineralogical differences between the two units, the Murteree Shale has more favourable brittle properties than the Roseneath Shale, and is considered to be more amenable to hydraulic fracturing for

gas exploitation. However, the Roseneath Shale also has potential for gas stimulation, especially in intervals where siderite cement is prevalent.

Key word: Shale gas, Roseneath, Murteree, brittleness, plasticity, Cooper Basin

1. Introduction

Clay minerals are an integral part of almost all shales and represent an important parameter for unconventional reservoir characterization. Clay mineral analysis has long been important in studies of organic diagenesis and hydrocarbon emplacement of petroleum systems (e.g. Lee et al., 1985; Hunt, 1995). In conventional reservoirs, clay minerals are a minor component but may influence porosity and permeability. In contrast, clay minerals in unconventional shale reservoirs commonly occupy 20-80% of the rock volume and have a strong influence on porosity (Nadeau, 2000). In conventional and unconventional shale plays, brittleness is the parameter that characterizes how the rocks behave under stress. The main concept behind mineralogy-based brittleness is to identify stratigraphic intervals where the mineralogy is conducive to the minimisation of pumping pressures required to induce stimulate fracture patterns that can be induced to remain open.

Brittle indices based on mineralogy proposed by different authors are not consistent, attributing variable importance to different rock components. For instance Jarvie (2007) introduced an index to identify the best producing intervals in the Barnett Shale, based on quartz content Wang and Gale (2009) identified dolomite content as a key component to brittleness evaluation. In contrast, plasticity measures how material is deformed under load. Generally speaking, these two parameters as descriptors of rock properties, typically have an inverse relationship to one another. They have a profound influence on borehole and well stability in clay-rich units during coring, cementing and stimulation. The degree of plasticity has marked effects on hydraulic fracturing and influences fracture development in shales including fracture aperture, fracture length and fracture geometry (Slusser and Rieckmann, 1976). Formation plasticity is an important factor controlling fracture containment when working in thin (<10m) reservoir units where rapid plasticity changes occur between rock layers and horizontal stress variations are present (Medlin and Fitch, 1983). Variability in plasticity may be negligible for individual beds or thick homogenous stratigraphic intervals, but is amplified in complex heterogeneous units with interbedded horizons of differing lithology, which has implications for large-scale hydraulic fracturing treatments. Brittle mineral content is also an important factor for microfracture development, and the gas capacity of shales. Clay mineral content negatively influences brittleness and the capacity of rocks to naturally fracture or to be artificially induced to form fracture networks, as conducive to shale gas extraction (Zou et al., 2010). As noted by Zhishui and Zandong (2015) various minerals range in brittleness, and rocks with enhanced brittle mineral content are likewise higher in brittleness. Brittleness/plastic of shale gas need to be well understood in terms of fracture initiation and propogation, as well as fractures reopening. These are based on mineralogical (clay content), which is required for a good shale gas play(Britt and Schoeffler, 2009).Brittle shales are required for creation and propogation of hydraulic fractures and for heading off in ductile or plastic shales(Josh et al., 2012).In terms of rock properties, low Poisson's ratio and high Young's modulus values indicate higher brittleness. The role of petrophysical approach to shale gas reservoirs using wireline log based methods to identify organic matter, porosity, permeability, mineralogy and mechanical properties have been described by Jacobi et al 2008; Parker et al., 2009 and Jadoon et al 2016.

Zones of plastic behaviour are often heterogeneously distributed in thick reservoir intervals (Medlin and Masse, 1986). The most important factors controlling fracture containment is the plasticity of interlayers and horizontal stress variations, with depth below surface and bed thickness also having a big influence on fracture behaviour (Medlin and Fitch, 1983).

Rock composition and fabric are critical factors in the evaluation of unconventional hydrocarbon resources, as they control the brittleness and plasticity of the reservoir rock. The focus of this study is to evaluate the brittleness and plasticity of the Murteree and Roseneath shales through detailed investigations of mineralogy and petrology. The aim is to better understand the hydraulic fracturing potential of these two highly prospective shale units in the Cooper Basin, Australia.

2. Geological setting and petroleum geology of the Cooper Basin

The Cooper Basin is an intracratonic rift basin of Permian to Triassic age that extends from the north-eastern corner of South Australia into south-western Queensland (McKillop, 2013; Gravestock et al., 1998) (Fig. 1). The basin covers an area of approximately 130,000 km^2, of which ~35,000 km^2 are in NE South Australia. Three major troughs in the basin, known as the Patchawarra, Nappamerri, and Tenappera troughs, are separated by the Gidgealpa, Merrimelia, Innaminka and Murteree structural highs/ridges, which are associated with the reactivation of NW trending thrust faults beneath the basin (Wopfner, 1972). These three troughs preserve up to 2500 m of Permian to Triassic sedimentary fill, which is dominated by thick freshwater depositional successions of the Upper Permian Gidgealpa Group and the Upper Permian to Middle Triassic Nappamerri Group (Fig. 2) (PIRSA, 2000). The Cooper Basin is underlain by Precambrian to Ordovician sedimentary rocks of the Warburton Basin and intrusive granitoids (Klemme, 1980; Radkee et al., 2012). The tectonic event that separates the Cooper from the Warburton Basin is interpreted to be the Devonian-Carboniferous Alice Springs orogeny. Overlying and extending beyond the Cooper Basin are Jurassic-Cretaceous cover sequences of the Eromanga Basin (~1300 m thick), which form part of the Great Artesian Basin of eastern Australia(Jadoon et al., 2016)

The basal unit in the Cooper Basin is the Merrimelia Formation, which is considered the economic basement for hydrocarbon exploration (Williams and Wild, 1984; Williams et al., 1985) (Fig. 2). The Merrimelia Formation is Pennsylvanian to early Permian, based on palynological zonation (Price et al., 1985) and consists of conglomerate, sandstone and shale deposited in glacial palaeoenvironments. A variety of depositional settings are inferred, including glacial valleys, braided plains and lakes, which resulted in complex facies arrangements and irregular sediment thicknesses (Williams et al., 1984).

Overlying the Merrimelia Formation is the Tirrawarra Sandstone, which is characterized by thick, multi-story channel sandstones with quartz arenite compositions (Fig.2) (Kapel, 1972; Gostin, 1973; Thorton, 1979). The Patchawarra Formation overlies this unit, and is the thickest unit in the Cooper Basin, although it shows great lateral thickness variation (Gatehouse, 1972). It is thickest in the Nappamerri and Patchawarra troughs and thins by on lap and truncation onto the crests of major structures and at the basin margins (Batterby, 1976). The Patchawarra Formation represents an interbedded succession of minor channel lag conglomerates and massive, cross-bedded sandstones of fluvial origin, along with laminated siltstones, shales and coals that formed in abandoned channels, back swamps, and shallow lakes and peat mires. The overlying Murteree, Epsilon, Roseneath and

Daralingie formations record alternating lacustrine and lower delta plain environments, consisting mainly of interbedded fluvial-deltaic sandstones, shales, siltstones and coals (Kapel, 1972; Gostin, 1973; Thorton, 1979).

The Murteree Shale was defined by Gatehouse (1972) as the series of shales overlain by the Epsilon Formation and underlain by the Patchawarra Formation (Fig. 2). This unit consists of black to dark grey to brown argillaceous siltstone and fine-grained sandstone, becoming sandier in the southern Cooper Basin. Fine grained pyrite and muscovite are both characteristic of the Murteree Shale and significantly, carbonaceous siltstone is also present. The type section lies between 1922.9 – 1970.8 m in the Murteree 1 well. The Murteree Shale is widespread within the Cooper Basin in both South Australia and Queensland. It is relatively uniform in thickness, averaging ~50 m and reaching a maximum thickness of 86 m in the Nappamerri Trough, thinning to the north, and having a maximum thickness of 35m in the Patchawarra Trough. It is absent over the crestal ridges (Boucher, 2000). The Murteree Shale is early Permian (Price et al., 1985). A relatively deep lacustrine depositional environment has been interpreted for the formation, in part based on the rarity of wave ripples and other evidence of storm reworking, as would be expected for a more shallow lake system (Gravestock et al., 1995).

The Roseneath Shale was defined by Gatehouse (1972) as the suite of shales and minor siltstones that conformably overlie the Epsilon Formation (Fig.2). The unit was originally included as one of three units in the Moomba Formation by Kapel (1972). Gatehouse (1972) raised it to formation status. The type section lies between 1956.8 – 2024.5 m in the Roseneath 1 well (Gatehouse, 1972). The Roseneath Shale is composed of light to dark brown-grey or olive-grey siltstones, mudstones with minor fine-grained pyrite, and pale brown sandstone interbeds. It occurs across the central Cooper Basin but has been eroded from the Dunoon and Murteree ridges and crestal areas of other ridges during late Early Permian uplift. The Roseneath Shale is not as extensive as the Murteree Shale. It conformably overlies and intertongues with the Epsilon Formation, and is overlain by and also intertongues with the Daralingie Formation. Where the

Daralingie Formation has been removed by erosion, the Roseneath Shale is unconformably overlain by the Toolachee Formation. The Roseneath Shale reaches a maximum thickness of 105 m in the Strathmount 1 well and thickens into the Nappamerri and Tenappera Troughs (Boucher, 2000). It is considered to be early Permian in age (Price et al., 1985). A lacustrine environment of deposition, similar to that of the Murteree Shale, is inferred for the Roseneath Shale (Stuart, 1976; Thorton, 1979). Variations between massive to finely laminated, with minor wavy lamination and wave ripples, suggest possible storm reworking. Load and flame structures and slump folds indicate slope instability also occur. These features collectively suggest a slightly shallower lake-floor depocenter than for the Murteree Shale (Stuart, 1976; Thorton, 1979) (Fig. 2).

3. Methodology

Twenty-five wells were selected in this study to provide samples of the Roseneath and Murteree Shales, with a focus on wells in the Patchawarra, Nappamerri, Allunga and Tenappera troughs (Fig.1). Wells were also selected to range across the South Australian and Queensland portions of the Cooper Basin. A total of 295 samples were collected from the rock archives at DIMITRE (the Department for Manufacturing, Innovation, Trade, Resources and Energy) in Adelaide (SA) and Department of Natural Resources and Mines (DNRM) core library facilities in Brisbane (Qld).

Samples were analysed by x-ray diffraction (XRD), with use of the Source Rock Analyzer (SRA) to determine TOC (Total Organic Carbon) and examined by scanning electron microscopy (SEM) to characterize mineral distribution and fabric. For XRD, sample material was micronized and prepared as a smear which was irradiated between 3 and 70^0 2Θ using a Bruker® D4 Endeavour X-ray diffraction instrument with a Lynx-Eye detector. The instrument was run at 40 kV and 30 mA and features a fixed divergence slit geometry (0.5^0), an anti-scatter slit with both primary and secondary Soller slits at 4^0. The diffraction patterns were recorded in steps of 0.017^0 2Θ with 0.5 second counting time per step, and logged to data files for analysis. The results of the x-ray diffractometry were analysed using the PDF-4 minerals database 2013 (peak identification) and then quantified using Jade 9 and Topas 4.2 software. The technique identified mineral phases in the samples studied: quartz, kaolinite, mica/illite, siderite, feldspar and oxides. The quantitative analysis does not make allowance for amorphous material.

Plasticity index (PI) (see Casagrande, 1932) and liquid index (LI) were used to identify the behaviour of the clay, to a liquid limit of 100% and plasticity up to 60%. Plasticity index is calculated using clay mineral content of the samples obtained by XRD analysis (Casagrande, 1932, 1958; Rahman et al., 2000). The plasticity value depends upon clay composition as expressed by the percentages of the clay minerals. The plastic limits show the transition between liquid and plastic behaviour and provide significant information about the behaviour of clay when stressed.

The degree of brittleness, or brittleness index (BI), was calculated based on the mineralogical composition of the samples. In formulating this index, Jarvie (2007) and Wang (2009) included dolomite and calcite as carbonate phases. However, the mechanical behaviour of all carbonate minerals is essentially identical. Only siderite was identified by XRD in the samples studied here although SEM imaging shows that other carbonate phases may be present. Accordingly the brittleness index has been modified to:

BI = Qtz+Carbonate /Qtz+Carbonate +Clay+TOC

TOC values used in the index were obtained by SRA pyrolysis across the sample set.

A FEI Quanta 250 environmental scanning electron microscope (ESEM) was used to identify the quartz, clay and carbonate mineral constituents, their textural relationships, kerogen occurrence and pore morphology in the shales. Polished billets and fresh rock chips were mounted on stubs and gold coated. Micrometer scale elemental analysis was completed using an EDS (Energy Dispersive Spectroscopy) system with a silicon drift detector. The methodology included documentation of the types and abundance of different pores and pore fillings These attributes of potential resource shales are important, as they affect rock strength, which influences hydraulic fracture patterns However, a caveat to this part of the study is that the areas examined by SEM for each sample are extremely small and may not completely represent overall reservoir characteristics. Petrographic analysis of the samples using thin sections was also conducted, and these results are presented in Jadoon et al. (2017). Estimation of organic content, mineralogy, porosity and permeability of the petrophysical models, which were used to help analyse and evaluate nearby wells. Core plugs under confining stress with Hg pressure-pulse-decay results are presented in Jadoon et al.(2016).

Petrophysical analysis was performed using the Senergy 4.6 Mineral Solver software module. Shale volume (Vshl) was evaluated using gamma ray (GR) log data employing minimum and maximum values for clean sands and shales, respectively. The linear shale volume methodology was applied (Crain, 2000): *volume of shale = (GR log - GRclean)/ (GRshale-GRclean).* The scaling values for GR data employed were gamma-ray clean (GRcln = 100 API) and gamma-ray shale (GRshl = 180 API). Core XRD data were obtained and the desired Mineralogical composition by volume was modelled using a Multi Mineral Model Programme available from Interactive Senergy Petrophysics (IP) referenced to the compositions determined for selected samples by XRD. After several iterations, alignment was achieved for modelled and XRD determined mineral volumes for the horizons which provided.

4. Results

XRD results of Roseneath and Murteree shale samples are shown in (Fig. 3, Tables 1-3) and the supplementary information. The data illustrate mineral abundance values throughout the shales. All samples are dominated by clay minerals (kaolinite and illite/mica), quartz and siderite. Based on XRD analysis, carbonate contents are mainly in the form of siderite. XRD patterns of the samples are provided in supplementary paper. The analyses are presented as totalling to 100%. No allowance is made for amorphous material and SEM imaging indicates it is not in general volumetrically significant. Expandable clay (smectite) was not detected by XRD. SEM imaging shows the rare presence of dolomite in some samples, but this mineral phase was are not detected by XRD. Results of the XRD analysis are consistent with those obtained by petrography as reported by Jadoon et al. (2016).

4.1. Roseneath Shale composition

The composition of the Roseneath Shale, across the basin from the Patchwarra Trough to Allunga Trough, is dominated by clay minerals and quartz. The clay mineral assemblage consists predominantly mica/illite and kaolinite, with some chlorite. Siderite is the most abundant carbonate. Minor amounts of albite and K-feldspar are represented. Trace Ti-oxide (rutile, anatase) is also noted in most of the samples (see Figs. 3a- 3f). Expandable smectite clay was not detected by XRD.

The mineralogy identified by XRD analysis of selected well samples are presented in (Table 2) and supplementary paper. The data indicates the following minerals by proportion: quartz 22-51 %, mica/illite 21-48 %, kaolinite 9-21 % siderite 7-49 %, k-feldspar 0-3 %, Ti-oxide

0-1.3 %. TOC contents range from 3-36.8 %. With rare exceptions, the sample set indicates a high level of consistency in quartz (35-40%), mica/illite (45-50%), kaolinite (12-20%) (see Figs. 3a-3f). Siderite content is the most variable component. The data suggest a background value of 1-5%, but locally high values of 7-20% are common, indicating horizons that have preferentially attracted cementation. The highest values, between 46 and 49%, are considered to reflect siderite concretions.

4.2. Murteree Shale composition

The composition of the Murteree Shale is similar to the Roseneath Shale (see Table 3) and supplementary paper, with the following mineral proportions: quartz 24-87 %, mica/illite 17-56 %, kaolinite 9-15 % siderite 10-45 %, feldspar 0.7- 2.2 %, and Ti-oxide 0.1-1.89%. TOC values ranges 1-10 wt% (Table 3) and Appendix-5. With uncommon exceptions, a high level of consistency among the major components is similarly indicated: quartz 45-50 %, mica/illite 40-45% and kaolinite 12-15%. The sample set identified rare horizons dominated by quartz (>60%) (see Fig. 3j). Siderite content is variable, with background values of 1-5% commonly exceeded, and some values as high as 33-45%.

Petrophysical modelling indicates variability in the mechanical properties of the Roseneath and Murteree shales. For example, the Roseneath Shale in Encounter-1 is locally quartz rich, indicating brittleness and fracability, whereas clay rich parts represent plastic zones (Fig. 11). For Roseneath Shale in the Biglake-70 well, the clay mineralogy indicates plastic zones at depths between 7900 to 7950 ft (Fig. 10). In the Dirkala-2 well the most favourable brittle zones in the Murteree Shale are at depth of 6205- 6215ft and 6280- 6315ft, whereas plastic zones occur between 6215-6250 ft and 6290-6310 ft (Fig. 12).

5. SEM examination of Roseneath and Murteree Shale samples

The results of the SEM analyses of the Roseneath and Murteree samples examined (see Fig. 4) are consistent with the XRD data, showing that quartz and clay are dominant, and that both shales have very similar textures. Most grains are < 8 μm in size but muscovite sheets may be larger (Fig. 4g) and range to 80 μm across. Carbonate cement is commonly represented.

SEM images allow pore types to be identified, but do not provide a measure of permeability and they typically under represent the total amount of porosity because their representation is largely two dimensional. Organic material commonly occurs as kerogen domains. These may be clumped within the clay matrix and domains are typically 2-10 µm across. The images examined show internal pores of micron size (Fig. 4i). Other pores are of inter- and intra-grain location, and are most evident in association with siderite cement where they are typically elongate in shape with maximum dimensions ranging to 20 µm (Fig. 4c) but typically from 0.4 to 1 µm in diameter. Visual estimates of porosity based on intercrystal pores indicate values of 2-3% in the siderite cement in both shales. Intergranular pores between organic matter and siderite are characteristics of both shales but are of small dimensions, generally no more than a micron across. In some cases, larger pores are partially occupied by diagenetic clay (Fig. 4b, c, i and l).

6. Brittlness and plasticity of the Roseneath and Murteree shales

A rock is considered to be plastic if it absorbs a high amount strain before fracturing; brittle rocks are unable to accommodate significant strain before fracturing, resulting in open microfractures after hydraulic fracturing. In conventional reservoirs brittleness is mainly used to evaluate behaviour during drilling (Jin et al., 2014). Brittleness is considered a key parameter for hydraulic fracturing initiation and propagation in low permeability rocks, like gas shales (Altindag, 2003; Holt, 2011) Plasticity in general increases with reduced brittleness, and plays an important role in assessment of within-rock sealing properties of shale. Brittle behaviour is characterized by a lack of irreversible deformation before failure (plasticity) and a loss of load bearing capacity when the rock is deformed after failure. Brittle behaviour is thus reciprocal to plasticity.

6.1. Brittle index

Quartz richness inherent to many productive shale gas plays has a significant role in the fracturing potential of the reservoir rocks. Quartz content is the important factor affecting fracture development, and this is usually quantified by the brittle index (Loucks and Ruppel, 2007; Jarvie et al., 2007; Wang and Gale, 2009). Proposals of brittle index (BI) are based on the mineral composition employing the ratio of the most brittle mineral to sum of the other minerals in a given sample. Jarvie et al. (2007) proposed an index using quartz in the numerator, and the sum of quartz, clay, and calcite in the denominator.

$BI_{\text{Jarvie (2007)}}$ = Qtz/Qtz+Cal+Clay minerals

The Brittle index was redefined by Wang and Gale (2009) who added dolomite to quartz in the numerator, and TOC and dolomite in the sum of constituent minerals of the rock in the denominator of the expression. They considered dolomite as primarily diagenetic and thus contributing to brittle behaviour. Their brittle Index was expressed as:

$BI_{\text{Wang (2009)}}$ = Qtz+Dol/Qtz+Dol+Cal+Clay minerals+TOC

These approaches differ slightly from one another, particularly with the inclusion of TOC and dolomite in the expression. Dolomite content influences brittleness whereas TOC influences plasticity. For the shales examined here, carbonate is exclusively a crystalline diagenetic material and a contributor to brittle behaviour. This study includes siderite in the calculation of BI, with this mineral influencing brittleness in a similar fashion to dolomite. Accordingly, the brittle index used here is modified to:

BI = Qtz+Carbonate /Qtz+Carbonate +Clay minerals+TOC

Brittle index values for the Roseneath Shale range from 0.3-0.55 and those for the Murteree Shale are 0.5-0.85 (Fig. 5). Elevated values are associated with horizons that have preferentially attracted cementation. Brittleness may also be considered in terms of three mineral phases contributing to the brittle index quartz, clays minerals and carbonates, plotted on a ternary diagram (Figs. 6-7). These plots suggest that brittleness of the Roseneath and Murteree shales broadly overlap, but is slightly enhanced for the Murteree Shale brittleness.

