LITHOFACIES AND SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE KOCKATEA SHALE, DANDARAGAN TROUGH, PERTH BASIN

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ABSTRACT

Initial studies affirm large-scale shale-gas potential for the Permo-Triassic intervals of the Perth Basin. The Dandaragan Trough, as a major depocentre in the basin and with the highest number of wells intersecting these intervals, has possibly the greatest shale-gas potential in the area. The primary self-contained shale-gas system proposed for the Dandaragan Trough is in the basal Kockatea Shale (Hovea Member), which was deposited during the Late Permian-Early Triassic. Seven lithofacies have been identified in a continuous 35 m core from the Hovea Member of the Kockatea Shale at Redback–2. Among recognised lithofacies, besides siliceous mudstone, which contains clastic particles, most are representative of deposition in a shallow marine environment with different energy levels. Bioturbated lithofacies reveal deposition in a higher-energy environment compared with the other lithofacies. The sequence stratigraphic framework of the Hovea Member is established based on diagnosis of the lithofacies, cyclical stacking patterns, transgressive surfaces of erosion (TSE), and condensed sections (CSs). The framework supports deposition mainly in an aqueous environment with rare regressions. Periodic tectonic activity can be revealed in high-frequency relative sea-level changes during Hovea Member deposition. Gamma ray (GR) log analysis indicates that the highest GR peak is related to black-shale lithofacies with 1.75% TOC content. The greatest amounts of TOC, however, exist in the fossiliferous mudstone and pyritic mudstone lithofacies. A north–south GR correlation of the Hovea Member shows nearly the same lithological distribution throughout the trough despite its thinning in various areas.

KEYWORDS

Dandaragan Trough, shale gas, Kockatea Shale, Hovea Member, thin-section petrography, scanning electron microscopy (SEM), core sample, lithofacies, stratigraphic framework, Early Triassic interval, depositional environment, strata stacking patterns, gamma-ray parasequences, gamma-ray patterns, relative sea-level changes, sequence boundary, condensed section, transgressive surface of erosion, transgression event (TR), regression event (RE), lithological variation, heterogeneity, total organic carbon (TOC), pyritic mudstone, black shale, siliceous mudstone, siliceous calcareous mudstone, calcareous mudstone, fossiliferous mudstone, bioturbated mudstone.

INTRODUCTION

Shale is considered a mudstone in sedimentary classification systems and is easily distinguished from other mudstones with its fissile and laminated attributes (Zahid et al, 2007). Due to having a high percentage of clay minerals, shale has very low matrix permeability. This characteristic, however, makes shale an ideal self-contained source-reservoir system with both conventional and unconventional reserves (Talukdar, 2008). Shale-gas systems as a new source of energy have grown globally during the past decades. In the US, natural-gas production from shale has increased dramatically from 1% of total gas production in 2000 to 20% in 2012 (Stevens, 2012), and is assumed to exert great influence on the worldwide gas market structure (James A. Baker III Institute for Public Policy, Rice University, 2011) by adding diversity to the energy mix and raising fuel supply flexibility (Freeland, 2011). These types of reservoirs are increasingly considered to be promising because their excellent production rate leads to them being assessed to be technically recoverable reserves (US Energy Information Administration, 2011). Being continuous (Shirley, 2001), deposited across wide areas, and the longevity of shale gas offers strong reasons for studying these reservoirs. Discovering shale reservoirs is, nevertheless, challenging since each reservoir has substantial differences in reservoir quality and production outcome. Lithological variation caused by sedimentology, diagenesis, and structural history control these differences (Bustin et al, 2008; Evdokimov et al, 2006). Complexity in quantifying shale reservoirs, because of local heterogeneity, is another difficulty in these reservoirs. Defining the geological properties of shale-gas reservoirs is considered one of the most challenging studies concerning the unique characterisation for each reservoir. To assist in determining these properties, core observation is used to obtain a preliminary assessment of lithofacies, depositional processes, and regional variability of vertical facies.

Winning (2012) believes shale-gas exploration can double natural-gas resources in Australia and convert the country into the world's largest natural-gas store. Exploration for such resources, however, is still in its infancy (Bradshaw and Hall, 2012). Numerous geological and geochemical studies have been published (Thomas and Barber, 2004; Grice et al, 2005a) about the northern Perth Basin. The biomarker potential of the Permo-Triassic intervals of the basin was studied by Grice et al (2005b). Detailed geochemical and stratigraphic studies have been undertaken to identify the source rock distribution in the offshore northern Perth Basin (Grosjean et al, 2011; Jones et al, 2011). None of these studies, however, have been conducted with the aim of shale-gas prospectivity evaluation.

As there are a limited number of wells drilled with the purpose of evaluating shale-gas potential, the sequence stratigraphic framework of the Hovea Member in this study is based on its cored intervals at Redback–2. Despite studying and correlating the sequence stratigraphic framework in a limited number of wells, the study reveals a detailed sequence stratigraphic framework for the Hovea Member in the Dandaragan Trough (Fig. 1). Thomas and Barber (2004) also present detailed analysis of the lithofacies and source rock potential of the Hovea Member of the Kockatea Shale based on continuous core, cuttings, and side-wall core (SWC) at Hovea–1, –2 and –3 wells, as well as correlations with wells/fields included in the present study.

