



Facies analysis, depositional environment interpretation and lithostratigraphic architecture to predict reservoir potential of the Devonian Ravendale Interval in the Bancannia Trough, western Darling Basin, SE Australia

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Abstract

This paper discusses the facies sequence character for sandstone rocks of the subsurface upper Middle Devonian and Upper Devonian Ravendale Interval in the Bancannia Trough, western Darling Basin. The integration of multiple correlation techniques (recognition of changes in core and cutting facies, electrofacies and lithostratigraphic-facies associations) has helped define an internal stratigraphic correlation framework for the Ravendale Interval. This provides a powerful tool for understanding the distribution of the lithostratigraphic architectural controls on reservoir potential. This study has re-evaluated the stratigraphic boundaries of the Ravendale Interval (bottom and top) using marked changes in gamma-ray and sonic log characteristics, and depth estimates of the boundaries were derived from the wireline log data in the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells. The internal stratigraphy of the Ravendale Interval consists of 20 facies and 19 subfacies that define 4 facies associations (FA). These facies associations are characterised as facies association-A (FAA), a braided channel-fill system; facies association-B (FAB), a meandering channel-fill system; facies association-C (FAC), a multistory fluvial channel-fill complex system, and facies association-D (FAD), a meandering channel delta system. The Ravendale Interval has been subdivided into five wireline log lithostratigraphic units (RI1, RI2, RI3, RI4 and RI5, in ascending order) in the three available wells. Use of the suggested wireline log lithostratigraphic unit correlations versus facies association of the Ravendale Interval has the potential to refine existing stratigraphic sequence schemes and, given the higher resolution and more detailed correlation, may significantly improve subsurface sedimentological framework relationships in lithostratigraphic unit reconstructions. Wireline log correlations indicate that potentially productive sand-rich units of the major Ravendale Interval in the Bancannia Trough can be correlated over large distances, suggesting significant continuity into lightly drilled and undrilled areas, and aid in the prediction of potential hydrocarbon-bearing reservoirs within the Darling Basin region.

Keywords Bancannia Trough · Darling Basin · Ravendale Interval · Wireline logs · Facies and subfacies · Facies associations · Electrofacies · Lithostratigraphic units · Reservoir units

Introduction

Recent data and interpretation have enhanced our understanding of the prospectivity of the ‘frontier’ Darling Basin, a large and thick Palaeozoic basin in western New South Wales, back-arc to the Palaeozoic Lachlan Fold Belt. This paper discusses the possibility of the Bancannia Trough, a deep fault-bounded depository in the western edge of the Darling Basin, to host significant petroleum potential through development of a sedimentological framework and stratigraphic correlation. The development of this framework can be facilitated by recognition