6.2. Plasticity Index

Plasticity is defined by the lack of strain reversibility upon stress release. The plasticity of shale is influenced by its clay content and the type of clay minerals present (Krynine and William, 1957). Plasticity generally increases with reduced brittleness and plays an important role in the assessment of the mechanical properties of the Roseneath and Murteree shales. There is a broad correlation between the clay mineral composition of a given rock and its behavior under stress. Illite and kaolinite clays are usually inactive, whereas montmorillonite clays range from inactive to active. Generally, active clays have relatively high water holding capacity and high cation exchange**.** A classification of plasticity in relation to the liquid limit was provided by Bell (2007) and is summarized in (Table 4).

Atterberg's limits are widely used as measure of plasticity. This measurement is based on the moisture content at which a clay rich sample undergoes a change in behaviour. Enhanced moisture content is associated with elevated plasticity and vice versa (Moore, 1965, Van der Velden, 1979 and Bekker, 1981). Casagrande (1958) studied different types of clay and evaluated plasticity by Atterberg limits whereby the liquid and plastic limits define the span of plastic behaviour. Standardized methods to determine the relationships between the clay content, plasticity and liquid limits of illite, kaolinite and montmorillonite clay have been developed. In our study we used the methodology of Dumbleton and West (1966), as modified by Reeve (1980) and based on the work of Casagrande (1958).This approach has been widely adopted method for evaluating plasticity in clay-rich materials (e.g. Dumbleton. 1966; Bekker, 1981; Ribeiro e al, 2005; Bergaya et al., 2006; Bell 2007; Modesto and Bernardini, 2008; Andrade, 2010). A relationship between plasticity index (PI) and liquid limit with respect to plastic behaviour has been developed by Reeves and Cripp (2006) based on the work of Casagrande (1932). By using the clay content of the samples evaluated in this study to estimate these parameters, the range of plastic behaviour likely to be shown by the Roseneath and Murteree shales can be estimated (Fig. 8). Low to intermediate plastic behaviour is likely for both units.

Relationship of plasticity index and percentage of plastic limit to plastic behaviour from Reeves and Cripp (2006) based on the work of Casgrande (1932). The behaviour of composites containing just a single clay type is also plotted using data from Dumbleton and West (1966) and Rama Rao (1978) with value of liquid limit percentage as shown. Composites containing illite are more prone to plastic behaviour than those containing kaolinite. Which is the dominant by using the clay content of the samples evaluated in this study, they can be plotted on the chart.

6.3. Petrophysical modelling

The results from petrophysical section Roseneath and Murteree cored interval confirmed a high heterogeneous quartz/muscovite, illite associated kaolinite and siderite.The particular depth is the high level of variance in quartz abundance with fluctuation in the at order of more than 50% depth 7874 ft in Big Lake 70 well and Encounter-1 well at 10416 ft, while in Murteree Dirkala-2 well at 6205-6215 and 6280-6315ft (Figs. 10-12). Hill and Mauger et al. (2016) reported Holdfast-1 well experienced hydraulic fracturing at the six sites within the cored interval for Roseneath and Murteree shales were scanned with HyLogger 3 technology. The results show that the three perforation points in the shale units contained siderite cement and high quartz content involves an elevated brittleness.

7. Discussion

The data presented here show that although the Roseneath and Murteree shales are overall characterised by mineralogical uniformity, some horizons and thin intervals show variation that has significance for their potential as gas producers.

7.1 Textures and mechanical behaviour

The Roseneath and Murteree shales are composed mostly of clays minerals and quartz with subordinate, variable amounts of siderite, and very minor feldspar. Mineralogical trends are apparent down core with the main mineral phases varying with depth (Figs. 3a-n). Reservoir quality of shale depends on porosity. Interparticle and intraparticle pores associated with detrital illite and other minerals are important and these pores need to be interconnected for permeability. SEM imaging shows a random orientation of detrital components, including clay minerals, with intergranular pore space. Imaging shows that intercrystal and intra crystal pores are characteristic of authigenic siderite (Figs. 4e and i).

SEM study shows the overall fabric of clay domains and non-clay minerals (quartz, mica, siderite, calcite, dolomite) which are randomly distributed in both shales. Based on these observations both the Roseneath and Murteree shales have low permeable and porosity at 1 to 2% (Fig. 4). The type, abundance and distribution of these pores within the shales will also affect the rock strength and hydraulic fracture pattern. According to (Zhishui and Zandong, 2015) rock brittleness decreases with increasing porosity, and is enhanced in rocks saturated with gas compared to those saturated with water or oil. Mineral variability indirectly influences hydraulic fracturing through the effect of different minerals on fracability(Fig.9). This effect is evaluated mineralogical composition and its influence on brittleness (Sondergeld et al., 2010). Zones with high quartz and siderite content are more brittle than those with high clay content. The silica-rich zones are considered to have better long term productively from induced fractures compared to zones with high clay content (Jarvie et al., 2007; Passey et al., 2010). Brittle mineral content is an important factor influencing matrix porosity, microfracture development, and the effectiveness of fracking in facilitating shale gas production (Zou et al., 2010). Zones with plastic behavior are often heterogeneously distributed in thick reservoir intervals (Medlin and Masse, 1986). While some prospective shales behave like brittle materials at the highest confining stresses of practical interest, other units are brittle at low confining stress, but plastic to some degree at high confining stresses which are typical of deeper wells. Results of tensile stress/strain investigations show that plasticity effects in shales are likely to be more important in controlling fracture continuity than other factors including field stress (Medlin and Masse, 1986). The capacity for induced fractures in shale with abundant quartz or carbonate is substantial. Brittle mineral content is generally higher than 40% and clay mineral content is less than 30% for shale than can be commercially exploited (Sondergeld et al., 2010).

The plasticity chart (Fig. 8) shows low to intermediate plastic behaviour for the Roseneath and Murteree shales. Shale plasticity depends on the clay minerals present, particularly smectite, illite, and chlorite (Zhang et al., 2008). For the shales studied here, illite and kaolinite dominate clay spectra and influence plasticity. Illite is more prone to plastic behaviour than kaolinite. The clay content of the Roseneath and Murteree shales in general ranges from 35 to 50%, with clay minerals dominantly represented mica/illite and lesser amounts of kaolinite and subordinate chlorite. Trace smectite shows in in the Roseneath Shale and lacking from the Murteree Shale based on the data presented here. In addition to mineral composition other factors that will affect fracability include the degree and scale of stratification and porosity (Wang and Gale, 2009).

The water retention capacity of the Roseneath and Murteree shales is controlled primarily by grainsize and organic matter content. In general, the higher the percentage of silt and clay sized particles, the higher the water holding capacity because small have a much larger surface area than the larger sand particles. The amount of organic material in a shale also influences the water holding capacity because of its open structure. In addition, organic matter has the capacity to hold cations which act to hold water molecules (Hudson 1994; Passey et al., 2010) influencing plasticity. Cation exchange capacity estimates the total amount of exchangeable cations that a rock/soil can adsorb (Minasny et al. 1999; Rawls et al. 2003). Quartz-rich shale has a low cation exchange (Halliburton, 2014). Our study shows that amorphous organic matter content of both shales are moderate to high with a consequential influence on plasticity. This is especially true for the Roseneath Shale where TOC ranges as high as 36%.

Petrophyisical modelling (Figs. 10-12) suggests variability in brittle behaviour based on changes in mineralogy through different well intersections of the Roseneath and Murteree shales. For example, thin intervals of the Roseneath Shale in the Encounter 1 well have enhanced carbonate cement and the interval between 3170 and 3175 m in this well has enhanced quartz content. Intervals ranging to 20 m in thickness in the Dirkala-2 well have enhanced quartz content. Direct plots of brittle index for several well intersections of the shales show significant brittle enhancement over intervals ranging to 7 m in thickness. (Fig. 12).

7.2. Siderite cement

The late diagenetic formation of siderite from calcite plays an important role for secondary porosity. The transformation, like the replacement of calcite by dolomite is accompanied by a volume reduction (Pearce et al., 2013). The consequential development of secondary porosity is clear from siderite developed in both the Roseneath and Murteree shales. SEM imaging (Fig. 4) show siderite as lath-shaped crystallites with appreciable intergranular pore space. The secondary porosity not only improves fracability, it also increases total porosity (Ahmad, 2014).

The presence of siderite in both shales has been a matter of discussion and is a major challenge for the oil industry. According to Buffin (2010) siderite affects wireline logs because of its high density, which prejudices density tool logging in oil and gas industry. Litho-density (PEF) logging is responsive to siderite with incorrect estimates of porosity as a consequence (Glover, 2010). SEM imaging shows trace dolomite is also present in the shales. Both these carbonate phases are thought to be secondary, after calcite. Albitisation of calcic plagioclase and carbon dioxide sourced from organics during diagenesis are considered to provide the source materials for calcite. Similar values of carbon isotopes from both carbonates and carbon dioxide sourced from the Cooper Basin (Schulz- Rojahn, 1993) support this suggestion. In the formation of secondary carbonate phases from calcite. Calcium ions are replaced by those of iron and magnesium present in intergranular formation water according to the following chemical reactions:

$CaCO_3$(calcite) + Fe_2+ = $FeCO_3$ (siderite)+ Ca_2+ (calcium ion)

$2CaCO_3$(Calcite) + Mg_2+ = $MgCa(CO_3)_2$ (dolomite)+ Ca_2+ (calcium Ion)

In addition to being a persistent minor component of the Roseneath and Murteree shales, siderite is concentrated in horizons of preferential cementation as well as in concretions. Dolomite, is rare and of little consequence. The source of iron sponsoring the diagenetic change from calcite to siderite is uncertain. Pyrite occurs in the shales, but only as an accessory mineral and still retained as iron sulphide. It is unlikely to provide the iron source. It is thought the source must be from formation waters moved upwards during compaction and diagenesis of stratigraphy underlying the shales perhaps from deeply buried units of the underlying Warburton Basin.

7.3. Comparison with American gas shales

The best known and most productive shale gas basins in the USA are the Fort Worth basin, Applachian basin, and the Eagle Ford trend. It is instructive to compare the mineralogical composition of shales in the Cooper Basin with the Mississippian Barnett Shale in the Fort Worth Basin, and the Devonian Marcellous Shale in the Appalachian Basin. They are composed essentially of clay minerals, quartz, carbonate, and organic matter, with accessory feldspars, mica, pyrite and sulfates. Barnett Shale is unusually quartz-rich due to a high content of biogenic silica. It is composed of 35-50% quartz, 27% illite with minor smectite, 8-19% calcite and dolomite, 7% feldspars, 5% organic matter, 5% pyrite, 3% siderite, and traces of native copper and phosphate (US Energy, 2011). Composition of the Marcellus Shale is 27-30% quartz, 9-34% illite, 1-7% mixed layer clays, 3-4% chlorite, 3-48% calcite, 0-10% dolomite, 0-4% sodium feldspar, 5-13% pyrite, and 0-6% gypsum (Bruner and Smosna, 2011) (Table 6).

The Roseneath and Murteree shales of the Cooper Basin are both rich in quartz and clay minerals, and hence represent comparable lithologies, especially so with respect to the Barnett Shale. Siderite cement common in both shales. For the Barnett Shale it was found that a high percentages of quartz sponsored brittleness (Jarvie et al., 2007), with important implications for fracture stimulation. Variation in clay, quartz and carbonate contents result in different fracture gradients.

In comparison to the Roseneath and Murteree shales the Barnett Shale has more quartz and less clay content. However, some horizons in these Cooper Basin shales have higher quartz contents and more closely resemble lithologies of the Barnett Shale. Higher clay minerals contents in the Roseneath and Murteree shales enhances plasticity, but the lack of smectite has the opposite effect. Barnett shale clays are dominantly illite but includes minor smectite (Loucks and Ruppel, 2007) which influences plasticity. In comparison, the Roseneath and Murteree shales are dominated by illite and kaolinite which do not have significant bound water. Siderite cemented zones in the both shales favour brittle behaviour thus enhancing fracture potential. The presence of carbonate cement in the Cooper Basin units is a difference from the Barnett Shale in which carbonate components represent detrital grains. How such rocks may respond to fracking remains to be tested.

8.Economic viability

According to Beach Energy, 2011 the Cooper Basin is also thought to contain one of the largest tight gas resources in Australia. For example, there is an estimated 300Tcf of tight gas in the Beach Energy owned and operated PEL218 alone. Exploration and evaluation activities are already underway within the Cooper Basin. Various companies including Beach Energy, Senex, Drillsearch, Strike Energy, Santos and a number of joint ventures are undertaking shale and tight gas and oil exploration and evaluation programs.

Some of the larger exploration programs underway include the South Australian Cooper Basin Joint Venture exploration program (Santos 66.6 per cent and operator, Beach 20.21 per cent and Origin Energy 13.19 per cent) and Beach Energy's Nappamerri Trough Natural Gas project. Chevron was also formerly involved in the Nappamerri project. There are so many wells of different companies are successful in various fields like Moomba, Big Lake, Toolachee etc. eg: Encounter-1, 2 of beach Energy was successful shale gas exploration well located within the Nappamerri Trough in South Australian sector of the Cooper Basin. Wireline log evaluation completed on Encounter-1 interprets the primary targets as being gas saturated. The Toolachee, Daralingie and Patchwarra Formations, which overlie and underlie the Roseneath Murteree interval are also interpreted to be gas saturated.

9.Environmental Impact

According to Beach Energy Encounter-1 well reports of Environmental, 2011 aspects of the environment addressed that are potentially impacted by fracture stimulation activities include: Aquifers, where the potential hazards are mainly related to injection of fracture stimulation fluids. Soil, shallow groundwater, surface water, fauna and flora, where the potential hazards are mainly related to storage and handling of fuel, chemicals and flowback fluids. Other issues such as public safety and risk, cultural heritage, noise and air emissions, radioactivity and seismicity, where the potential hazards are related to a more general range of site activities.The assessment of potential impacts to deeper aquifers indicates that:

Leakage to aquifers due to loss of well integrity is not likely to occur and the risk is managed by

well design and construction, pressure testing and cement bond logging, monitoring of injection pressures, safety trip out systems on pumping units, and installation of a tubing string after stimulation. Fracture propagation into overlying Great Artesian Basin (GAB) aquifers and potential

contamination of these aquifers is not likely to occur due to the significant physical separation between the targets and the GAB aquifers and the geomechanical properties of the strata. Leakage to GAB aquifers through geologic media is not likely to occur, as the Permian target intervals are separated from the GAB by approximately 400 metres of limited permeability Nappamerri Group siltstone. Furthermore, seismic information indicates there are no large scale faults that connect the Permian to the GAB.

With respect to impacts to soil, shallow groundwater and surface water, the assessment indicates that. Spills or leaks of fuels and stimulation additives are mitigated by storing and handling of materials with appropriate secondary containment and immediate clean up and remediation of any spills. Pond design, construction, location and operational controls mitigate risks to the integrity of the pond liner and wall that may result in spills or leaks of pre-stimulation water or flow-back fluids that are contained within the ponds. Spill response procedures result in immediate assessment,fencing, clean up and remediation measures in the event of a leak or spill.Wells will not be situated in areas that are subject to regular flooding to avoid inundation from flood events.The exploration and appraisal activities are generally spread out in nature with only a small number of existing water wells in the vicinity. The hydrological impact of sourcing water from shallow groundwater is expected to be relatively short-lived and limited in extent. Water supply wells and existing stakeholder bores will be monitored for potential impacts. The body of this EIR reviews the potential of the activities to impact on public safety, cultural heritage, stock, native fauna and flora or result in significant noise and air emissions, radioactivity and seismic events. Each of these has been assessed to be a low risk. With the fracture stimulation activities,increased traffic has the potential to result in road safety incidents. This risk will be reduced by installing signage, communicating activity plans with stakeholders to increase awareness of activity,posting speed restrictions as required, conducting on-going driver training and dust mitigation measures where appropriate to improve visibility. Beach is confident that with the implementation of the management measures outlined in the EIR, the proposed activities do not present a significant level of environmental risk.

8. Conclusions:

- This study provides a robust characterization of mineralogy for the Permian Roseneath and Murteree Formations in the Cooper Basin as a means of assessing their plasticity and brittleness properties.
- Based on higher quartz and siderite content in the Murteree Shale, this unit has greater brittleness and is more amenable to hydraulic fracturing and gas shale extraction.
- Both shales have a high clay content which favours plastic behaviour. Good sealing properties are indicated but plasticity will present a challenge for hydraulic fracturing.
- Both shales contain intervals with enhanced quartz content and/or siderite cement which are more favourable to fracture generation.
- Both units compare favourably with better known shale gas reservoirs in North America, especially the Barnett Shale of the Fort Worth Basin and suggests promise for successful shale gas exploration in the Cooper Basin.

Acknowledgement:

Quaid Khan Jadoon would like to acknowledge his Ph.D. funding provided by the Graduate Research School (GRS) support program at James Cook University Queensland Australia. DMITRE (Department for Manufacturing, Innovation, Trade, Resources and Energy, Government of South Australia) generously provided core samples for this study. Quaid Khan is grateful for the technical services rendered by Trican Geological Solutions Ltd Calgary, Alberta, Canada, in respect to the XRD data. Quaid Khan also acknowledges Prince Owusu Agyemang and colleagues of sedimentology research group (Gravel Monkeys) at JCU and Assistant Geologist Fawahid A.K Jadoon (Comsat). Senior Technical advisor and Team Lead Tahir M. Khan (LMKR). Special thanks to Syed Anjum Shah Chief Geologist Saif Energy Islamabad provided valuable insights in this study.

References

Ahmad, M Haghighi M, 2014. Petrophysical and mineralogical evaluation of shale gas reservoirs (Cooper Basin) SPE Asia Pacific Oil and Gas Conference, 2012 - onepetro.org.

Altindag, R.,2003. Correlation of specific energy with rock brittleness concepts on rock cuttings, J. South Afr. Inst. Min. Metallurgy 103 (3) 163e172.

Andrade, F.A., Al-Qureshi, H.A., Hotza, D., 2010. Modeling of clay paste extrusion through a rectangular die. Int. Rev. Chem. Eng. 2 (4), 478–483.

Battersby, D.G., 1976. Cooper Basin gas and oil fields. In: Leslie, R.B., Evans, H.J. and Knight, C.L. (Eds), Economic geology of Australia and Papua New Guinea, 3, Petroleum. Australasian Institute of Mining and Metallurgy. Monograph Series, 7:321-368.

Bekker, 1981 P.C.F. Bekker Simple clay testing methods Ziegelindustrie International, vol. 9, Bau-Verlag, Wiesbaden, Germany (1981), pp. 494–503.

Bergaya, F., Theng, B.K.G., Lagaly, G. (Eds.), 2006. Handbook of Clay Science. Elsevier,Amsterdam, pp. 141–246.

Bell, F. G., 2007. Engineering Geology, 2nd Edition. Elsevier, London.207-248.

Beach Energy, 2011 www.beachenergy.com.au/IRM/content/annualreport/ar2011.pdf

Boucher, R.K., 2000. Analysis of seals of the Roseneath and Murteree Shales, Cooper Basin, South Australia. South Australian Department of Primary Industries and Resources. Report Book 2001/015.

Bruner, K.A. and Smosna, R. A., 2011 Comparative study of the Missisipian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin. Technology Laboratory (NETL), US Department of Energy (USDOE). Report.

Britt, J. Schoeffler, The geomechanics of a shale play: what makes a shale prospective SPE125525 (2009) 9pp.

Buffin A.J., 2010, Petrophysics and Pore Pressure: Pitfalls and Perfection: AAPG Geosciences Technology Workshop, Singapore.

Casagrande, A., 1932. Research on the Atterberg limits of soils. *Public Roads,* 13:121-136. , 1948. Classification and identification of soils. Am. Soc. Civil Engineers Trans., 113:901-931.

Casagrande, A., 1958. Notes on the design of the liquid limit device. Geotechnique 8(2), 84-91.

Crain, E. R., 2000, Crain's Petrophysical handbook, Access via: https://spec2000.net/11-vshtoc.htm.

Dumbleton, M.J., West, G., 1966. Some factors affecting the relation between the clay minerals in soils and their plasticity. Clay Miner. 6, 179.

Gatehouse, C.G., 1972 Formations of the Gidgealpa Group in the Cooper Basin. Australasian Oil & Gas Review 18:12, 10-15.

Glover, P. 2010. Measurements of the photo-electric absorption (PEF) litho-density log for common lithologies. Petrophysics MSc Course Notes the lithodensity Log, pp 146.

Gostin, V.A., 1973. Lithologic study of the Tirrawarra Sandstone based on cores from the Tirrawarra Field. Report for Delhi International Oil Corporation (unpublished).,pp 97- 120.

Gravestock et al., 1995. Strzelrcki, South Australia, sheet SH54-2, South Australia. Geological Survey. 1:250 000 Series- Explanatory Notes.

Gravestock, D.I, Hibburt, J.E., Drexel, J.F. (Eds), The Petroleum Geology of South Australia, Vol. 4: Cooper Basin. South Australian Department of Primary Industries and Resources. Report Book 98/9, 129-142.

Halliburton, 2014 www.halliburton.com/...and.../evaluation-reactive-clay-indian-shale.pdf.

Hill, A.J., Mauger, A.J (2016) HyLogging unconventional petroleum core from the Cooper Basin, South Australia. Australian Journal of Earth Sciences volume 63, issue 8, Pages 1087-1097.

Holt, R., E. Fjær, O. Nes, and H. Alassi, 2011, A Shaly Look at Brittleness: 45th US Rock Mechanics/Geomechanics Symposium, 26-29 June 2011, San Francisco, CA, ARMA-11-366.

Hudson, B.D. 1994. Soil organic matter and available water capacity. *J. Soil Wat. Con.*, 49(2): 189-194.