This paper presents the results of lithofacies and sequence stratigraphic analysis of a continuous 35 m core from the Hovea Member of the Kockatea Shale at Redback–2 in the Dandaragan Trough (Fig. 1). The aims of this study were to:

1) identify different lithofacies through studying cores, petrographical, mineralogical, and geochemical analyses;
2) determine and correlate gamma ray parasequences (GRPS); and,
3) establish a sequence stratigraphic framework for the target shale-gas reservoir in the Dandaragan Trough.

REGIONAL GEOLOGY

The Perth Basin is a deep, elongate, north–south trending trough, which extends about 100,000 km along the WA margin from Geraldton in the north to Augusta in the south (Eyles et al, 2006), and covers 45,000 km² onshore and 55,000 km² offshore. The basin is separated from the Carnarvon Basin in the north by the Northampton Block (Rabnawaz, 2009). The eastern margin is delimited by the north-to-south-trending Darling Fault, which has more than 15 km of lateral movement on the western, downthrown side (Jones, 1976). Structurally, the basin is a complex rift-sag with two main tectonic phases: a southwesterly Permian extension; and, a northwesterly Early Cretaceous transtension during break-up. Dextral and sinistral movements are identified during these phases along the Darling Fault. The basin is divided by basement-related regional faults that were frequently reactivated by subsequent tectonic events creating wrench-induced anticlines, horizontal displacements, and further faults (Crostella, 1995). The main depocentres of the basin consist of the Dandaragan Trough in the onshore northern Perth Basin, the Houtman/Abrolhos sub-basins in the northern offshore, the Bunbury Trough in the onshore southern Perth Basin, and the Vlaming Sub-basin in the offshore part of the basin (Bradshaw et al, 2000). The Dandaragan Trough, as a main depocentre contiguous to the Darling Fault, and containing over 15,000 m of Silurian to Cretaceous sediments deposited in its half-graben structure, has attracted the most attention. The trough is formed by rifting during the Early Permian and Neocomian as part of the final separation phase of Australia and India. Towards the south and west, the Dandaragan Trough is flanked by two shallow basement features of the Harvey Ridge and the Beagle Ridge. The Bunbury Trough is separated from the Dandaragan Trough by oblique extension of the Harvey Ridge. To the south, the deep graben shallows to 1,000 m of Permian to Cretaceous deposition (Playford et al, 1976). During the Early Permian and Early Cretaceous, continuous intracratonic sedimentation occurred in the onshore northern Perth Basin but with local discontinuities (Crostella, 1995). The signature of high marine extinction at the Permo-Triassic boundary (Erwin et al, 2002; Benton, 2003) raises the possibility of high hydrocarbon potential in the period (Thomas et al, 2004). Initial studies on the Perth Basin confirm shale-gas potential in the Permo-Triassic intervals of the basin, especially in the northern part. The Triassic Kockatea Shale thickly expanded above the northern Perth Basin, ranging from nearly 200 m in the north to almost 1,100 m on the Cadda Shelf. This thickness fluctuation is depositionally controlled in response of progressive onlap onto the Northampton Block and northern Beagle Ridge.

LITHOFACIES

As well as all the knowledge about physical properties of the reservoir at various scales, lithofacies identification is extremely important in distinguishing and correlating the shale reservoir's key features (Siripitayananon et al, 2001) including brittleness, depositional environment, TOC, and thermal maturity. The determination of gamma ray (GR) response for individual lithofacies in cored intervals, and comparing these patterns with GR logs in uncored wells, assists in recognising and correlating these lithofacies. Lithofacies can be initially identified based on visual core descriptions based on structure, texture and colour variability, all of which partly reflect changes in depositional environment and environmental energy. Thirty-five metres of continuous core from the Kockatea Shale was studied and this lead to a preliminary recognition of several distinct lithofacies. Some significant features in lithofacies such as condensed section (Fig. 2B), pyritic nodules, and streaks of various minerals (Figs 2A, 2C, and 2D) were also identified. To check the accuracy of the
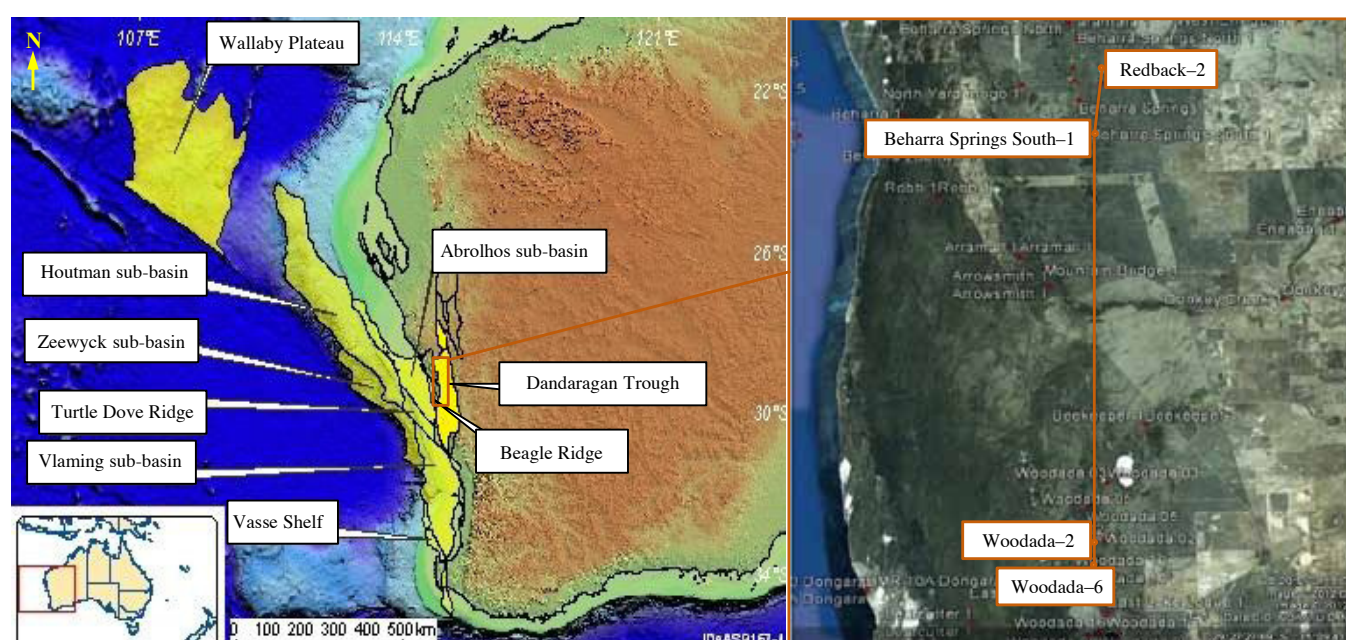