Hunt J. M. Petroleum Geochemistry and Geology. – New York: W. H. Freeman and Company, 1995.

Jacobi, J. Breig, B. LeCompte, M. Kopal, G. Hursan, F. Mendez, S. Bliven, J.Longo Effective geomechanical and geochemical characterisation of shale gas reservoirs from the wellbore environment: Caney and the Woodford Shales (2008) SPE124231, 20pp.

Jadoon, Q., Roberts, E.M., Blenkinsop, T., Wust, R. Henderson.B., Mtelela.Lithological and facies analysis of the Roseneath and Murteree shales, Cooper Basin, Australia.Journal of Natural Gas Science and Engineering 37(2017) 138-168.

Jadoon, Q.K., Roberts. E., Blenkinsop, T., Wüst, R.A.J.2016 Organic petrography and thermal maturity of the Permian Roseneath and Murteree shales in the Cooper Basin, Australia, Int. J. Coal Geol., http://dx.doi.org/10.1016/j.coal.2016.01.005.

Jadoon,Q.K., Roberts. E., Blenkinsop,T., Wüst,R.A.J., Shah, A. Petrophysical evaluation and uncertainty analysis of Roseneath and Murteree shales reservoirs in the Cooper Basin, Australia.Journal of Petroleum Science and Engineering Elsevier 2016. (*10.1016/j.petrol.2016.06.010*

Jadoon Q.K., Roberts. E., Blenkinsop,T., Wüst, R.A.J., Shah,A. Mineralogical modelling and petrophysical parameters in Permian gas shales from the Roseneath and Murteree formations, Cooper Basin, Australia Petroleum Exploration and Development. Australia PETROL EXPLOR. DEVELOP, 2016, 43(2); 277-284. (Published) *http://www.sciencedirect.com/science/article/pii/S1876380416300313*

Jarvie D.M., Hill R,J., and Ruble T.E.(2007) Unconventional shale-gas systems: The Mississipian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment[J]. AAPG Bulletin. 91, 475-499.

Jin, X., S. Shah, J. C. Roegiers, and B. Zhang, 2014, Fracability evaluation in shale reservoirs — An integrated petrophysics and geomechanics approach: Hydraulic Fracturing Technology Conference, Society of Petroleum Engineers, SPE-168589-MS.

Josh, M., Clennell, B., Siggins, T., 2009. Practical broadband dielectric measurement of geological samples. 50th SPWLA Annual Logging Symposium, Woodlands Texas, June 21–24, 2009.

Kapel, A.J., 1972. The geology of the Patchawarra area, Cooper Basin. APEA Journal, 12:53-56.

Klemme, H.D., 1980. Petroleum basins- classifications and characteristics. Journal of Petroleum Geology vol.3, pp. 187-207.

Krynine, D. P. and William, J. R. 1957. Principles of Engineering Geology and Geotechnics. McGraw – Hill Book Company, NY. 159, 537.

Lee, M., J. L. Aronson, and S. M. Savin, 1985, K/Ar dating of time of gas emplacement in Rotliegendes sandstone, Netherlands. AAPG Bulletin, v. 69, p. 1381 1385.

Loucks R.G and Ruppel S.C.(2007) Mississipian Barnett Shale: Lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth Basin, Texas. AAPG Bulletin, 91, 523-533.

McKillop, M.D. 2013. The Adavale Basin. In: Jell, P.A. (ed.), Geology of Queensland. Geological Survey of Queensland, Brisbane, 175–183.

Medlin, W.L. and Fitch, J.L, (1983) Abnormal treating pressures in MHF treatments, Proc. SPE Annual Technical Conference and Exhibition, San Fransisco, CA.

Medlin, W.L., and Masse, L., 1984. Laboratory experiments in fracture propagation. SPE J., v. 24, no. 3, p. 256-268.

Medlin W.l. Masse L., 1986 - Journal of Petroleum Technology - Vol. 38 - Issue 9 – 1986- SPE-11068-PA. Publisher (SPE) Society of Petroleum Engineers. MicKirdy, D.M., R.E.Cox, J.K. Volkman, and V.J Howell. 1986. Botryococane in a new class of Australian crude oils. Nature, 320(6057), 57-59.

Minasny, B., and A. B. McBratney (1999), A rudimentary mechanistic model for soil production and landscape development, *Geoderma*, 90, 3–21, doi:10.1016/S0016-7061(98)00115-3.

Modesto, C.O., Bernardini, A.M., 2008. Determination of clay plasticity: indentation method versus Pfefferkorn method. Appl. Clay Sci. 40 (1–4), 15–19.

Moore, H.D., Jr,1965, Quadrant Formation and Permian strata in the Phillipsburg(Maxville) and Garrison districts, in Billings Geol. Soc., Geology of the Flint Creek Range, Montana, 16th annual Field conference, August 1965; Billings, mont., p, 67-72.

Nadeau,P.H., 2000, The Sleipner Effect: a subtle relationship between the distribution of diagenetic clay,reservoir porosity, permeability, and water saturation. Clay Minerals, 35, 185-200.

Passey Q.R., Bohacs K.M., Esch W.L., Klimentidis. R., Sinha.S (2010) from oil- prone source rock to gas-producing shale reservoir-Geologic and petrophysical characterization of unconventional shale-gas reservoirs, SPE 131350.

Parker, D. Buller, E. Petre, D. DreherHaynesville Shale — Petrophysical Evaluation (2009) SPE122937, 11pp.

Pearce M.A., E. T. Nicholas, M. H. Robert and James S.C. (2013). "Reaction Mechanism for the Replacement of Calcite by Dolomite and Siderite: Implications for Geochemistry, Microstructure and Porosity Evolution during Hydrothermal Mineralization." Contrib Mineral Petrol (2013) 166:995-1009.

PIRSA,2000.www.pir.sa.gov.au/__data/assets/pdf_file/0019/27226/cooper_prospectivity.pdf__Retrieved on the 16/06/2013. ____

Price, P.L., Filatoff, J., Williams, A>J., Pickering, S.A., & Wood, G.R., 1985- Late Paleozoic and Mesozoic palynostratigraphic units, CSR Ltd: Oil & Gas Division. Unpublished company report 274/25.

Price, L.C., & Barker, C.E., 1985- Suppression of vitrinite reflectance in amorphous-rich kerogen- a major unrecognised problem, *Journal of Petroleum Geology 8, 59-84.*

Radkee, B.M., Kellett, J.R., Ransley, T.R., Bell, J.G., 2012. Lexicon of the lithostratigraphic and hydrogeological units of the Great Artesian Basin and its Cenozoic cover. A Technical Report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

Rahman, M. F. (2000). Hydraulic Conductivity and Chemical Compatibility of Some Victorian Soils used as Liners for Waste Containment. PhD Thesis, School of the Built Environment, Victoria University of Technology.

Rama Rao, Ravulaparti (1978) A study of swelling clay.PhD thesis. http://theses.gla.ac.uk/6340.

Rawls, WJ, Pachepsky, YA, Ritchie, JC, Sobecki, TM and Bloodworth, H. (2003). Effect of organic carbon on soil water retention. Geoderma. 116, 61 – 76.

Reeve, M J, HALL, D G M, and BULLOCK, P. 1980. The effect of soil composition and environmental factors on the shrinkage of some clayey British Soils. Journal of Soil Science, Vol. 31, 429–442.

Reeves. G.M and Cripp. J.C (2006) Clay materials used in construction. Geological society Engineering special publication No.21. Published by the Geological society London.

Ribeiro, M.J., Ferreira, J.M., Labrincha, J.A., 2005. Plastic behaviour of different ceramic pastes processed by extrusion. Ceram. Int. 31 (4), 515–519.

Schulz Rojhan, J.P(1993) Calcite-cemented zones in the Eromanga Basin: clues to petroleum migration and entrapment? The APEA Journal , 33,1, pp. 63-76.

Slusser, M.L. and Rieckmann, M. March 1976: "Fracturing Low Permeable Gas Reservoirs," Erdoel-Erdgas Zeitschrijj 92.Sondergeld, C. H., Newsham, K. E., Comisky, J. T., & Rice, M. C. (2010). Petrophysical considerations in evaluating and producing shale gas resources, the Society of Petroleum Engineers (SPE) 131768, 23-25, Pittsburgh.

Sondergeld, C. H., Newsham, K. E., Comisky, J. T., & Rice, M. C. (2010). Petrophysical considerations in evaluating and producing shale gas resources, the Society of Petroleum Engineers (SPE) 131768, 23-25, Pittsburgh.

Stuart, W.J., 1976. The genesis of Permian and lower Triassic reservoir sandstones during phases of southern Cooper basin development. APEA Journal, 16:37-47.

Thornton, R.C.N., 1979. Regional stratigraphic analysis of the Gidgealpa Group, southern Cooper Basin, Australia. South Australia. Geological Survey. Bulletin, 49.

US Energy, 2011. https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf. Retrieved on the 16/08/2014.

Van der Velden A. Proterozoic crustal transition beneath the Western ... Geology. 1979;7:653—657. 30.

Wang, F. P., and J. F. W. Gale, 2009, screening criteria for shale-gas systems: Gulf Coast Association of Geological Societies Transactions, 59, 779–793.

William, B.P.J., & Wild, E.K., 1984- The Tirrawarra Sandstone and Merrimelia Formation of the southern Cooper Basin, South Australia the sedimentation and evolution of a glaciofluvial system. The APEA journal 28:1, 156-66.

Williams, B.P.J., Wild, E.K., & Suttill, R.J., 1985-Paraglacial aeolianites: Potential new hydrocarbon reservoirs, Gidgealpa Group, southern Cooper Basin. The APEA journal 25:1, 291-310.

Wopfner, H., 1972-Depositional history and tectonics of South Australian sedimentary basins. South Australian Mineral Resources Review 113, 32-50.

Wopfner, H., 1972-Depositional history and tectonics of South Australian sedimentary basins. South Australian Mineral Resources Review 113, 32-50.

Zhang Changjiang, Pan Wenlei, and Liu Guangxiang (2008) Dynamic evaluation to the cap formation of Silurian argillaceous rock, Southern China [J].Natural Gas Geoscience.!9, 301-310(in chinese).

Zhishui LIU, ZandongSUN, New brittleness indexes and their application in shale/clay gas reservoir prediction. Petroleum Exploration and Development. Volume 42, Issue 1, February 2015, Pages 129-137.

Zou Caineng, Dong Dazhong, and Wang Shejiao (2010) Geological characteristics, formation mechanism and resource potential of shale gas in China [J]. *Petroleum Exploration and Development*. **37**, 641–653).

S. No	Formation	Minerals
1	**Roseneath Shale**	quartz, kaolinite, mica/illite, feldspar, chlorite, siderite, (dolomite), (pyrite), rutile, anatase.
2	**Murteree Shale**	quartz, kaolinite, mica/illite, feldspar, chlorite, siderite, (dolomite). (pyrite), rutile, anatase.

Table 1: Mineralogy of the Roseneath and Murteree shales. Components were identified from SEM imaging and XRD analysis.

Well Name	N	Total Clays wt %		Quartz wt %		Total carbonates wt %		Feldspar/Albite wt%		TOC wt %	
		average	range	average	range	average	range	average	range	average	range
Big Lake 43	4	35	34-37	34	30-40	14	9-20	10	9-11	2.5	1.5-3
Big lake 48	6	40	38-46	35	26-50	25	5-36	-	-	2.5	1.7-3.5
Dullingary N-18	6	46	44-49	31	29-35	19	17-21	2.6	2-3.0	2.5	2- 4
Kerna-6	5	48	47-47.9	35	31-35	12	8 8.7	3	2.8-4.0	2.5	2-3.5
Vintage Crop-1	30	48	34-57	35	14-48	7	1- 44	4.6	3.5-6.7	2.25	1.97-3.77
Moomba-73	10	47	41-50	35	35-42	5	5-6.6	4	3-4	1.95	1- 3
Moomba-76	8	46	38-49	38	32-39	10	6-14	4	3-5	1.80	1-2.3
Moomba-133	7	44	39-53	36	32-40	10	9-14	3.6	3.1-4.8	1.80	1-2.5
Moomba-145	5	44	41-47	36	33-40	14	10-19	3.4	3.1-3.8	1.90	1-2.8
Toolachee N-1	9	41	32-46	42	35-56	10	6-15	3.6	2.9-4.0	3.00	1.5-4
Toolachee-39	20	38	30-46	35	33-45	10	6-2	3.5	2.5-6	3.00	1-4.5
Yapini-1	7	35	29-39	45	38-56	13	7-25	2.5	2.3-2.8	2.5	2-4.00
Tirrawarra-2	8	45	9-60	43	32-	2	0.8-6	1	0.4-1.7	18.00	0.43- 36.8

Continues…

…Continued

Well Name	N	Total Clays wt %		Quartz wt %		Total carbonates wt %		Feldspar/Albite wt%		TOC wt %	
		average	range	average	range	average	range	average	range	average	range
Moomba-46	20	55	35-69	43	18-51	13	1.2-49	1.5	0.3-2.2	1.80	1-2.5
Ashby-1	4	45	29-47	50	44-66	6	1.4-4	1.6	1.6-2.9	1.5	1.6-2
Encounter-1	47	50	38-69	40	22-52	12	2.2-46	1.1	0.5-1.7	2.50	1.5-4.5
Epsilon-1	15	45	30-55	33	26-65	5	2.1-8	1.5	0.5-1.5	2.60	1.5-3.5
Della-1	11	56	56-67	30	20-35	4.5	1.9-14	1.1	0.4-1.3	2.5	1.5-4

Table 2: Weight percent composition of samples from Roseneath Shale determined by X-ray diffraction (minerals) and by source Rock analysis (TOC).N=number of samples.

Well Name	N	Total Clays wt %		Quartz wt %		Total carbonates wt %		Feldspar/ Albite wt%		TOC wt %	
		average	range	Average	range	average	range	average	range	average	range
Dirkala-2	14	45	30-50	44	30-58	12	6-33	5	2-2.8	2.5	1.47-4.5
Dullingary N-18	6	43	44-45	33	29-38	20	17-25	2.5	2-3.0	-	-
Kerna-6	5	48	47-49	34	31-38	12	9-15	3	2.8-4.0	-	-
Vintage Crop-1	26	45	34-57	35	14-42	10	1-12	4.6	2.5-6.5	2.50	1.38 - 4.22
Moomba N-1	4	43	36-52	45	31-54	6	4-9	4.2	3.5-5.3	1.50	1.2- 25
Moomba-73	10	45	41-45	39	35-45	9.8	5-15	3	3-3.7	1.50	1- 2
Moomba-76	8	46	38-48	38	32-49	9	7-12	4	3-5	1.45	1.3- 1.90
Moomba-133	4	40	38-50	38	30-41	12	8-16	3.6	3.1-4.8	1.50	1.5-2
Munkarie-02	5	44	40-47	39	36-43	10	9-12	3.8	3.1-4.3	2.5	2- 4
Toolachee E-2	12	40	29-46	42	33-57	11	5-15	3.7	2.9-5	2.5	1- 3.35
Toolachee E-25	10	42	37-48	41	35-50	11	7-15	3.7	3.3-4.2	2.5	1.5 -3.8
Toolachee-39	20	38	28-43	41	33-56	13	7-18	2.5	2.5-5	2.5	2- 4
Tirrawarra-2	26	45	9-77	47	32-87	2	0.8-6.9	1	0.4-1.7	15	1.43- 370
Epsilon-2	26	50	25-67	35	26-71	6	2.1-9	1.2	0.4-2.2	4.00	1.24 - 30
Moomba-66	7	33	26-52	45	40-61	4.5	2-17	1.2	0.3-1.2	2.00	0.93 - 4
Toolachee-29	28	40	40-65	48	30-58	12	6-18	1.5	1.2-2.3	2.25	2- 4.5
Ashby-1	3	40	29-40	52	38-69	4	1.4-7	1.6	1.3-2.8	1.50	1-2
Encounter-1	31	45	38-58	45	20-55	12	15-45	1.1	0.5-1.6	2.25	1.35-3.5
Moomba-N-1	4	38	36-52	45	31-55	6	4.6-8.9	4.2	3.5-5.3	1.50	1- 2.5
Big Lake -43	3	35	34-37	34	29-40	14	9-20	10	9-11	2.00	1- 3.5

Table 3: Weight percent composition of samples from Murteree Shale determined by X-ray diffraction (minerals) and by source Rock analysis (TOC). N=number of samples.

Plasticity	Range of Liquid Limit
Low plasticity	<35
Intermediate palsticity	35-50
High plasticity	50-70
Very High plasticity	70-90
Extra High Plasticity	>90

Table 4: Plasticity according to liquid limit (Bell, 2007)

.

Shale	Plasticity	Range of Liquid Limit	Plastic Index
Roseneath	Low - Intermediate	22-42%	6- 25.5%
Murteree	Low -intermediate	22-45%	5- 24%

Table 5: Classification of the plasticity of the shale samples.

Shale	Basin	Age	Basin type	TOC	BI%	Depth	Mineral composition
Barnett	Fort Worth	Mississippian	Foreland	1-10%	<1	2000 -2800 m	35–50% quartz, 27% illite with minor smectite, 8–19% calcite and dolomite, 7% feldspars, 5% organic matter, 5% pyrite, 3% siderite, and traces of native copper and phosphate material
Marcellus Shale	Appalachian	Devonian	Foreland	2-6%	<1	1500 -2500 m	27–31% quartz, 9–34% illite, 1–7% mixed- layer clays, 0–4% chlorite, 3–48% calcite, 0–10% dolomite, 0–4% sodium feldspar, 5–13% pyrite, and 0–6% gypsum.
Eagle Ford	East Texas	Late -Cretaceous	Passive margin	2-12%	<1	1200 - 4250 m	47% calcite, 11%quartz,3% pyrite, 25% illite, 17% kaolinite, 14% Albite, 3% dolomite, 19%muscovite.
Roseneath	Cooper	Permo-Triassic	Intracratonic	2- 30%	<1	1600 - 2000 m	30-50% quartz, 10-25% siderite, 1% rutile, 20-50% mica/illite, 15% kaolinite
Murteree	Cooper	Permo-Triassic	Intracratonic	2-6%	<1	1800 -2200 m	30-55% quartz, 10-25% siderite, 1% rutile, 20-45% mica/illite, 15% kaolinite

Table 6: Generalized mineralogy of gas producing American gas shales compared to the Roseneath and Murteree shales.

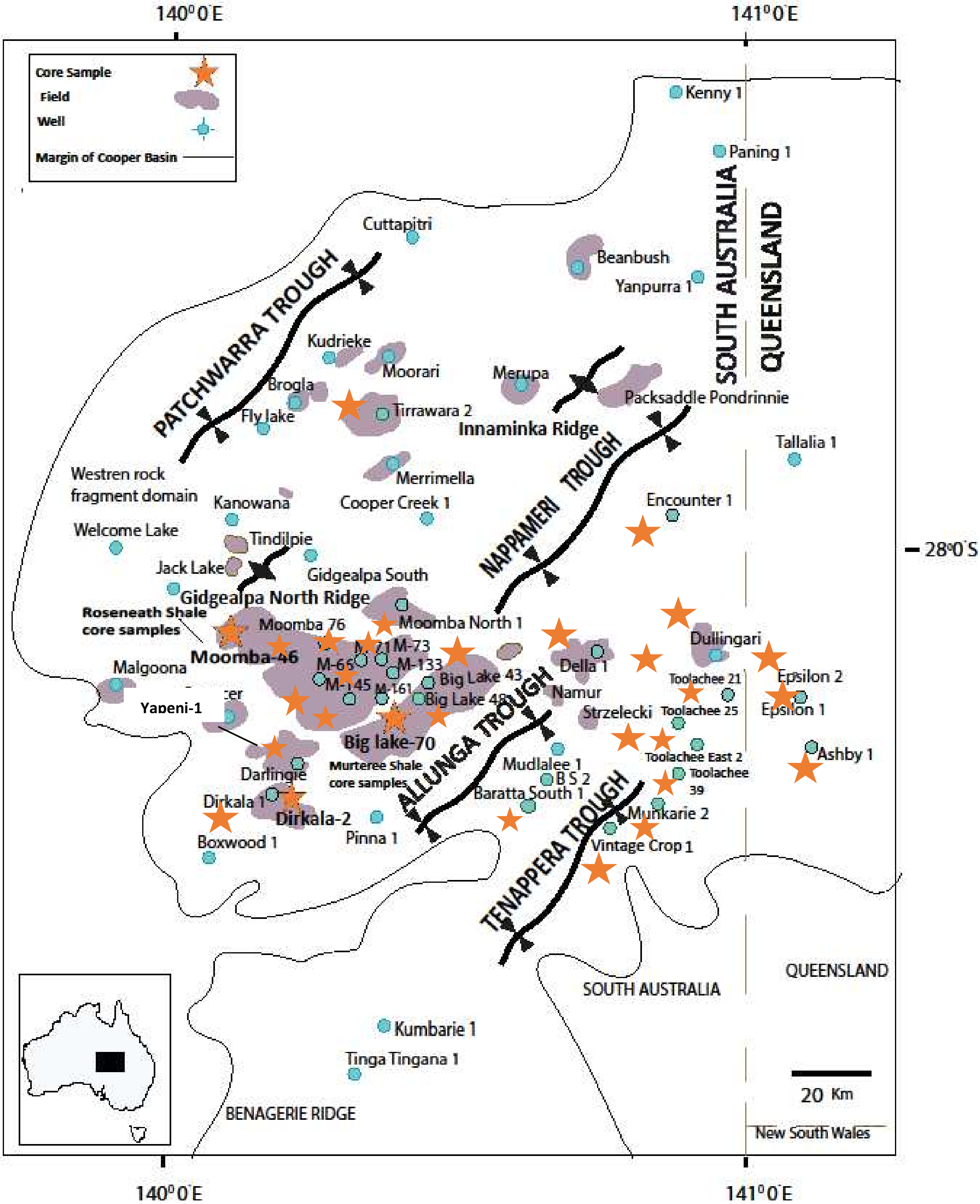


Figure 1: Map of the South Australia and Queensland sectors of the Cooper Basin showing the location of wells providing samples used in this study (stars), and unsampled wells (blue dots) (modified after Chaney et al., 1997).

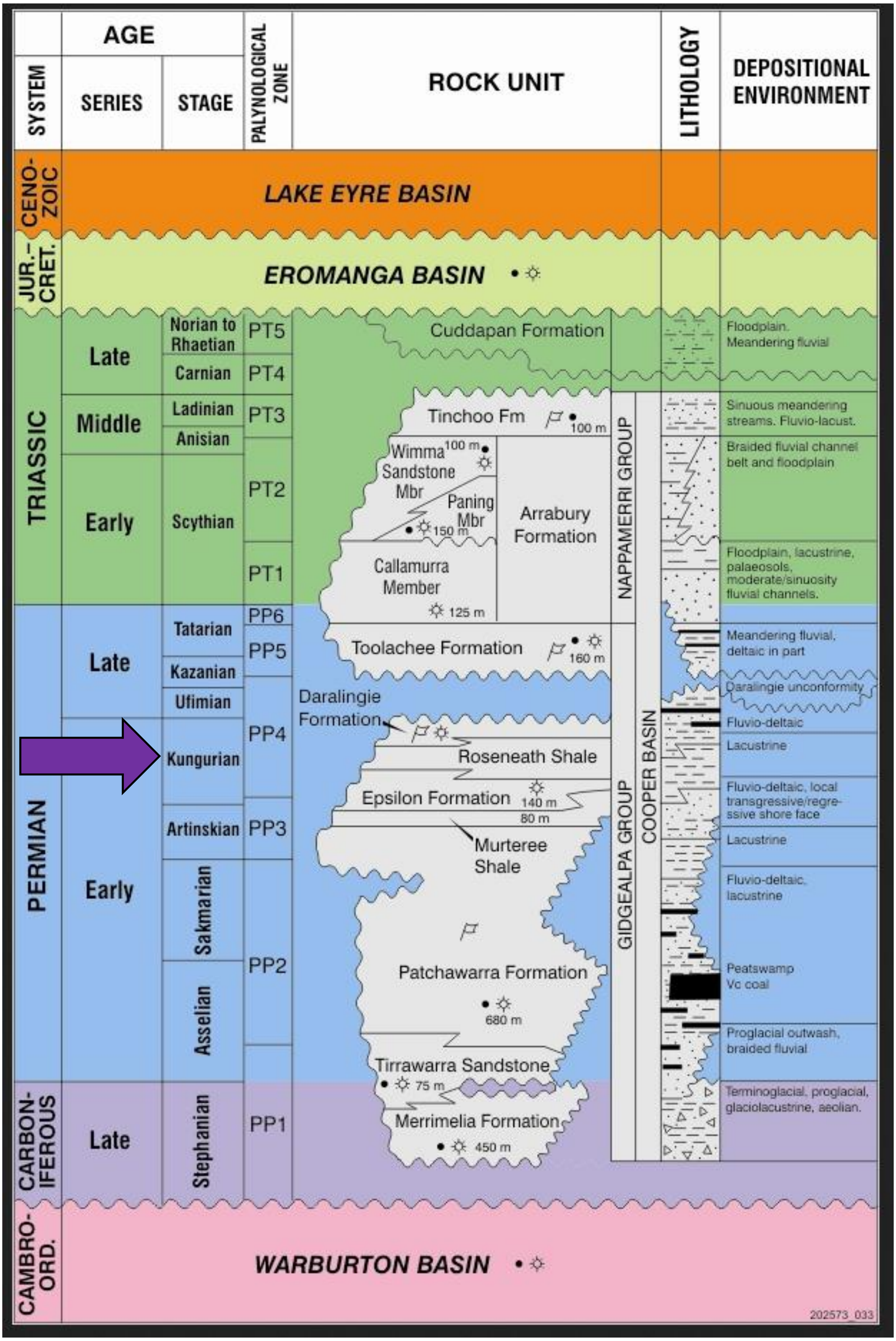


Figure 2: Stratigraphy of the Cooper Basin (PIRSA, 2007). Arrow shows the study interval that includes the Roseneath and Murteree shales. PIRSA 200171_2 and 200171_004.

S. No	Formation	Minerals
1	**Roseneath Shale**	quartz, kaolinite, mica/illite, feldspar, chlorite, siderite, (dolomite), (pyrite), rutile, anatase.
2	**Murteree Shale**	quartz, kaolinite, mica/illite, feldspar, chlorite, siderite, (dolomite). (pyrite), rutile, anatase.

Table 1: Mineralogy of the Roseneath and Murteree shales. Components were identified from SEM imaging and XRD analysis.

Well Name	N	Total Clays wt %		Quartz wt %		Total carbonates wt %		Feldspar/Albite wt%		TOC wt %	
		average	range	average	range	average	range	average	range	average	range
Big Lake 43	4	35	34-37	34	30-40	14	9-20	10	9-11	2.5	1.5-3
Big lake 48	6	40	38-46	35	26-50	25	5-36	-	-	2.5	1.7-3.5
Dullingary N-18	6	46	44-49	31	29-35	19	17-21	2.6	2-3.0	2.5	2- 4
Kerna-6	5	48	47-47.9	35	31-35	12	8 8.7	3	2.8-4.0	2.5	2-3.5
Vintage Crop-1	30	48	34-57	35	14-48	7	1- 44	4.6	3.5-6.7	2.25	1.97-3.77
Moomba-73	10	47	41-50	35	35-42	5	5-6.6	4	3-4	1.95	1- 3
Moomba-76	8	46	38-49	38	32-39	10	6-14	4	3-5	1.80	1-2.3
Moomba-133	7	44	39-53	36	32-40	10	9-14	3.6	3.1-4.8	1.80	1-2.5
Moomba-145	5	44	41-47	36	33-40	14	10-19	3.4	3.1-3.8	1.90	1-2.8
Toolachee N-1	9	41	32-46	42	35-56	10	6-15	3.6	2.9-4.0	3.00	1.5-4
Toolachee-39	20	38	30-46	35	33-45	10	6-2	3.5	2.5-6	3.00	1-4.5
Yapini-1	7	35	29-39	45	38-56	13	7-25	2.5	2.3-2.8	2.5	2-4.00
Tirrawarra-2	8	45	9-60	43	32-	2	0.8-6	1	0.4-1.7	18.00	0.43- 36.8

Continues…

…Continued

Well Name	**N**	**Total Clays wt %**		**Quartz wt %**		**Total carbonates wt %**		**Feldspar/Albite wt%**		**TOC wt %**	
		average	range	average	range	average	range	average	range	average	range
Moomba-46	20	55	35-69	43	18-51	13	1.2-49	1.5	0.3-2.2	1.80	1-2.5
Ashby-1	4	45	29-47	50	44-66	6	1.4-4	1.6	1.6-2.9	1.5	1.6-2
Encounter-1	47	50	38-69	40	22-52	12	2.2-46	1.1	0.5-1.7	2.50	1.5-4.5
Epsilon-1	15	45	30-55	33	26-65	5	2.1-8	1.5	0.5-1.5	2.60	1.5-3.5
Della-1	11	56	56-67	30	20-35	4.5	1.9-14	1.1	0.4-1.3	2.5	1.5-4

Table 2: Weight percent composition of samples from Roseneath Shale determined by X-ray diffraction (minerals) and by source Rock analysis (TOC).N=number of samples.

Well Name	N	Total Clays wt %		Quartz wt %		Total carbonates wt %		Feldspar/ Albite wt%		TOC wt %	
		average	range	Average	range	average	range	average	range	average	range
Dirkala-2	14	45	30-50	44	30-58	12	6-33	5	2-2.8	2.5	1.47-4.5
Dullingary N-18	6	43	44-45	33	29-38	20	17-25	2.5	2-3.0	-	-
Kerna-6	5	48	47-49	34	31-38	12	9-15	3	2.8-4.0	-	-
Vintage Crop-1	26	45	34-57	35	14-42	10	1-12	4.6	2.5-6.5	2.50	1.38 - 4.22
Moomba N-1	4	43	36-52	45	31-54	6	4-9	4.2	3.5-5.3	1.50	1.2- 25
Moomba-73	10	45	41-45	39	35-45	9.8	5-15	3	3-3.7	1.50	1- 2
Moomba-76	8	46	38-48	38	32-49	9	7-12	4	3-5	1.45	1.3- 1.90
Moomba-133	4	40	38-50	38	30-41	12	8-16	3.6	3.1-4.8	1.50	1.5-2
Munkarie-02	5	44	40-47	39	36-43	10	9-12	3.8	3.1-4.3	2.5	2- 4
Toolachee E-2	12	40	29-46	42	33-57	11	5-15	3.7	2.9-5	2.5	1- 3.35
Toolachee E-25	10	42	37-48	41	35-50	11	7-15	3.7	3.3-4.2	2.5	1.5 -3.8
Toolachee-39	20	38	28-43	41	33-56	13	7-18	2.5	2.5-5	2.5	2- 4
Tirrawarra-2	26	45	9-77	47	32-87	2	0.8-6.9	1	0.4-1.7	15	1.43- 370
Epsilon-2	26	50	25-67	35	26-71	6	2.1-9	1.2	0.4-2.2	4.00	1.24 - 30
Moomba-66	7	33	26-52	45	40-61	4.5	2-17	1.2	0.3-1.2	2.00	0.93 - 4
Toolachee-29	28	40	40-65	48	30-58	12	6-18	1.5	1.2-2.3	2.25	2- 4.5
Ashby-1	3	40	29-40	52	38-69	4	1.4-7	1.6	1.3-2.8	1.50	1-2
Encounter-1	31	45	38-58	45	20-55	12	15-45	1.1	0.5-1.6	2.25	1.35-3.5
Moomba-N-1	4	38	36-52	45	31-55	6	4.6-8.9	4.2	3.5-5.3	1.50	1- 2.5
Big Lake -43	3	35	34-37	34	29-40	14	9-20	10	9-11	2.00	1- 3.5

Table 3: Weight percent composition of samples from Murteree Shale determined by X-ray diffraction (minerals) and by source Rock analysis (TOC). N=number of samples.

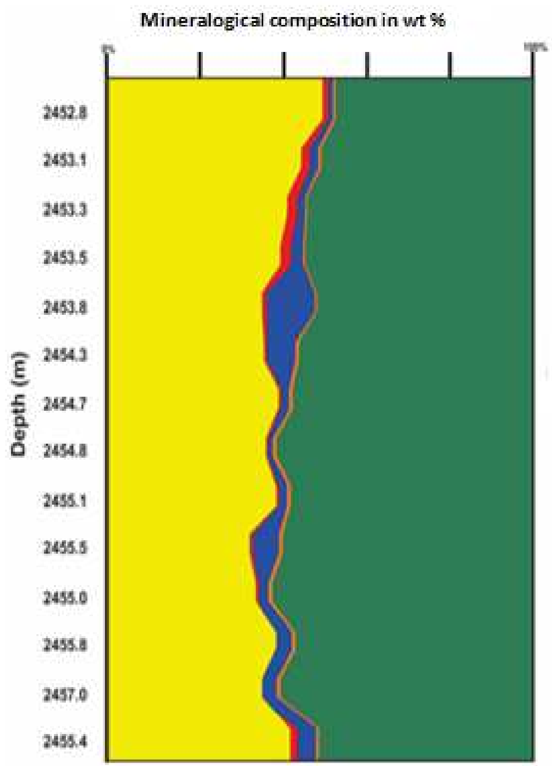


Figure 3a: Moomba-46 Well (Roseneath Shale)

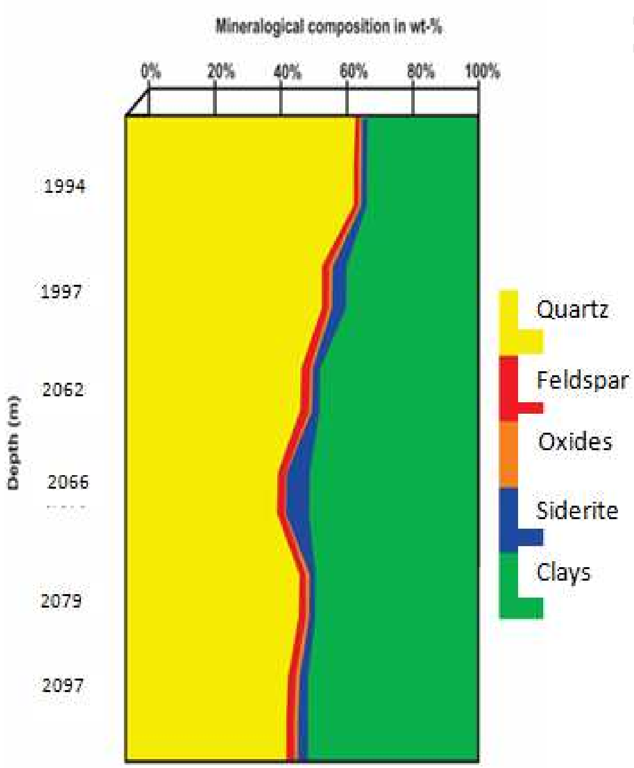


Figure 3b: Ashby-1 Well (Roseneath Shale)

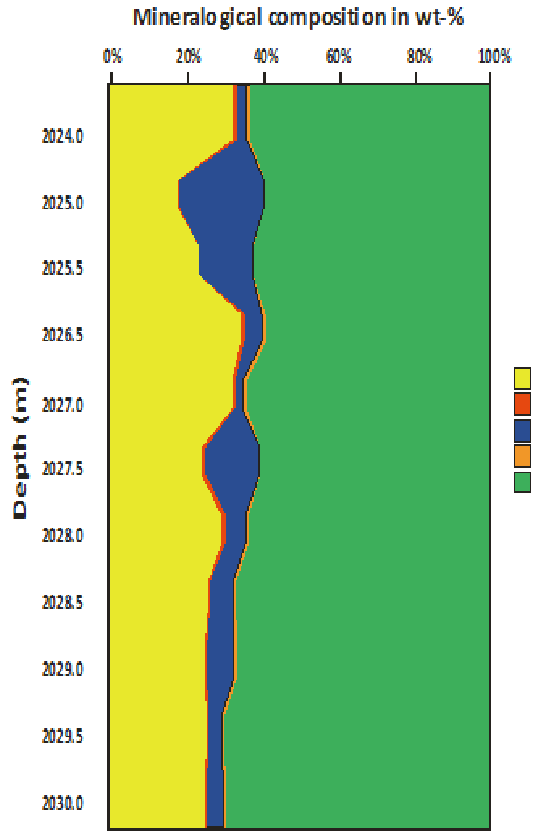


Figure 3c: Della-1 well (Roseneath Shale)

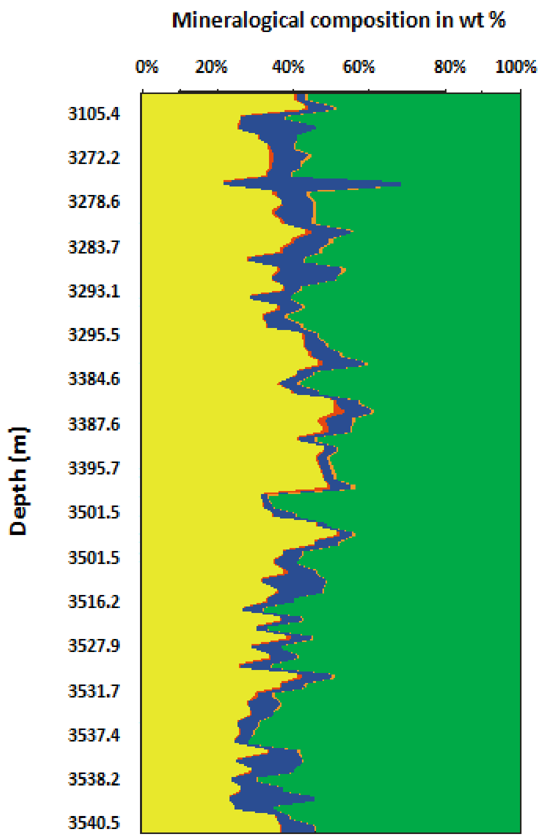


Figure 3d: Encounter-1 well (Roseneath Shale)

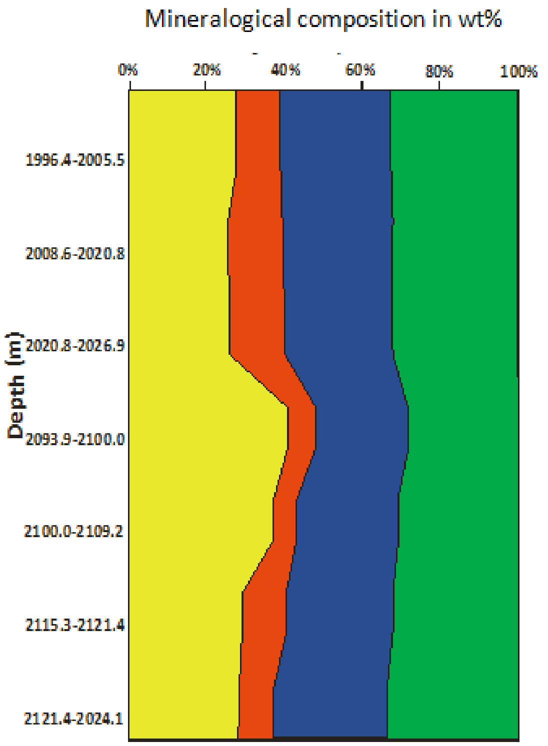


Figure 3e: Yapeni-1 well (Roseneath Shale)

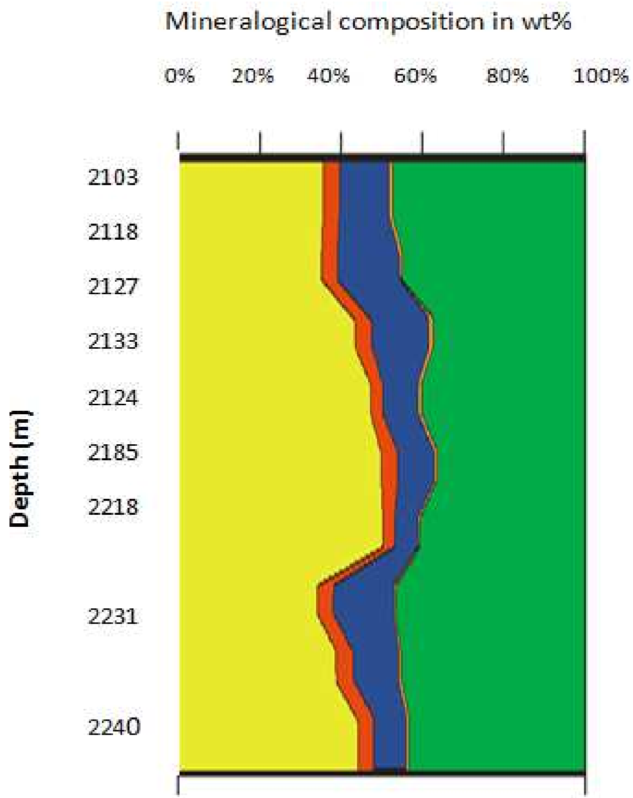
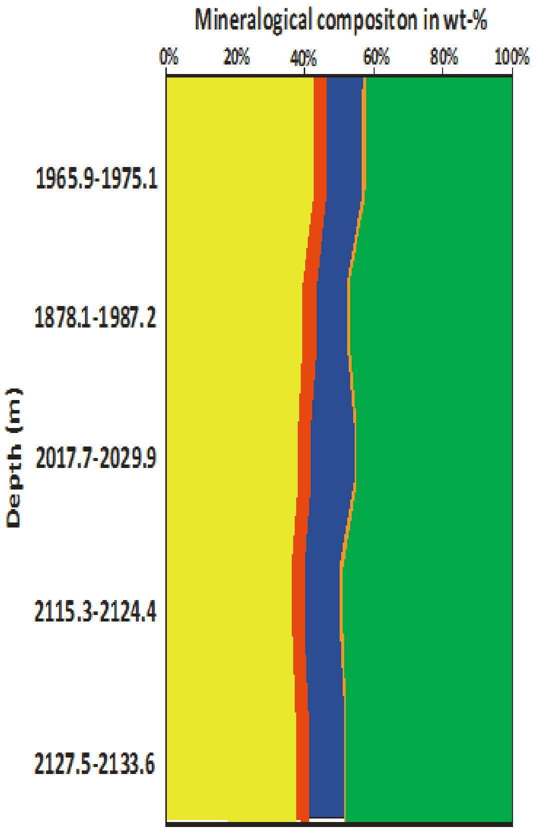


Figure 3f: Toolachee North-1 well (Roseneath Shale)