Figure 1. The location of the study area along with basin subdivisions (left; map modified from Geoscience Australia, 2012). Wells and transect location, Dandaragan Trough, Perth Basin (right).

identified lithofacies, cores were plugged in the area of distinctive lithofacies and were then examined with a microscope and analysed for mineralogical composition. Detailed core description of the shale layers, and analysing their petrographical and mineralogical aspects, determined seven lithofacies: fossiliferous mudstone; pyritic mudstone; siliceous calcareous mudstone; siliceous mudstone; calcareous mudstone; bioturbated mudstone; and, black shale.

The fossiliferous mudstone lithofacies is an important lithofacies in determining the depositional environment, and is pervasive for the Hovea Member. The lithofacies is brown with packed thin-walled brachiopods (Fig. 3A). Thin-section petrography shows brachiopod shells with clear signs of compaction, and alignment in the same direction (Fig. 3B). Rock-Eval analysis reveals a TOC value of <2 wt %. X-ray diffraction (XRD) analysis indicates high clay and carbonate content, which suggests abundance of carbonate in the fossils.

Pyritic mudstone refers to a pyrite-rich lithofacies with, usually, greenish-brown colour (Fig. 3C). The abundance of pyrite in this lithofacies is representative of reduced conditions during sedimentation that are considered to be a favourable condition for preserving organic matter in the rock. Petrographically, pyrite minerals can be detected by their rhombohedral crystal form. The framboidal pyrite can be clearly observed in the scanning electron microscopy (SEM) images (Fig. 3D). XRD analysis confirms the high pyrite content in this lithofacies. Geochemical analysis displays a TOC content of >4 wt % for this lithofacies, which shows preservation of organic matter.

The siliceous calcareous mudstone is mainly composed of a brownish-grey lithofacies (Fig. 3E). The lithofacies has both silica and carbonate components. Petrographical analysis shows a higher proportion of carbonate than silica, as carbonates are mixed with the matrix. A remarkable amount of calcite is confirmed by XRD analysis (Fig. 3F). High TOC values are estimated by Rock-Eval pyrolysis.

The siliceous mudstone refers to a moderately hard lithofacies, grey-black in colour with slight streaks of white crystalline calcite in some parts (Fig. 4A). There is a scarcity of silty and micaceous lithofacies with rare pyrite. Petrographical analysis of minerals in thin sections displays a high prevalence of quartz and clays with rare biotite in the matrix. There are no fossils (Fig. 4B). Organic richness of the lithofacies is confirmed with 2.2 wt % TOC. XRD analysis demonstrates the presence of quartz, mixed-layers of illite/smectite, chlorite, and pyrite. The proportion of quartz is considerably high with 50 wt %.

The calcareous mudstone is a compound of clay minerals and calcite, with a negligible amount of quartz (Fig. 4C). This facies has a strong reaction with hydrochloric acid. The SEM images do not display any distinctive features (Fig. 4D). As expected, calcite is confirmed by XRD analysis as having the highest proportion of this lithofacies. 2.5 wt % TOC is estimated in the lithofacies.

Bioturbated mudstone is a massive, grey, and bioturbated facies (Fig. 4E). Both petrographic and SEM images do not reveal any distinctive elements for the bioturbated mudstone. X-ray analysis shows relatively high quartz content along with clays. Rock-Eval pyrolysis indicates moderately high organic matter.