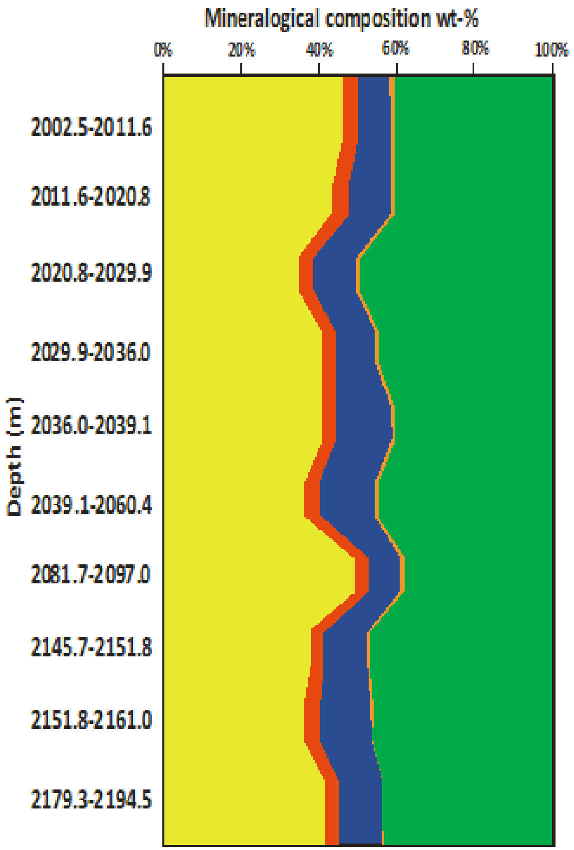


Figure 3g: Munkerie-2 well (Murteree Shale)

Figure 3h: Toolachee -25 well (Murteree Shale)

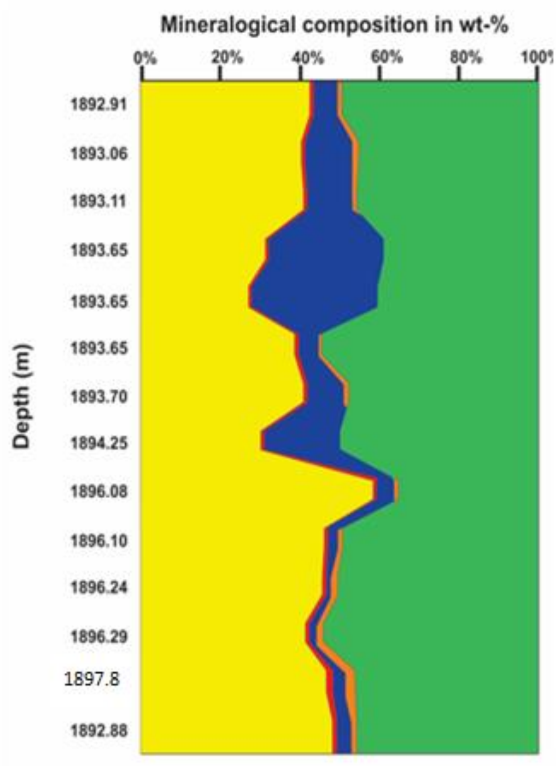


Figure 3i: Dirkala-2 well Murteree Shale

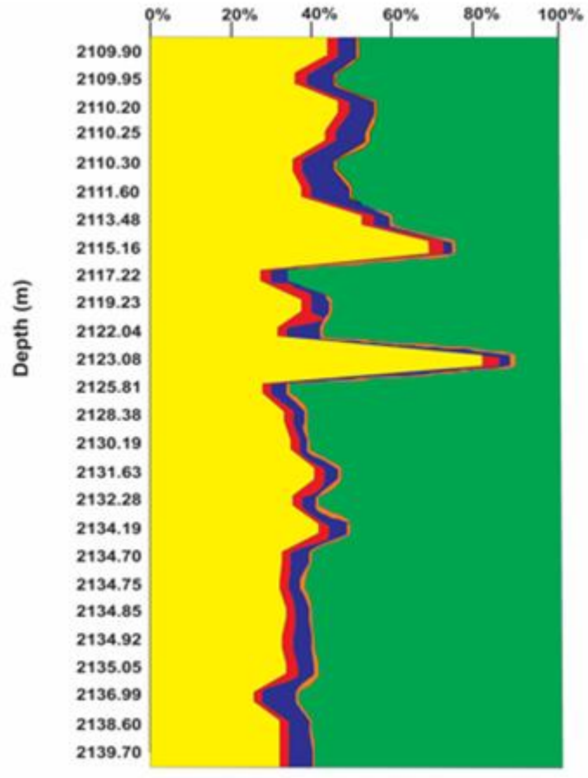


Figure 3j: Epsilon-2 well Murteree Shale.

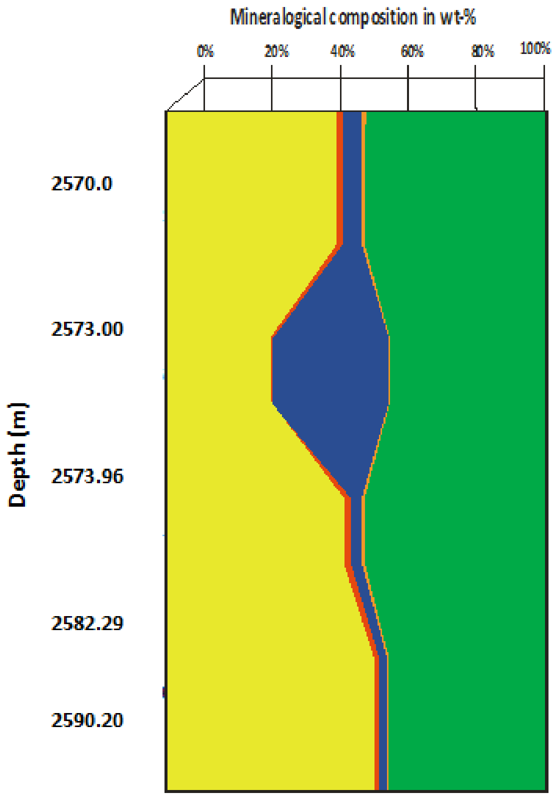


Figure 3k: Big Lake 48 well (Murteree Shale).

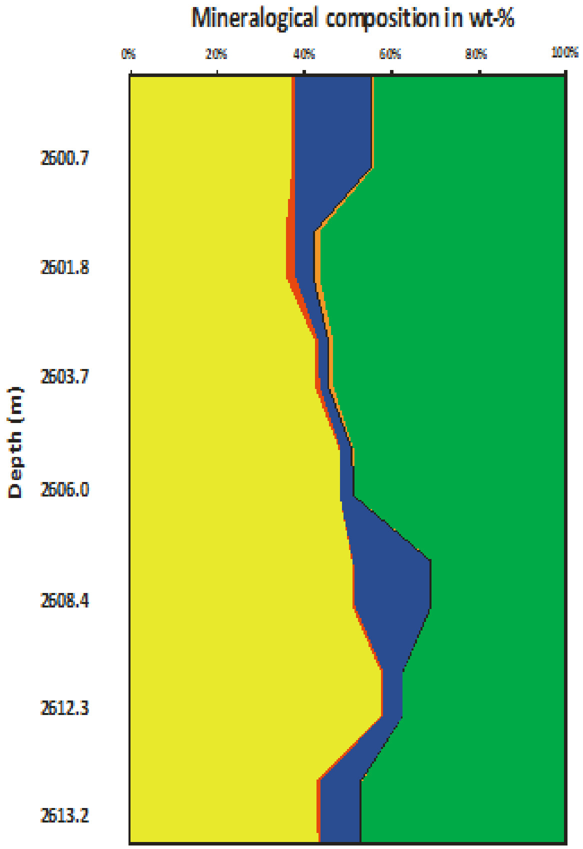


Figure 3l: Moomba-66 well (Murteree Shale).

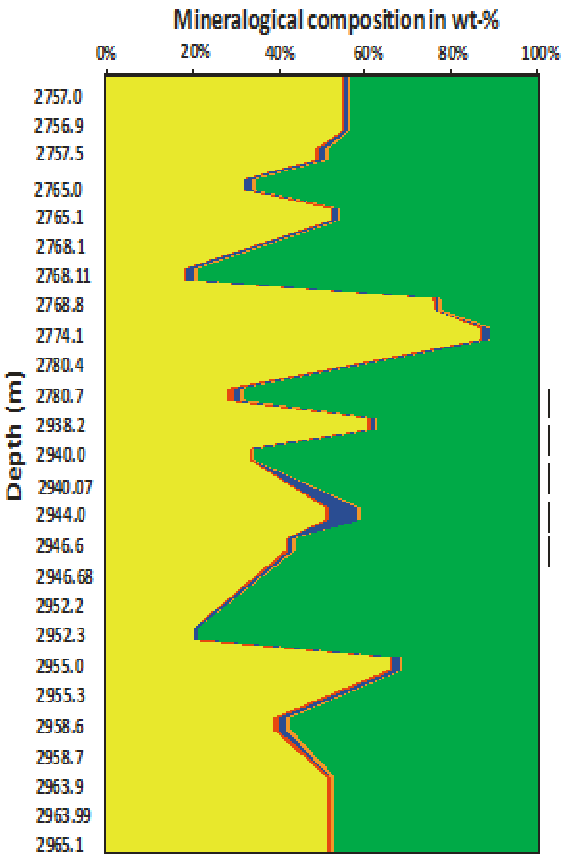


Figure 3m: Tirrawara-2 well (Murteree Shale).

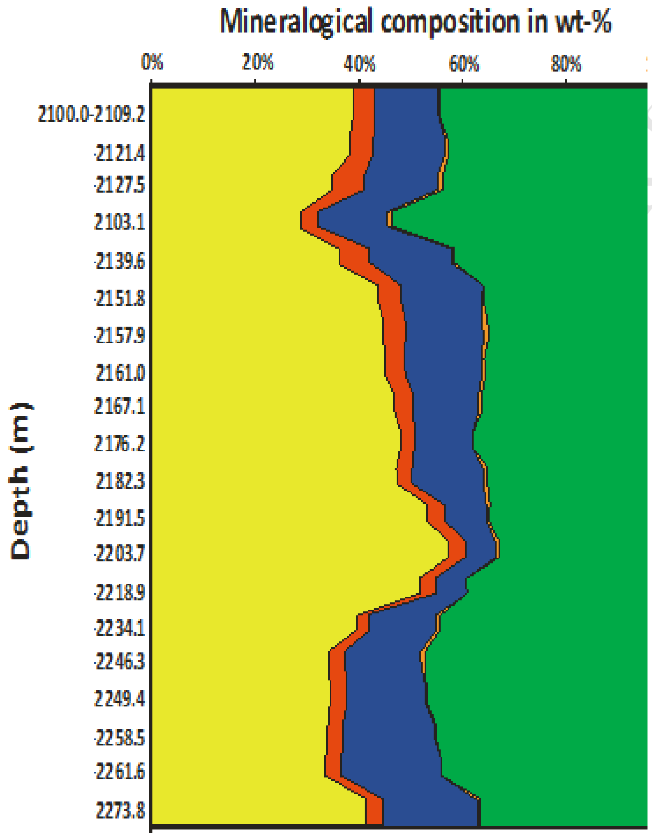
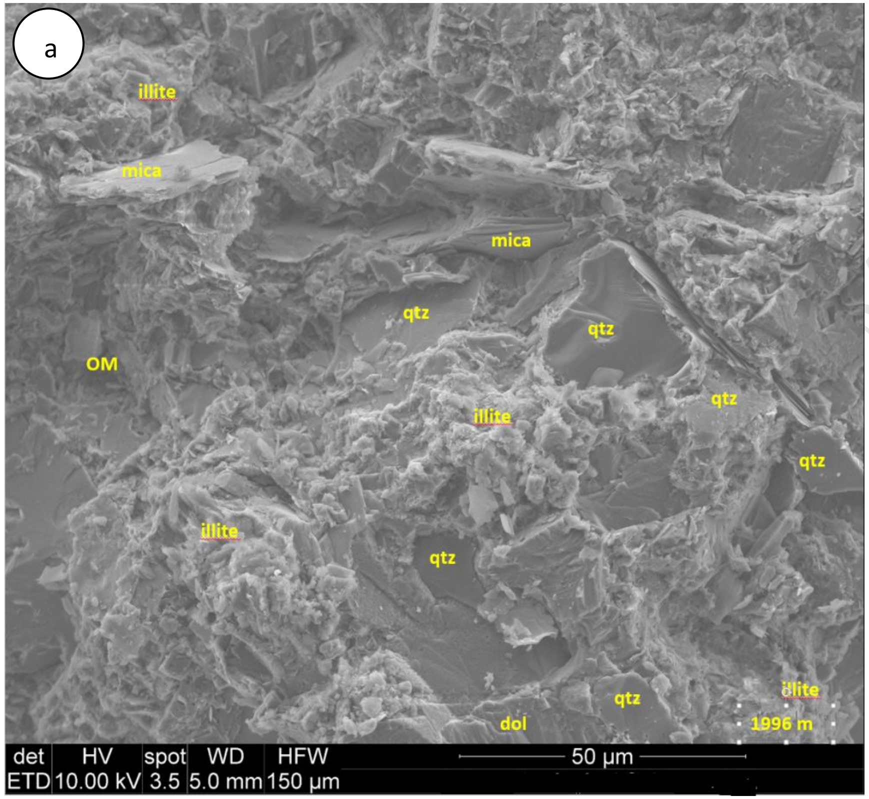
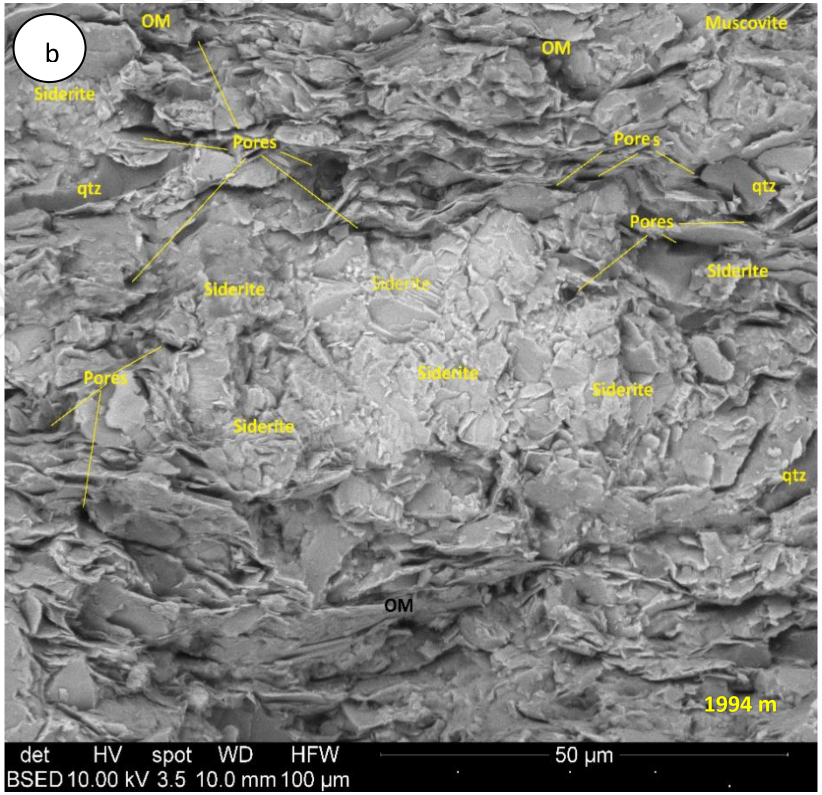


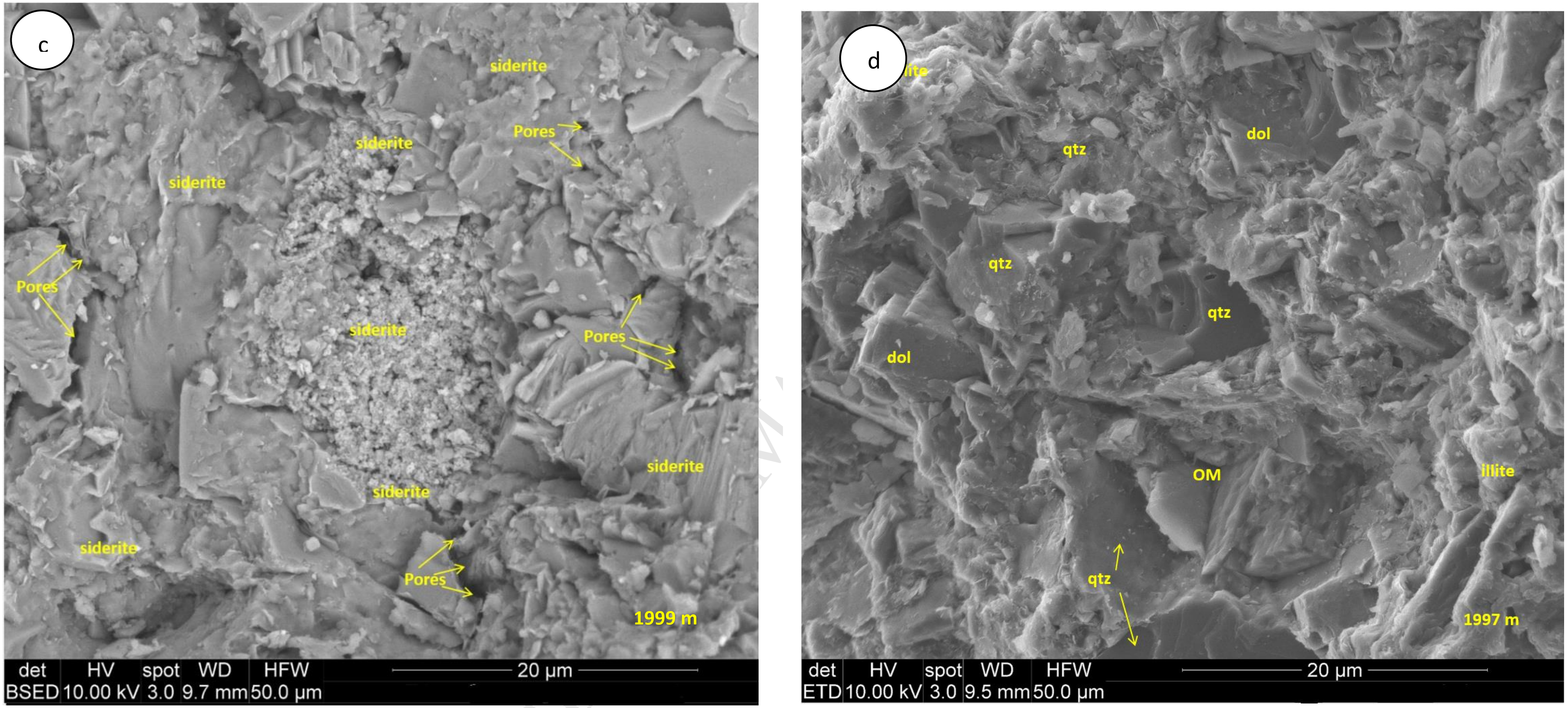
Figure 3n: Toolachee 29 well (Murteree Shale).

Figure 2: Contents of quartz (Yellow), siderite (blue), clay (green), feldspar(red) and Ti-oxide (orange) in the Roseneath Murteree shales based on quantitative analysis of XRD data (weight percentages) in Cooper Basin samples. Roseneath Shale: **a)** Moomba-46 well; **b)** Ashby-1 well; **c)** Della-1; **d)** Encounter well; **e)** Yapeni-1 well; **f)** Toolachee North-1; Murteree Shale **g)** Munkeri-2 well; and **h)** Toolachee -25; **i)** Dirkala-2 well; **j)** Epsilon-2; **k)** Big Lake-48 well; **l)** Moomba-66 well; **m**)Tirrawara-2; **n**) Toolachee-29 well.