The black shale is a massive black mudstone (Fig. 4F), which represents sedimentation in a quiet, low-energy environment. The dark colour and high amount of organic matter in this lithofacies demonstrates an anaerobic condition during deposition. Thin-section petrography of the black shale displays a dark matrix with a high amount of organic matter (Fig. 4G). SEM shows the dispersion of clay minerals in the lithofacies (Fig. 4H). XRD and Rock-Eval analysis confirm the high clay proportion with a remarkable amount of organic matter.

SEQUENCE STRATIGRAPHY INTERPRETATION

The interaction between habitation space and sediment supply refers to a sequence stratigraphy where eustatic sea-level change and tectonic subsidence intensely affects the habitat (Singh, 2008). The study of sequence stratigraphy based on GR log patterns associated with the identification of stratal stacking patterns helps with the recognition of a general sequence stratigraphic framework across the basin. There is, however, negligible understanding of this framework in fine-grained rocks (Bohacs, 1998). Sediment supply characteristics are the most effective way to establish the sequence stratigraphic framework in these types of rocks (Singh, 2008). Stratigraphic interpretation can be based on the depositional environment of the lithofacies and their occasional changes as evidenced by lithofacies stacking patterns (Bohacs and Schwalbach, 1992). Establishing a sequence stratigraphic framework for the deposition of the Hovea Member of the Kockatea Shale is the purpose of this study.

The Kockatea Shale was deposited during the Griesbachian age (251 ± 0.4–250.4 Ma; Hallam and Wignall, 1999). According to the various types of lithofacies stacking patterns recognised by Singh et al (2009), key stratigraphic surfaces—such as transgressive surfaces of erosion (TSE) and flooding surfaces (FS)—were identified in the stratigraphic interval along with sequential sea-level change events, which formed with a transgressive event (TR) and a regression event (RE). Five stratigraphic intervals containing complete or partial cycles of the TR and REs were determined from the GR log in the Hovea Member of Kockatea Shale at Redback–2.

Figure 2. Core photographs displaying various structures and significant surfaces. (A) Fracture filled with calcite (3,798.30–3,798.54 m). (B) Condensed section, a thin fossiliferous layer (white arrows) between pyritic mudstone lithofacies (3,798.84–3,799.09 m). (C) Fracture filled with calcite but not completely creating a natural fracture (white arrows) in the lithofacies (3,789.03–3,789.14 m). (D) Fracture filled with calcite but with no creation of natural fracture (3,790.21–3,790.30 m).

Stratigraphic intervals of Hovea Member, Kockatea Shale

STRATIGRAPHIC INTERVAL 1 (3,835.8−3,826.0 M)

This interval expresses the earliest transgression and regression sedimentation in the member, and contains two GR patterns (GRPs)—GRP-TR1 and GRP-RE—with an upward increasing GRPS and an upward decreasing GRPS, respectively (Fig. 5). The boundary between the two GRPS intervals is a distinct flooding surface (FS1), which demonstrates a lithofacies's change related to deposition in different environments. The interval composes mostly pyritic and calcareous mudstone coupled with fossiliferous and bioturbated layers. Since there is not any calcite in the pyritic mudstone lithofacies, the high presence of this lithofacies at GRP-RE1 can be explained by the relative sea level undergoing a slow fall with an equal rate of eustatic fall and subsidence. The TOC value decreases in the siliceous lithofacies compared to the pyritic mudstone.

STRATIGRAPHIC INTERVAL 2 (3,826.0−3,808.3 M)

There is no distinct lithofacies change at the boundary between interval 1 and interval 2, but it can be distinguished with a slight rise in sea-level change. The sea-level rise can be confirmed by the lithofacies's change from pyritic mudstone to black shale. Similar to interval 1, this interval also contains two GRPs—GRP-TR2 and GRP-RE2. The difference is that GRP-TR2 consists of two upward increasing GRPs instead of just one. The black-shale lithofacies is associated with the highest GR readings (Fig. 5). The contact surface between GRP-TR2 and GRP-RE2 is another flooding surface—FS2. It is difficult to distinguish the TSE at the base of the interval 2, as there are no changes in lithofacies; TOC values of the interval are not high in comparison with adjacent stratigraphic intervals.

STRATIGRAPHIC INTERVAL 3 (3,808.3−3,800.3 M)

The base of this interval is a TSE with a sharp decrease in the GR log response and the presence of the siliceous mudstone lithofacies (Fig. 5). In TR3, there are two GRPs of upward increasing GRPS, and an interval of constant GRPS. The upward increasing GRPS is composed of pyritic mudstone, black shale, and fossiliferous mudstone, while the constant GRPS is mostly fossiliferous mudstone. Similarly, GRP-RE3 is represented by the fossiliferous lithofacies; the low GR response in this lithofacies might be due to its high carbonate content. XRD results estimate 9.7% calcite for this lithofacies. The TOC curve displays high amounts of TOC in the interval.

STRATIGRAPHIC INTERVAL 4 (3,800.3−3,794.8 M)

The interval starts with a slow rise in relative sea level. The TR4 in the interval is represented by fossiliferous mudstone at the base, and continues with pyritic mudstone and a repeat of the fossiliferous mudstone. The high amount of TOC in this interval is confirmed by the presence of phosphatic fossils (3,798 m). RE4 also consists of fossiliferous mudstone. The difference in the GR response can be described by the different compositions of the various fossils. As there is no change between the lithofacies at the boundary between GRP-TR4 and GRP-RE4, the possibility of the presence of a FS at this boundary is unlikely.