Roseneath Shale






c
siderite
Pores
siderite
siderite
Pores
siderite
Pores
siderite
siderite
siderite
Pores
1999 m
det HV spot WD HFW 20 µm
BSED 10.00 kV 3.0 9.7 mm 50.0 µm
d
qtz
dol
qtz
qtz
dol
OM
illite
qtz
1997 m
det HV spot WD HFW 20 µm
ETD 10.00 kV 3.0 9.5 mm 50.0 µm

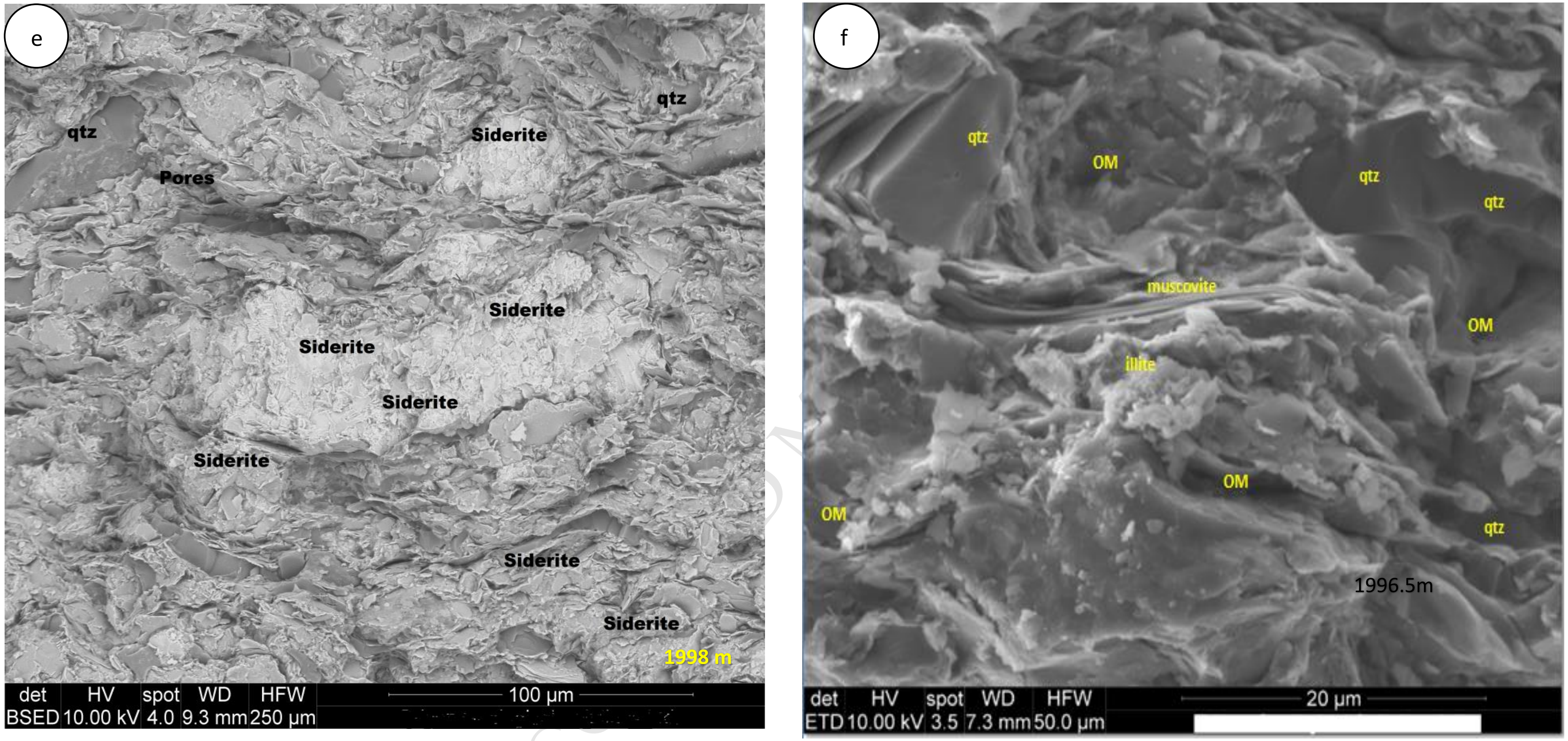
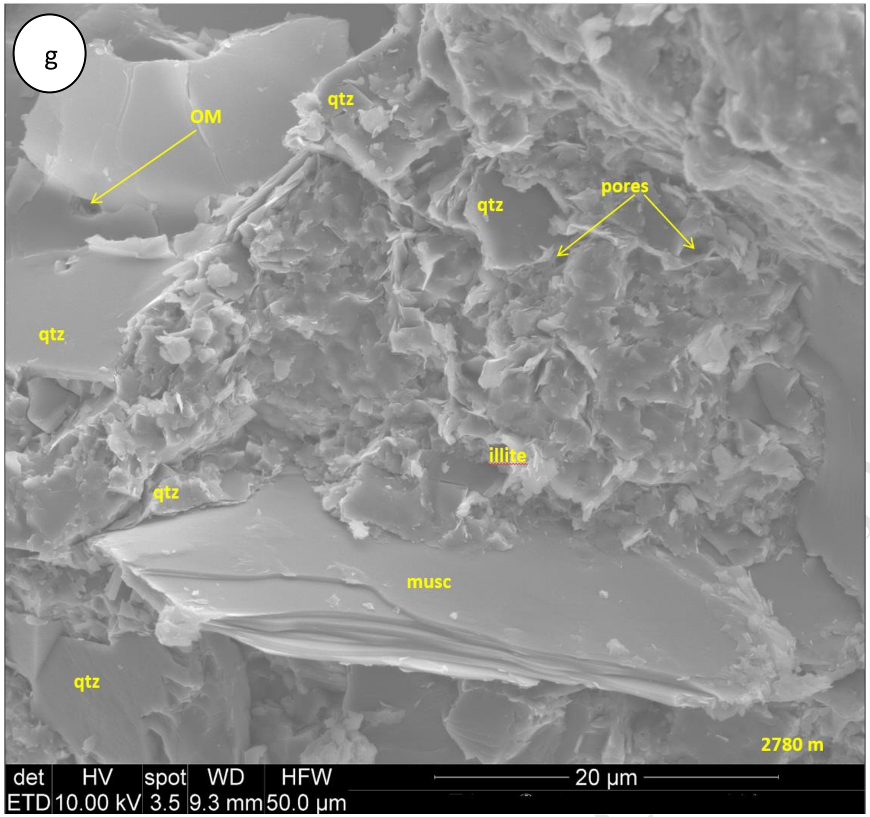
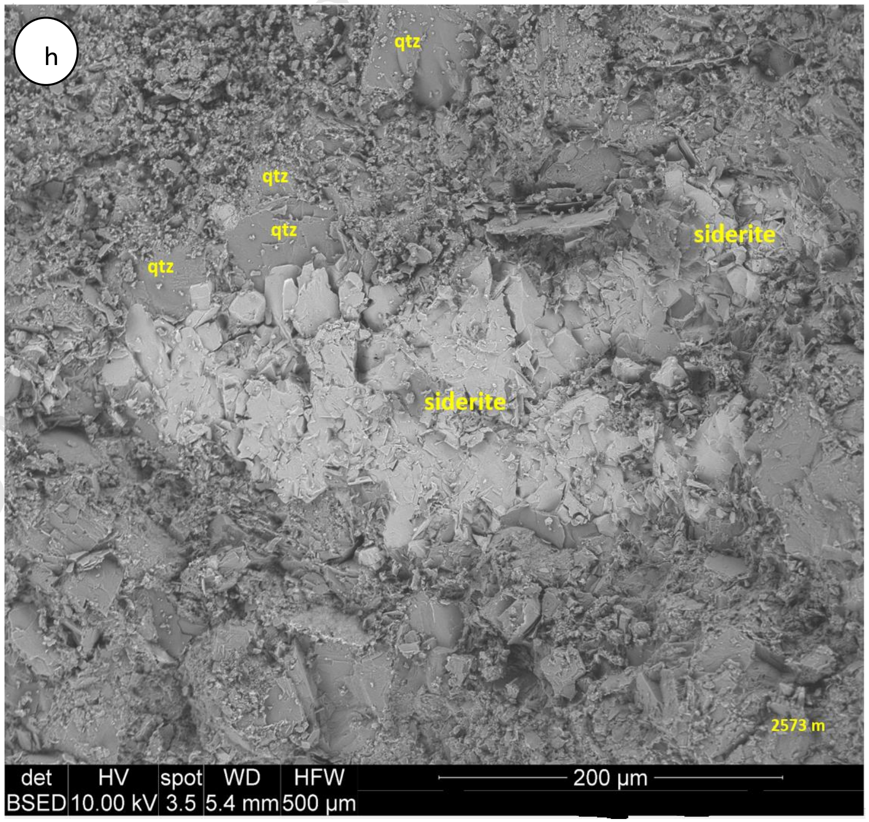
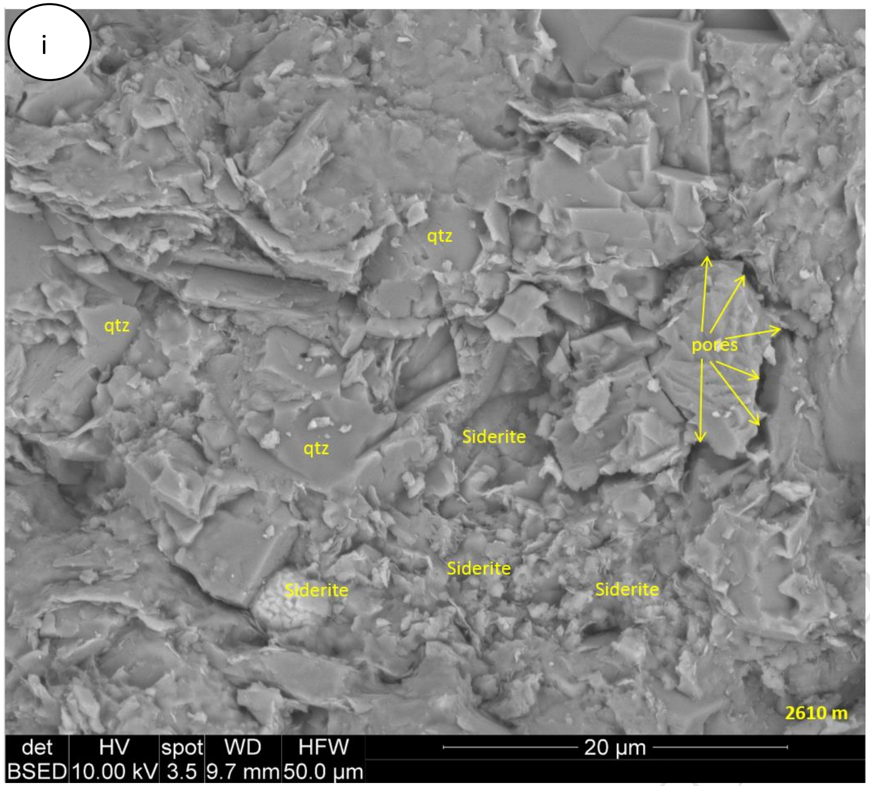


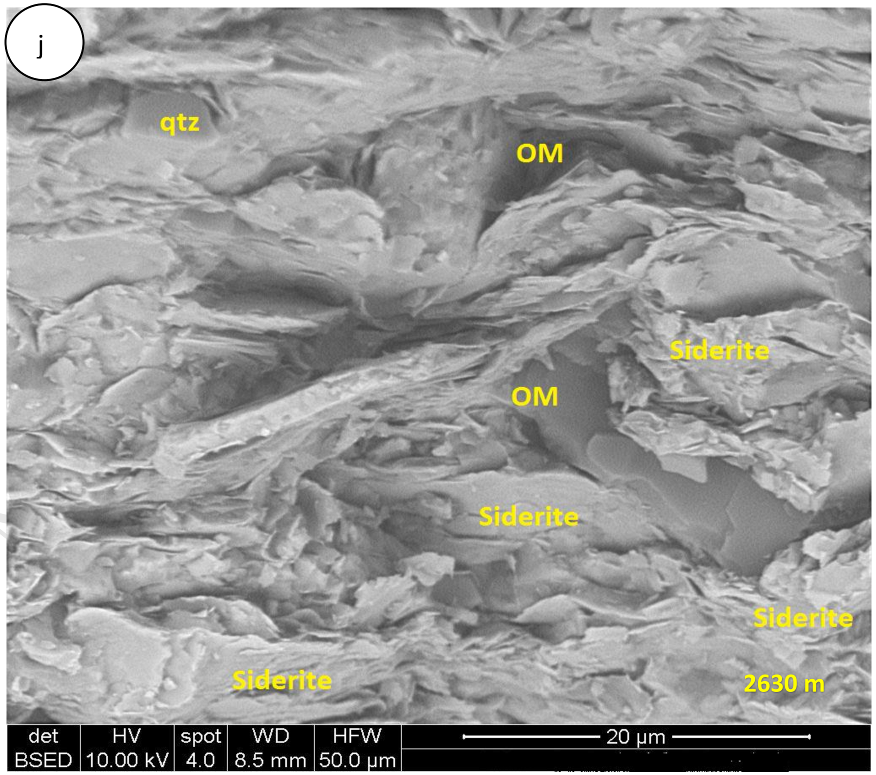
Figure 3: Roseneath Shale: a) Domains of randomly oriented clay minerals with scattered quartz grains and mica flakes. **b**) Siderite domain showing characteristics texture, with intergranular pores. **c)** Siderite domain showing ragged grain outlines, with associated porespace, suggestive of some dissolution. **d)** Randomly oriented clay crystallites forming a matrix to scatter quartz grains and dolomite rhombs. **e)** Blady Mn Siderite cement with very fine intergranular pores and quartz.**f)** Clay flakes with illite morphology as matrix to organic fragments, quartz and muscovite grains.

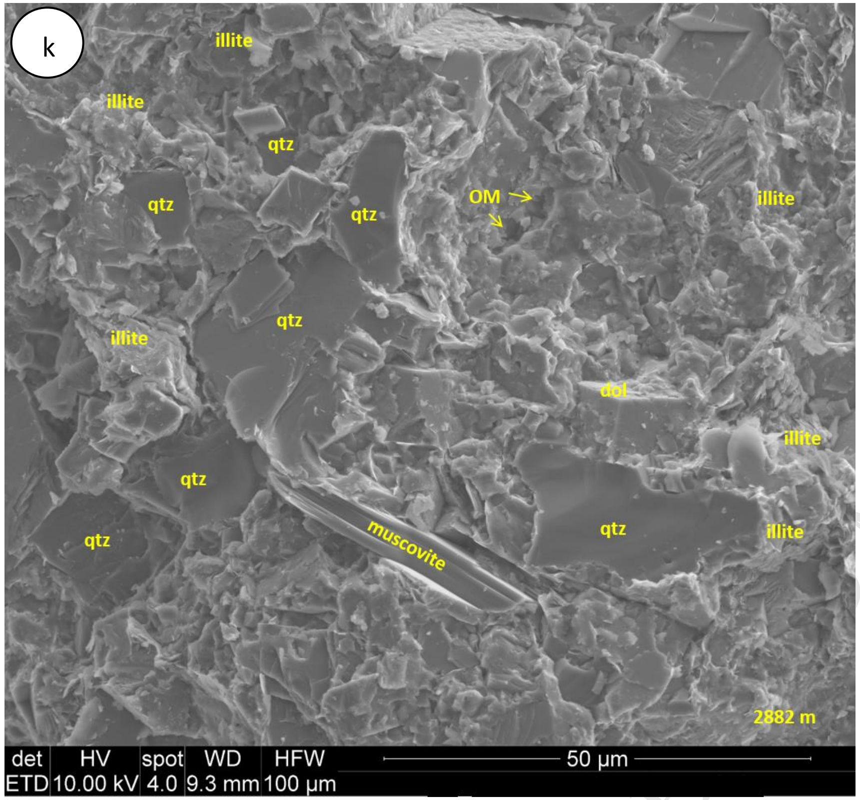
Murteree Shale

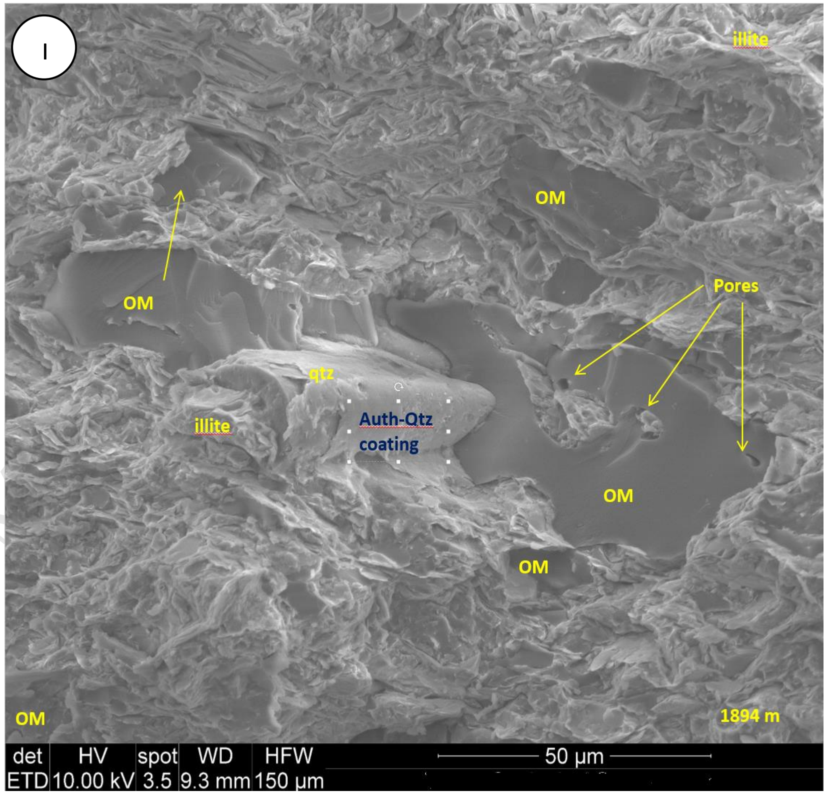





i
qtz
qtz
qtz
pores
Siderite
Siderite
Siderite
Siderite
2610 m
det HV spot WD HFW
BSED 10.00 kV 3.5 9.7 mm 50.0 µm
20 µm


j
qtz
OM
OM
Siderite
Siderite
Siderite
Siderite
2630 m
det HV spot WD HFW
BSED 10.00 kV 4.0 8.5 mm 50.0 µm
20 µm





Murteree Shale g) Muscovite flake embedded in a clay-rich matrix, mostly illite showing some pore space **h**) Another example of light grey area showing siderite and dark areas within organic matter could represent micro pore **i)** Siderite showing characteristics of bladed crystal habit associate with micro pores and quartz **j)** Coarse grained siderite associated with grains of organic matter; intergranular pore space is prominent. **k)** Showing a typical shale texture with scattered quartz grains plus a muscovite in a clay matrix showing illite morphology. **l)** Larger grains of (OM)organic matter with organopores embedded in a clay-rich matrix; a quartz grain shows diagenetic overgrowth.