STRATIGRAPHIC INTERVAL 5 (3,794.8−3,787.9 M)

This interval is composed of GRP-TR5 with the interval consisting of constant GR. The fossiliferous mudstone covers the whole interval.

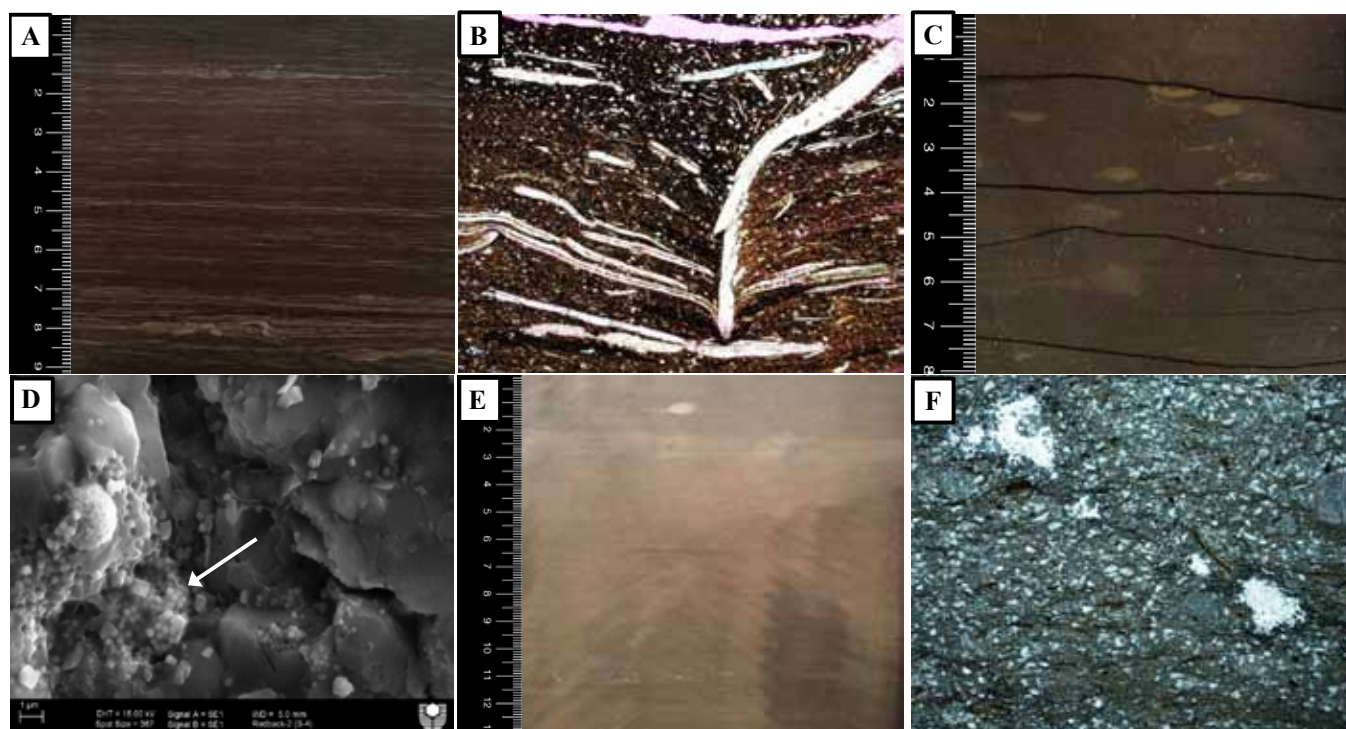Apart from an organic-richness measurement by TOC content, relative hydrocarbon potential (RHP; S1+S2/TOC)

Figure 3. Core photographs of lithofacies. Fossiliferous mudstone lithofacies (A−B): (A) thin-walled compacted brachiopods (3,794.81−3,794.90 m); and, (B) thin-section photomicrograph displays compaction bending fossils towards a distinct direction due to pressure, crossed polarized light at a low magnification of 2.5x (3,794.60 m). Pyritic mudstone lithofacies (C−D): (C) pyritic mudstone with a greenish-brown colour (3,805.60−3,805.68 m); and, (D) SEM image of pyritic mudstone indicating rhombohedral structure of pyrite (3,798.82−3,798.87 m). Siliceous calcareous mudstone lithofacies (E−F): (E) siliceous calcareous mudstone, brownish-grey lithofacies (3,802.08−3,802.23 m); and, (F) thin-section petrography showing the presence of siliceous calcareous mudstone, plain polarized light at a low magnification of 2.5x (3,808.15 m).

was also compared with identified sequence stratigraphic intervals, GR log and lithofacies at Redback–2. As with the TOC value, which shows its main shifts at stratigraphic surfaces, major shifts in the RHP trend are situated at TSE as well as at FS. Organic facies sequences can be identified from the RHP because the changes from anoxic to oxic conditions occur with a RHP increasing upward pattern, and changes from oxic to anoxic conditions occur along with a RHP decreasing upward pattern (Singh, 2008). The comparison of RHP with the sequence stratigraphic intervals acquired from the geological properties of the rocks shows good conformity.