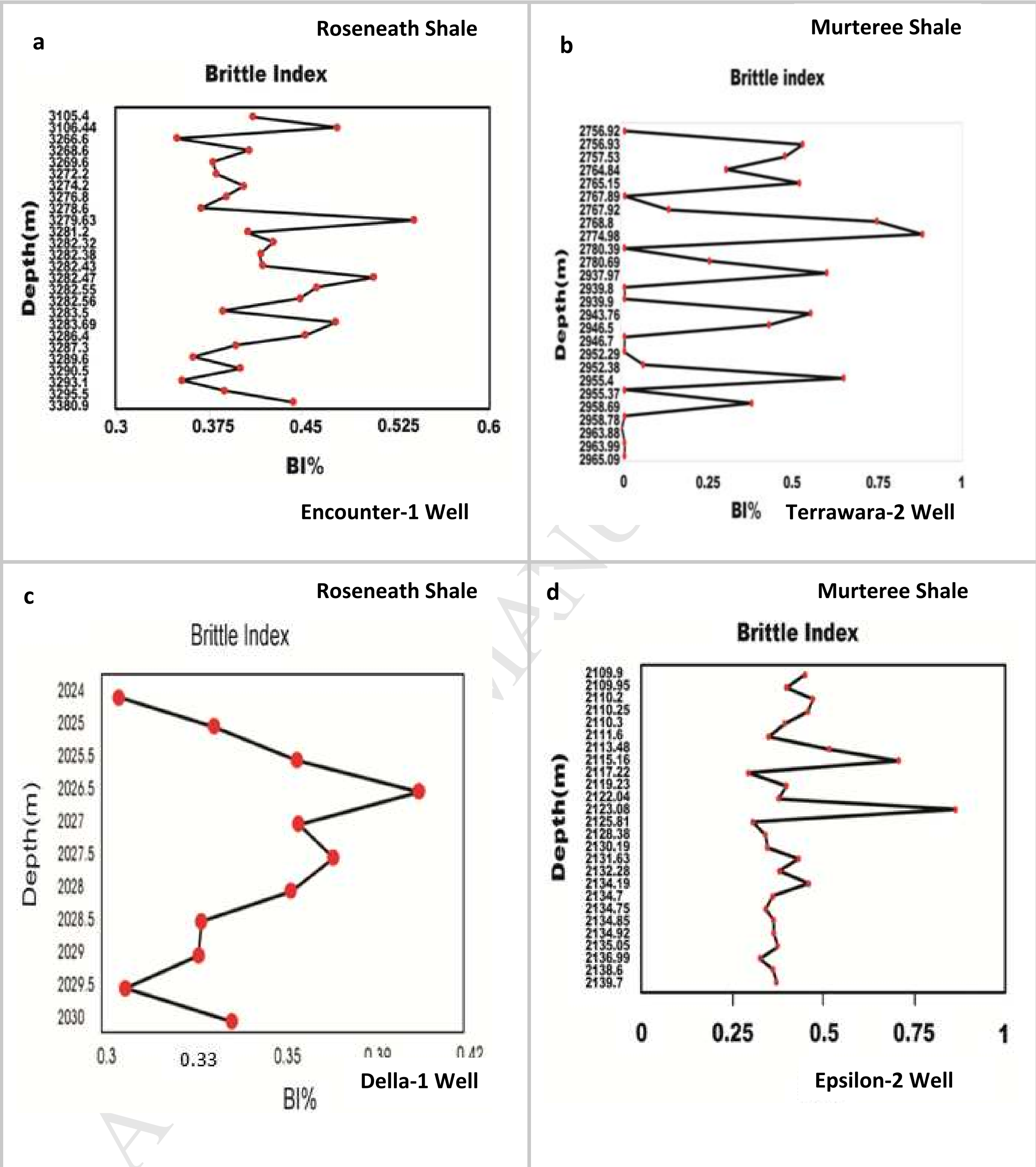
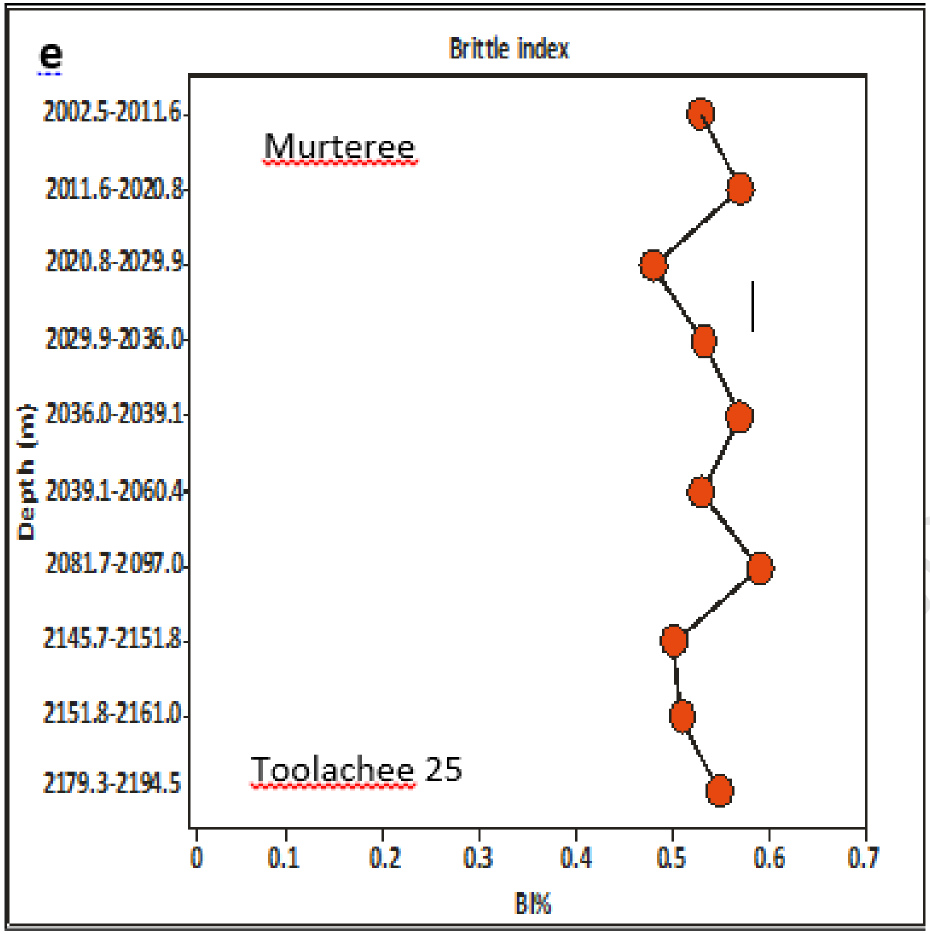
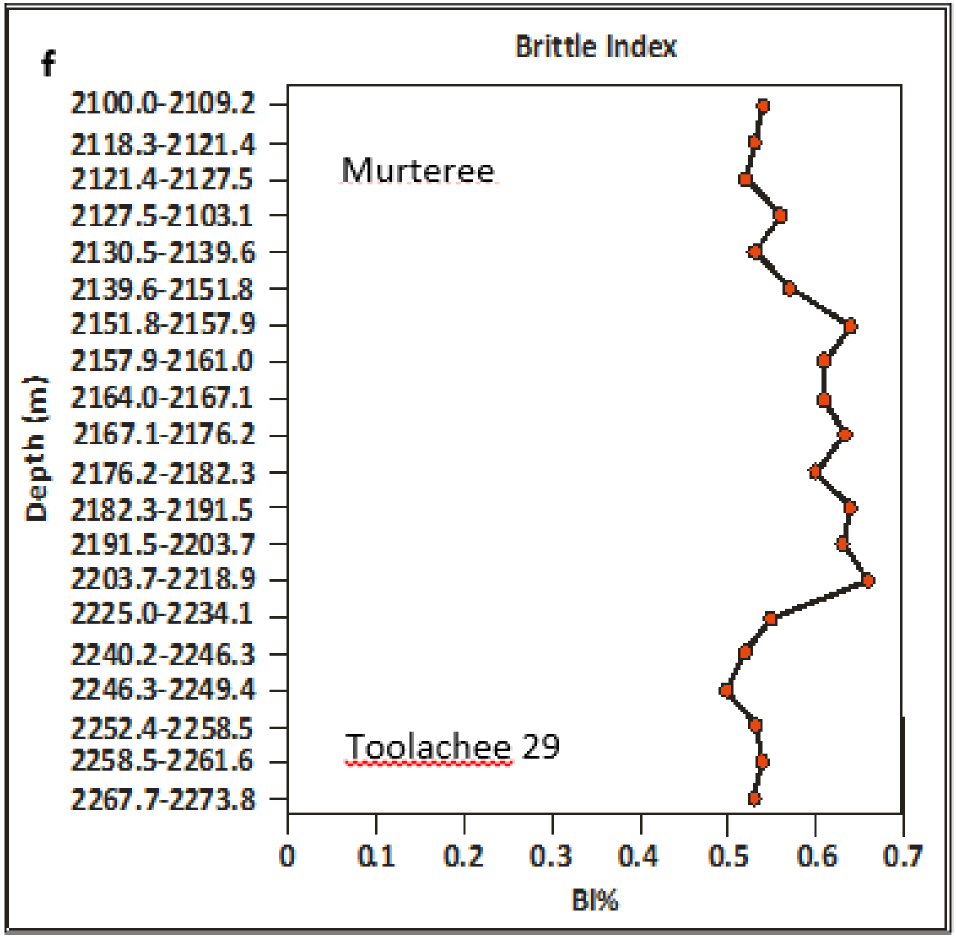
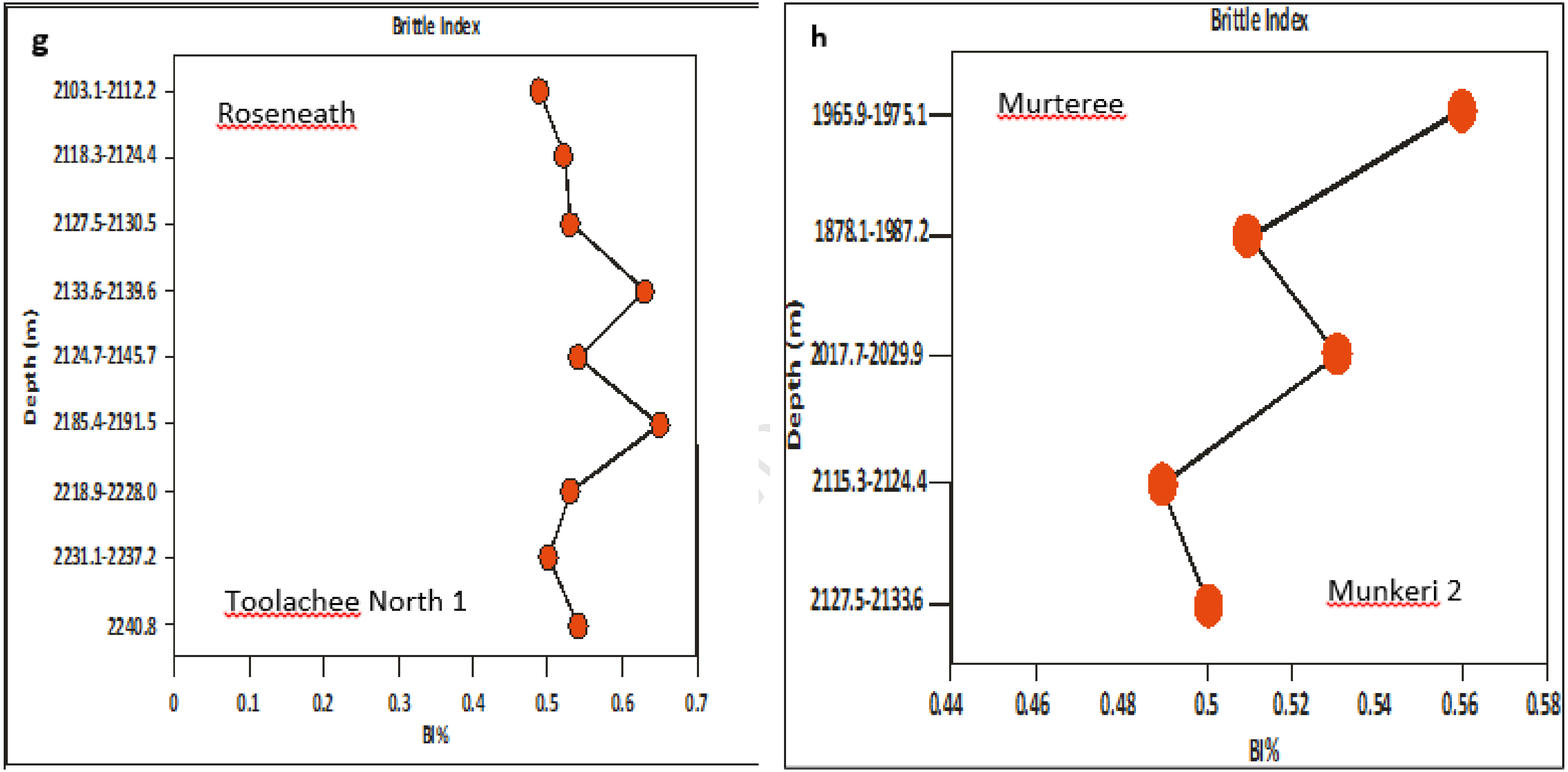


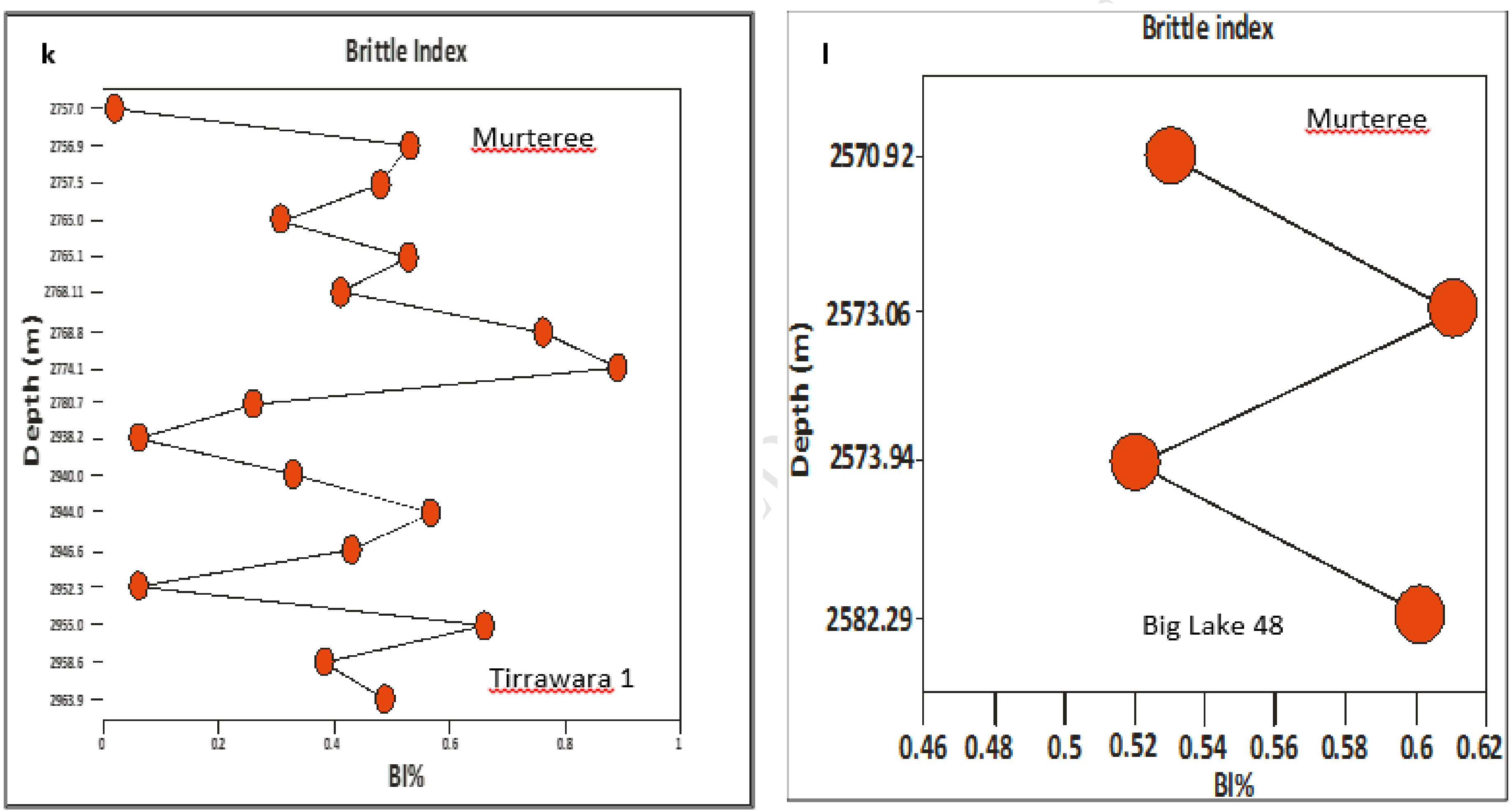
Figure 4: Examples of down hole variation in brittle index shown by the Roseneath and Murteree shales **a)** BI based on mineral composition of Roseneath Shale shows minimum brittleness **b)** shows minimum to maximum brittleness **c)** shows moderate brittleness **d)** maximum brittleness **e**) - **g**) moderate brittleness **h**)- **k**) shows minimum to maximum brittleness. **l**) shows minimum to moderate brittleness


e
Brittle index
Murteree
Toolachee 25
Depth (m)
2002.5-2011.6
2011.6-2020.8
2020.8-2029.9
2029.9-2036.0
2036.0-2039.1
2039.1-2060.4
2081.7-2097.0
2145.7-2151.8
2151.8-2161.0
2179.3-2194.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
BI%


f
Brittle Index
Murteree
Toolachee 29
Depth (m)
2100.0-2109.2
2118.3-2121.4
2121.4-2127.5
2127.5-2103.1
2130.5-2139.6
2139.6-2151.8
2151.8-2157.9
2157.9-2161.0
2164.0-2167.1
2167.1-2176.2
2176.2-2182.3
2182.3-2191.5
2191.5-2203.7
2203.7-2218.9
2225.0-2234.1
2240.2-2246.3
2246.3-2249.4
2252.4-2258.5
2258.5-2261.6
2267.7-2273.8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
BI%


g
Brittle Index
Roseneath
Toolachee North 1
Depth (m)
2103.1-2112.2
2118.3-2124.4
2127.5-2130.5
2133.6-2139.6
2124.7-2145.7
2185.4-2191.5
2218.9-2228.0
2231.1-2237.2
2240.8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
BI%
h
Brittle Index
Murteree
Munkeri 2
Depth (m)
1965.9-1975.1
1878.1-1987.2
2017.7-2029.9
2115.3-2124.4
2127.5-2133.6
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
BI%


i
Brittle Index
Roseneath
Yapeni 1
Depth (m)
1996.4-2005.5
2008.6-2020.8
2020.8-2026.9
2093.9-2100.0
2100.0-2109.2
2115.3-2121.4
2121.4-2024.1
0.5
0.55
0.6
0.65
0.7
BI%
j
Brittle Index
Murteree
Moomba 66
Depth (m)
2600.7
2601.8
2603.7
2606.0
2608.4
2612.3
2613.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


k
Brittle Index
Murteree
Tirrawara 1
Depth (m)
2757.0
2756.9
2757.5
2766.0
2766.1
2768.11
2768.8
2774.1
2780.7
2938.2
2940.0
2944.0
2946.6
2952.3
2955.0
2958.6
2963.9
0
0.2
0.4
0.6
0.8
1
BI%
l
Brittle index
Murteree
Big Lake 48
Depth (m)
2570.92
2573.06
2573.94
2582.29
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
BI%

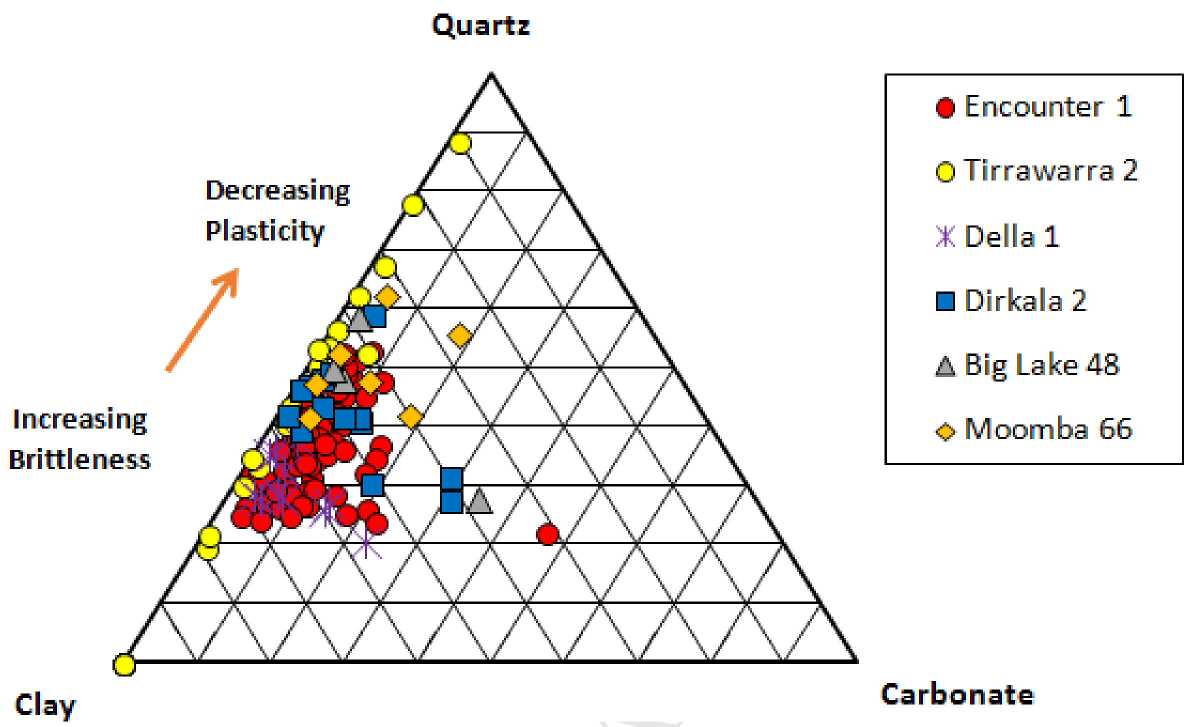


Figure 6: Quartz, Clay and Carbonate proportions for the Murteree Shale sampled from several wells in Cooper Basin South Australia

Plasticity	Range of Liquid Limit
Low plasticity	<35
Intermediate palsticity	35-50
High plasticity	50-70
Very High plasticity	70-90
Extra High Plasticity	>90

Table 4: Plasticity according to liquid limit (Bell, 2007)

.

Shale	Plasticity	Range of Liquid Limit	Plastic Index
Roseneath	Low - Intermediate	22-42%	6- 25.5%
Murteree	Low -intermediate	22-45%	5- 24%

Table 5: Classification of the plasticity of the shale samples.