AREAL CORRELATION OF STRATIGRAPHIC INTERVALS

The lithofacies were correlated with the GR response at Redback–2, and then these recognised GRPs for the stratigraphic intervals in Redback–2 were correlated with GR logs of other wells to study the lithofacies and stratigraphic intervals of the study area. After reviewing log data of various wells, a north–south transect through the Dandaragan Trough—consisting of Redback–2, Beharra Springs South–1, Woodada–2, and Woodada–6—was created. This cross-section shows that although the Hovea Member thins in Beharra Spring South–1 and Woodada–2, all lithofacies are still present across the trough (Fig. 6).

CONCLUSION

Considering the high priority of geological studies in detecting continuous shales with potential shale reservoir, 35 m of core through the Kockatea Shale at Redback–2 were reviewed, resulting in the recognition of seven lithofacies in the organically rich Hovea Member. The study then undertook a petrographical and mineralogical analysis of the lithofacies with respect to the general depositional environment. This was, generally, a quiet environment of deposition with reduced circulation, but the presence of turbulence in some lithofacies such as the bioturbated mudstone suggests some deposition under high-energy conditions. Furthermore, the fossiliferous mudstone lithofacies with a multitude of fossils indicates sudden environmental changes into poorly oxygenated conditions, which led to a mass death of fauna. The Hovea Member was deposited in shallow marine conditions. To determine a sequence stratigraphic framework of the identified lithofacies, GR log patterns associated with facies stacking patterns were studied, and resulted in the recognition of five stratigraphic intervals. Each stratigraphic interval contained an individual transgressive and regressive event, with exception of stratigraphic interval 5, which consists of a single regressive event. RHP also helped in detecting the depositional environment of the lithofacies, specifically regarding environmental oxygen. The sedimentary environment predicted by RHP was integrated with those acquired by sequence stratigraphy through
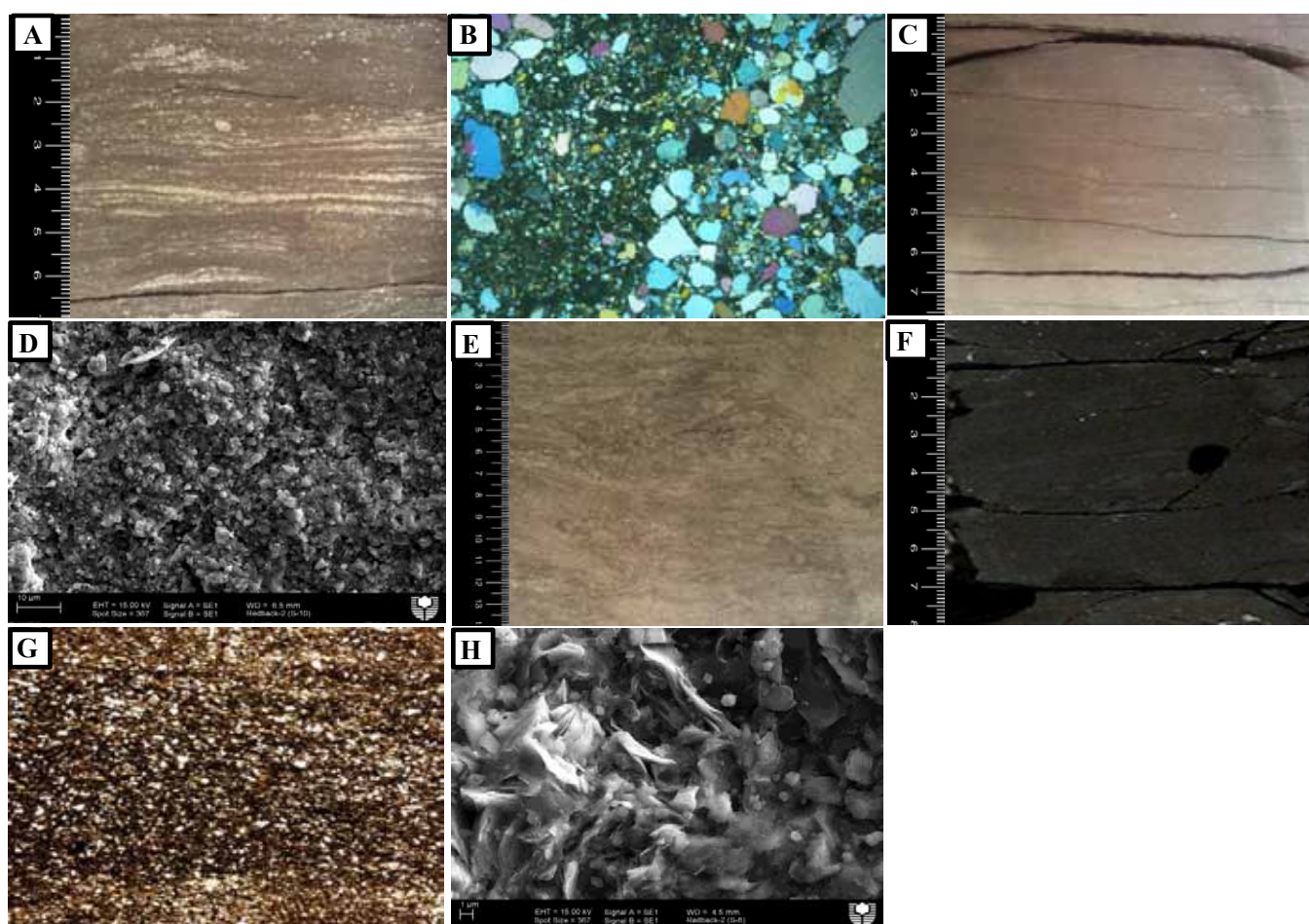