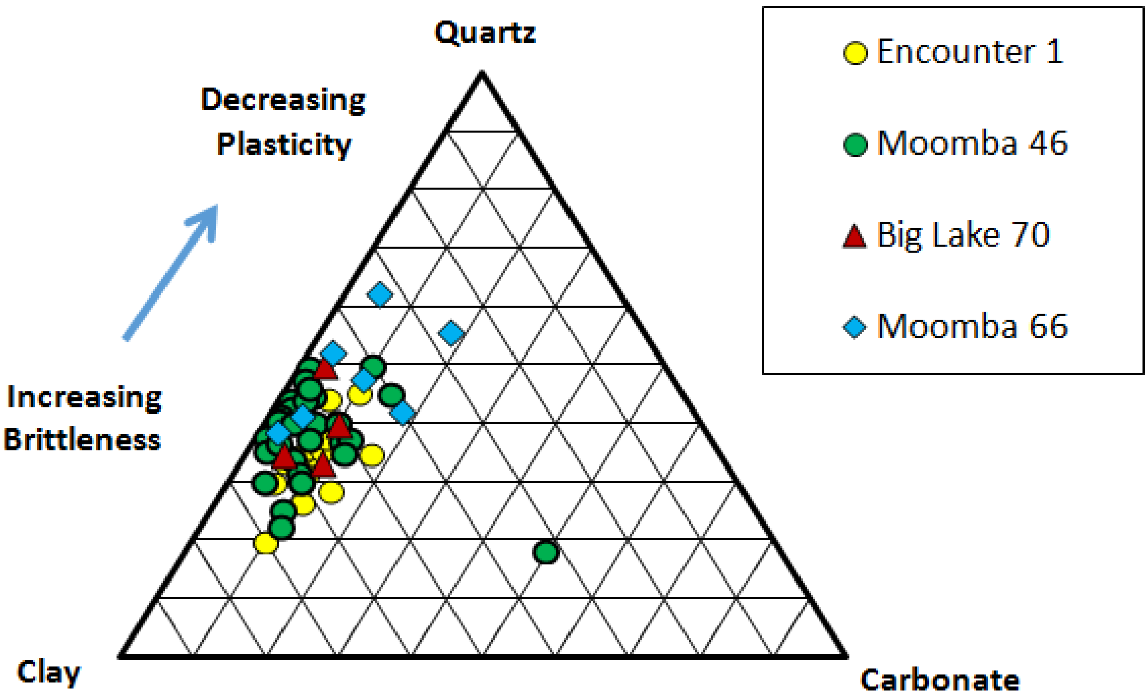


Figure 7: Quartz, Clay and Carbonate proportions for the Roseneath shale sampled from several wells in Cooper Basin South Australia

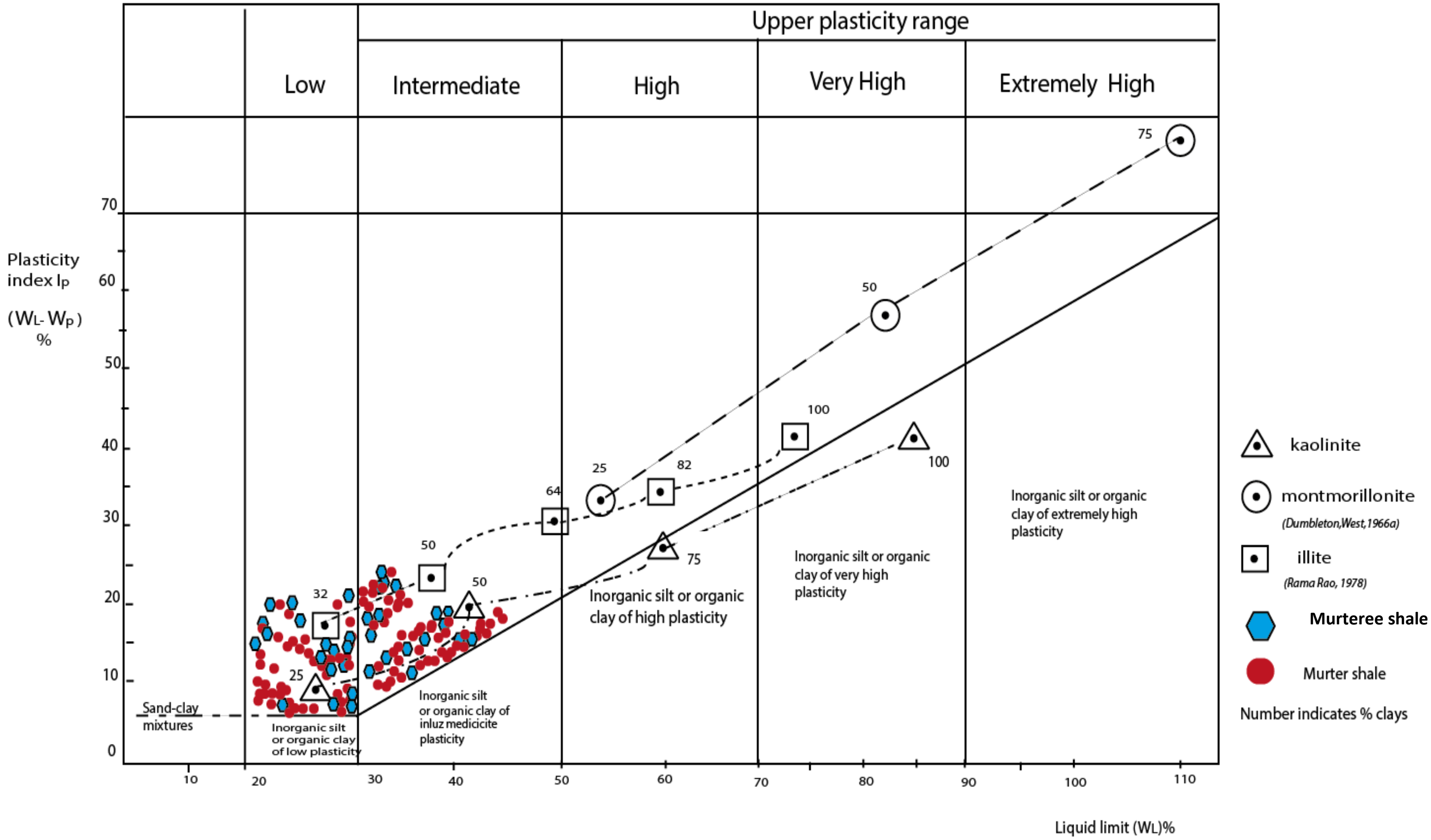


Figure 8: Plot of plasticity index against clay content (modified from Casagrande (1932) by (Reeves and Cripp (2006), showing the behavior inferred for the Roseneath and Murteree shales. On the basis of XRD data Plasticity Chart shows low to intermediate plastic behavior. Note that clay type is also an influence with trends as shown.

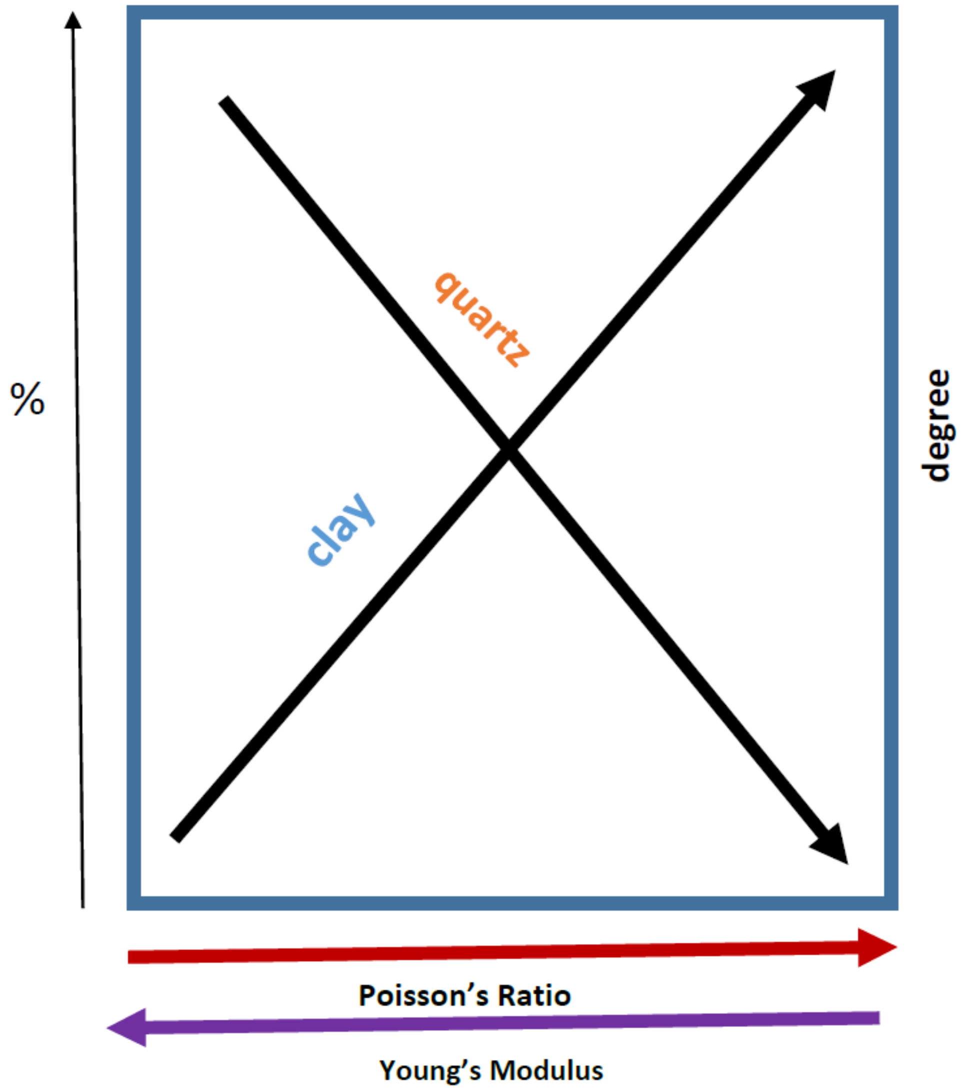


Figure 9: Mineralogical composition show brittle or plastic depending the properties of quartz and clay %. Young Modulus and Possion ratios are shown in this figure. (Bustin et al., 2006).

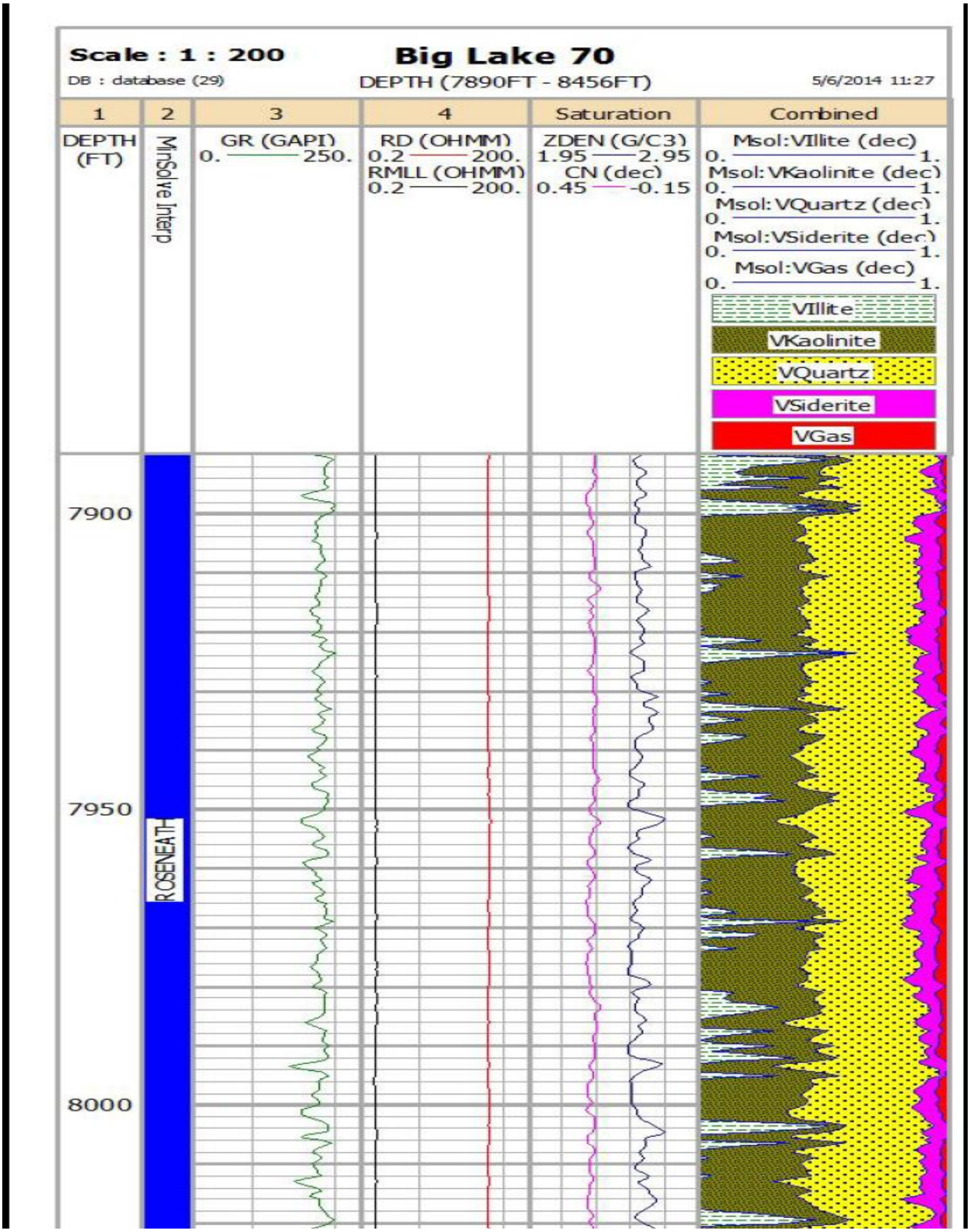


Figure 10: Petrophysical model shows Roseneath Shale in Big Lake 70 well the clay mineralogy indicate examples of plastic to brittle zones distributed through the shale intersection.

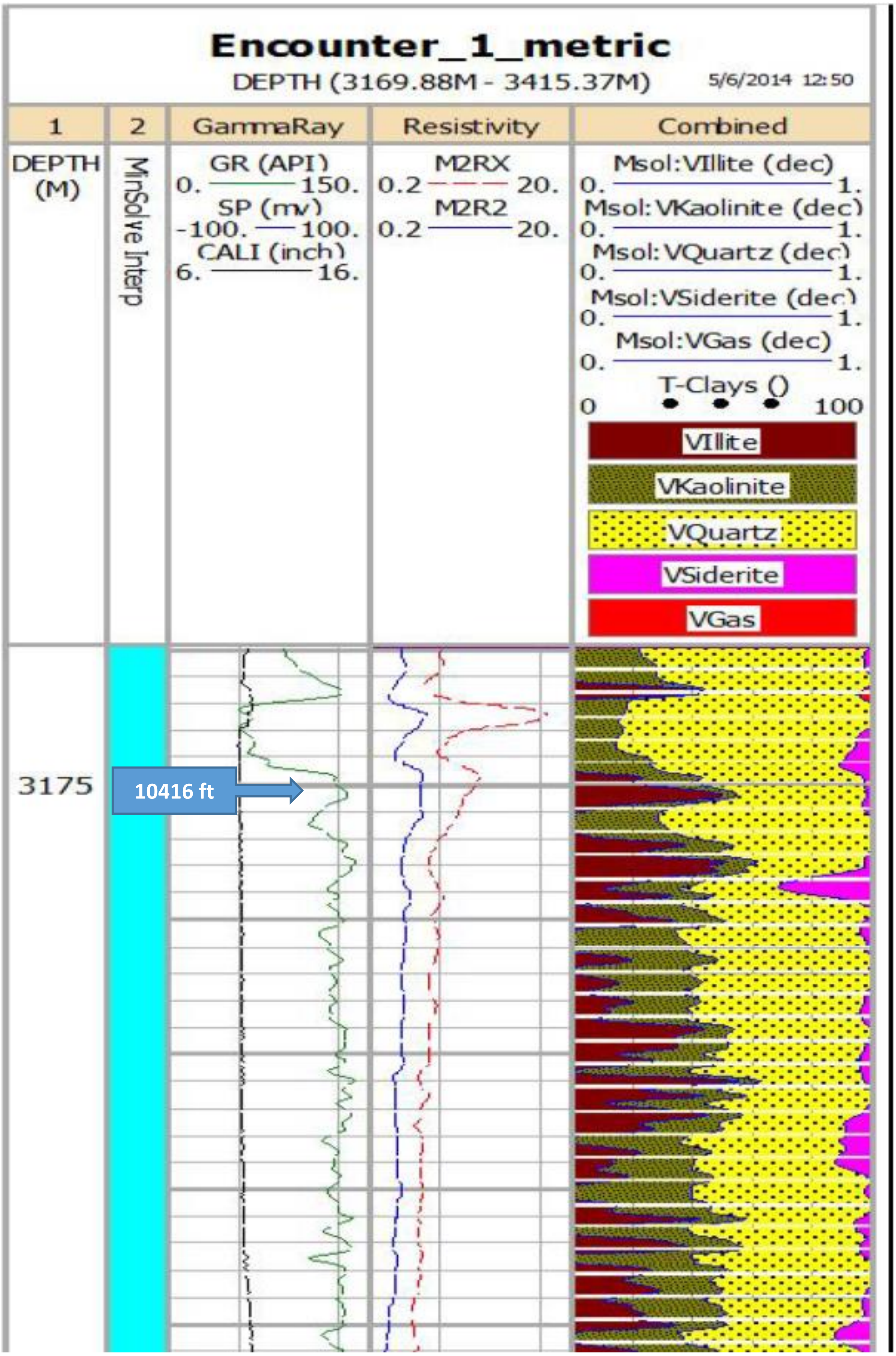


Figure 11: Petrophysical model shows Encounter-1 well Roseneath Shale quartz rich and clay mineral composition indicating brittle and plastic zones distributed through the shale intersection.

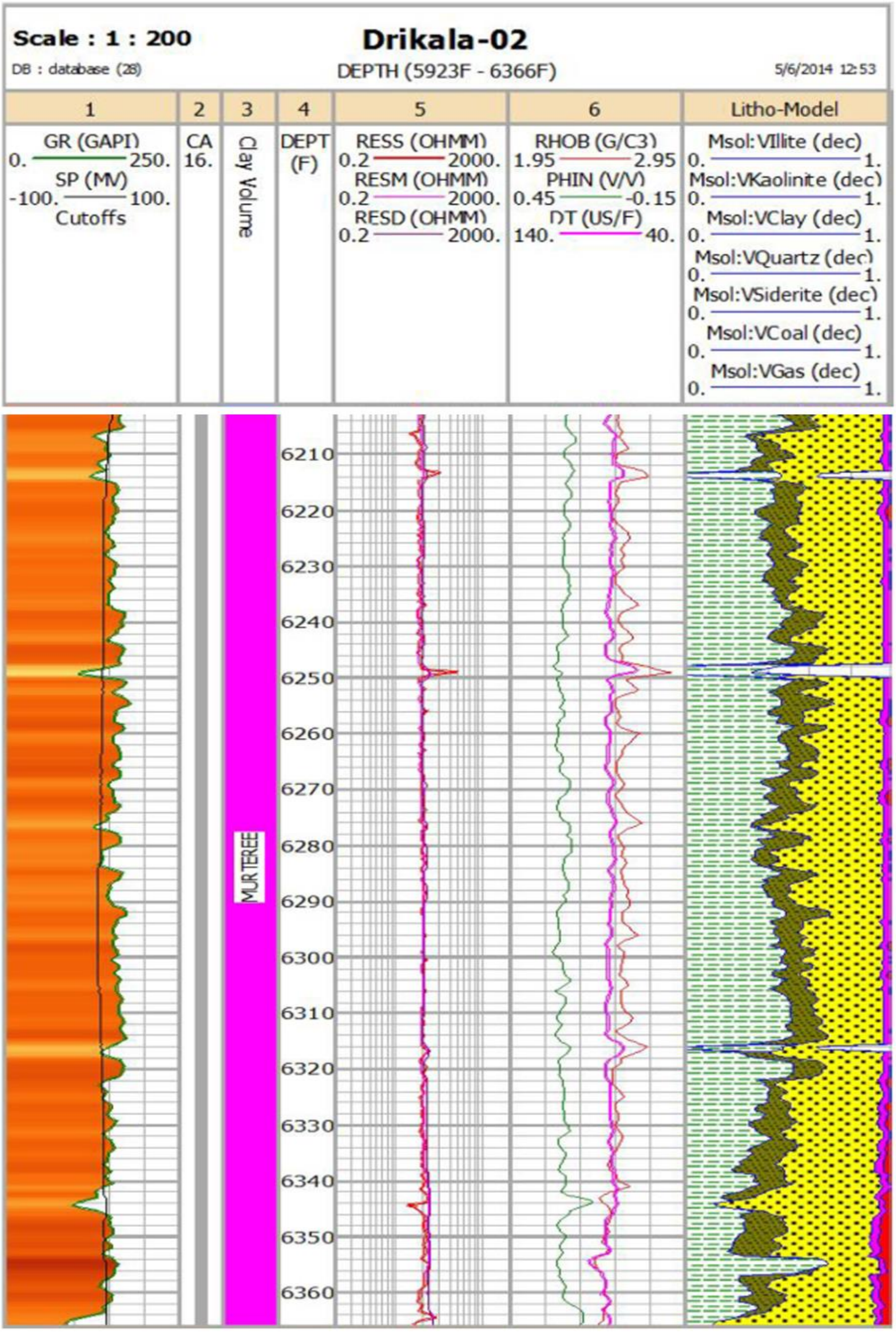


Figure 12: Petrophysical model wireline log shows quartz and siderite rich exhibit brittle zone in Murteree Shale in Dirkala-2 well distributed through the shale intersection.

Shale	Basin	Age	Basin type	TOC	BI%	Depth	Mineral composition
Barnett	Fort Worth	Mississippian	Foreland	1-10%	<1	2000 -2800 m	35–50% quartz, 27% illite with minor smectite, 8–19% calcite and dolomite, 7% feldspars, 5% organic matter, 5% pyrite, 3% siderite, and traces of native copper and phosphate material
Marcellus Shale	Appalachian	Devonian	Foreland	2-6%	<1	1500 -2500 m	27–31% quartz, 9–34% illite, 1–7% mixed- layer clays, 0–4% chlorite, 3–48% calcite, 0–10% dolomite, 0–4% sodium feldspar, 5–13% pyrite, and 0–6% gypsum.
Eagle Ford	East Texas	Late -Cretaceous	Passive margin	2-12%	<1	1200 - 4250 m	47% calcite, 11%quartz,3% pyrite, 25% illite, 17% kaolinite, 14% Albite, 3% dolomite, 19%muscovite.
Roseneath	Cooper	Permo-Triassic	Intracratonic	2- 30%	<1	1600 - 2000 m	30-50% quartz, 10-25% siderite, 1% rutile, 20-50% mica/illite, 15% kaolinite
Murteree	Cooper	Permo-Triassic	Intracratonic	2-6%	<1	1800 -2200 m	30-55% quartz, 10-25% siderite, 1% rutile, 20-45% mica/illite, 15% kaolinite

Table 6: Generalized mineralogy of gas producing American gas shales compared to the Roseneath and Murteree shales.

- This study is to evaluate the brittleness and plasticity of Roseneath and Murteree shales.
- It is better understand the hydraulic fracturing potential of these two highly prospective shale units in the Cooper Basin for Unconventional shale gas exploration.
- Clay minerals content strongly influences brittleness and the capacity of rocks to naturally fracture or to be artificially induced to form fracture networks, which are conducive to shale gas extraction.
- The higher quartz and siderite content in shale suggests the most favourable to hydraulic fracturing.