Figure 4. Core photographs of lithofacies. Siliceous mudstone lithofacies (A–B): (A) siliceous mudstone, grey-brown colour with siliceous (light colour) into the clay matrix (3,808.31–3,808.39 m); and, (B) thin-section photomicrograph displays high values of detritus quartz of various sizes, crossed polarized light with a low magnification of 2.5x (3,832.75–3,832.80 m). Calcareous mudstone lithofacies (C–D): (C) calcareous mudstone (3,834.50–3,834.55 m); and, (D) SEM images of calcareous mudstone, there is no particular alignment (3,834.50–3,834.55 m). (E) Bioturbated mudstone lithofacies (3,830.68–3,830.83 m). Black-shale lithofacies (F–G): (F) 3,819.32–3,819.36 m; and, (G) lithofacies composition can be roughly identified based on thin-section petrography: clay minerals (dark brown), fine-grained quartz (white), mica (light brown), and organic matter (black), plain polarized light at a low magnification of 2.5x (3,819.32–3,819.36 m). (H) SEM photograph shows the clay dispersion in lithofacies (3,819.32–3,819.36 m).
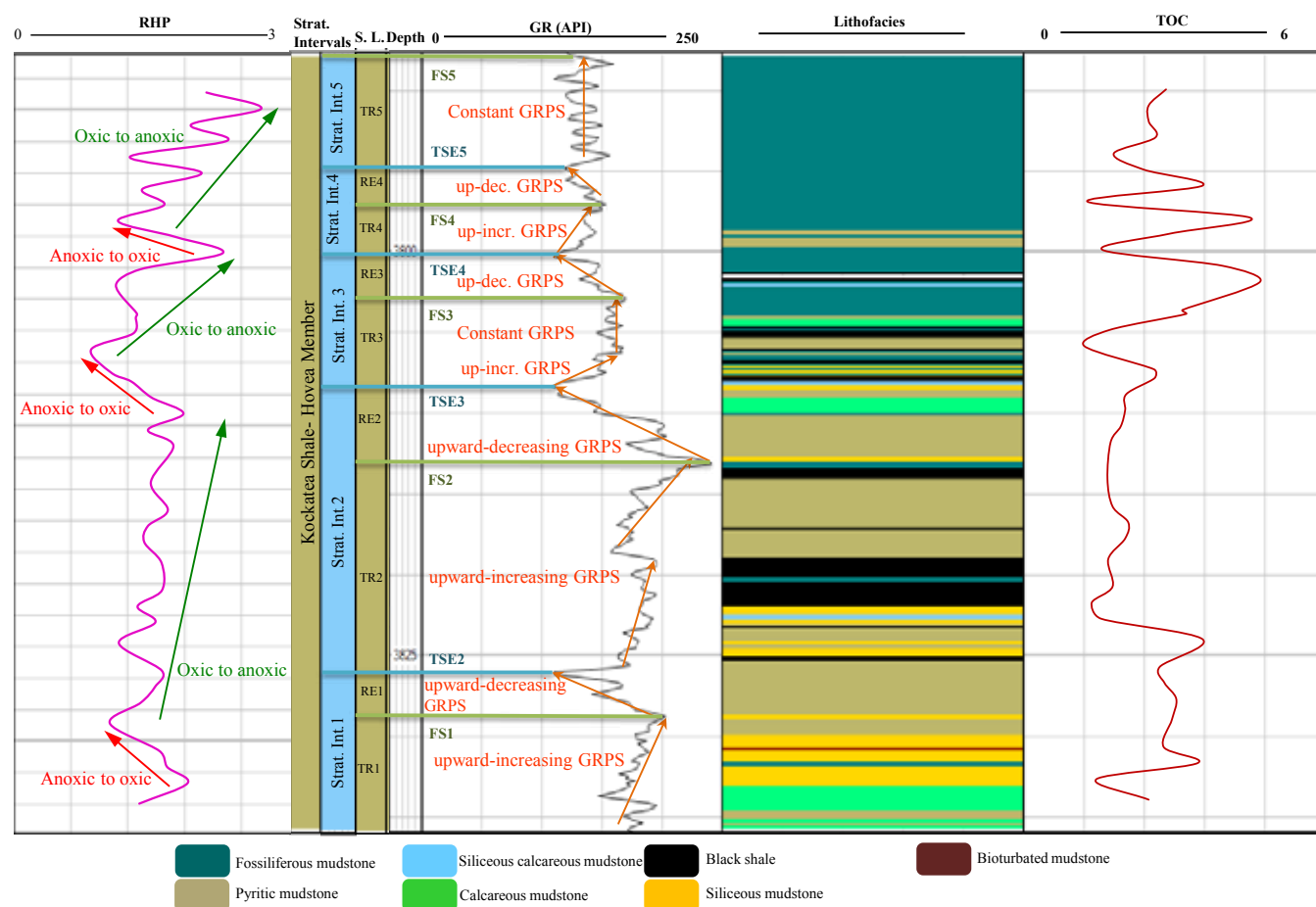
Figure 5. Sequence stratigraphic interpretation of the Hovea Member showing stratigraphic intervals 1–5 correlated to GR log, lithofacies, TOC, and relative hydrocarbon potential (RHP) from Redback–2, Kockatea Shale. See nomenclature for definitions of the abbreviations.
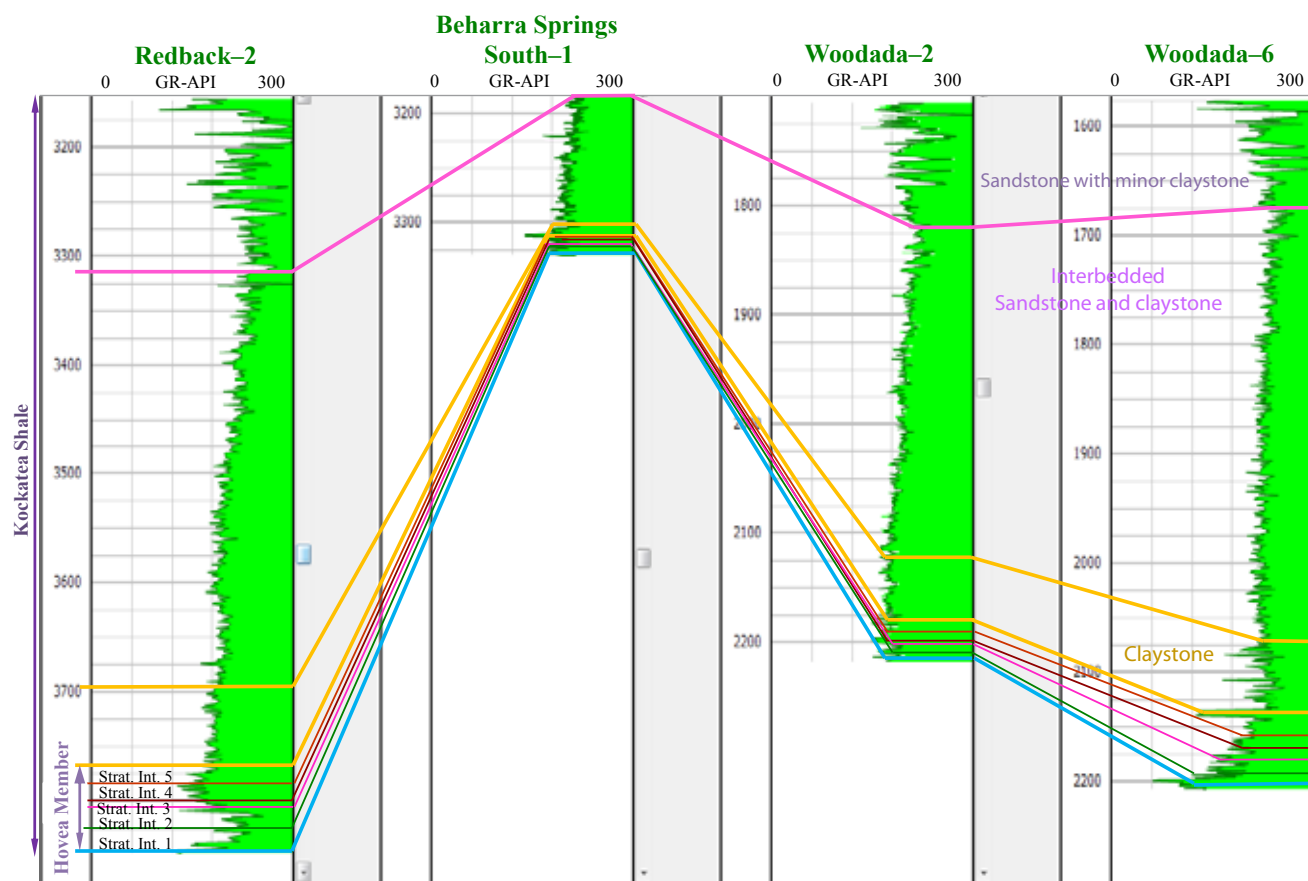

Figure 6. North–south cross-section of the Kockatea Shale (see Fig. 1 for location), Dandaragan Trough, Perth Basin.

stratigraphic interval and GRPs. A north–south cross-section through the Dandaragan Trough reveals the similarity of GRPs in selected wells, and subsequently the resemblance and presence of the various lithofacies across the Dandaragan Trough.

ACKNOWLEDGMENTS

NOMENCLATURE

GRPS	Gamma-ray parasequence
GRPs	Gamma-ray patterns
TR	Transgressive event
RE	Regression event
TSE	Transgressive surfaces of erosion
CSc	Condensed sections
FS	Flooding surface
Strat. Int.	Stratigraphic interval

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