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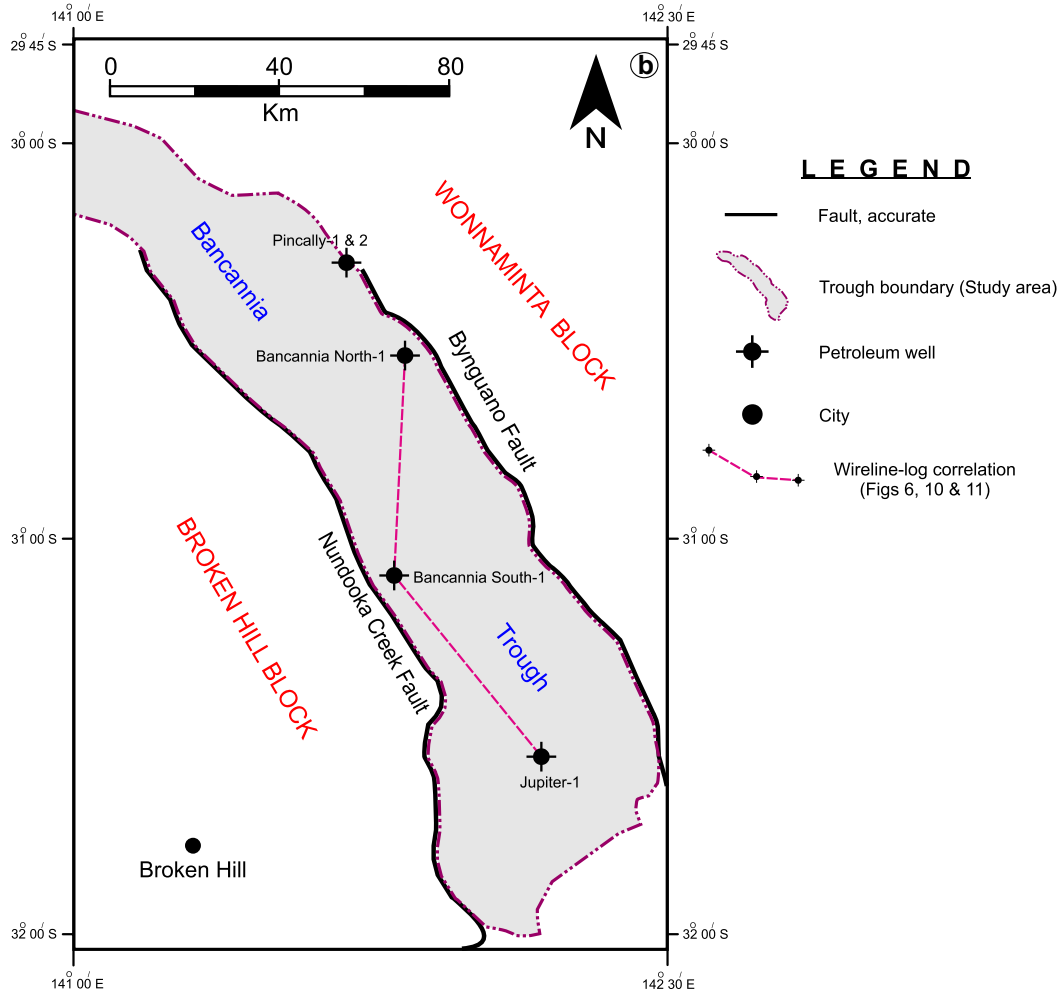
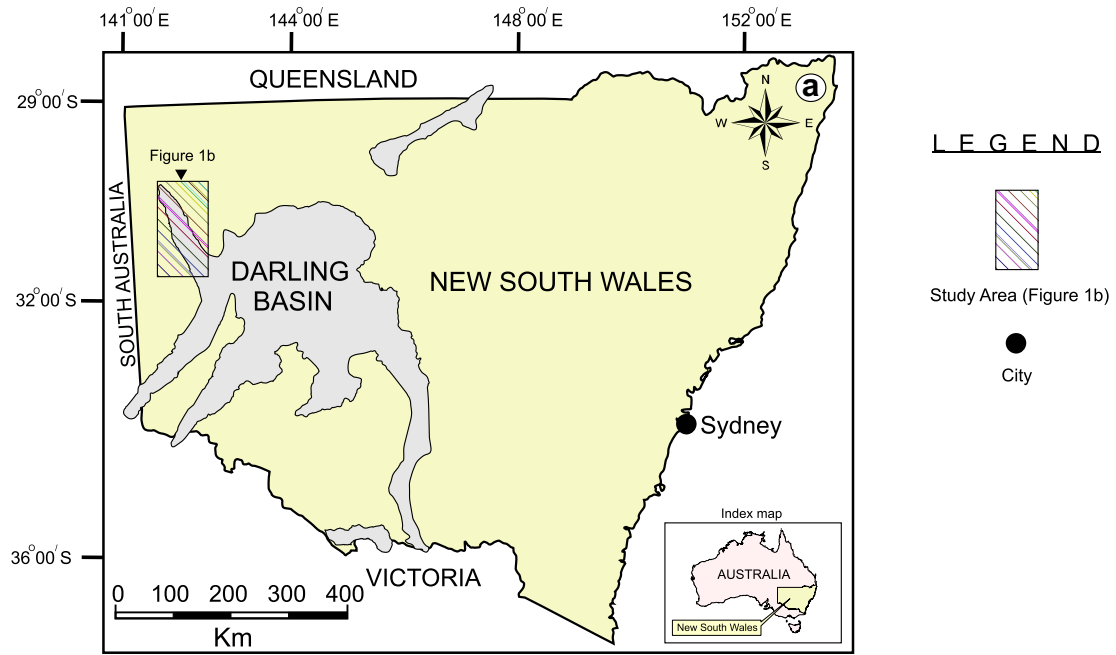


Fig. 1 Location maps: **a** geographical map of the Darling Basin with the studied area indicated within western New South Wales, SE Australia. **b** Simplified location map of the Bancannia Trough with boundaries modified after the Geological Survey of NSW (GSNSW), NSW Resources and Energy in Australia (formerly NSW Department of Mineral Resources 2003), as discussed in the text, and the three wells interpreted in this paper

of various facies within stratigraphic columns (cf. Walker 1984; Reading 1986). The term “facies” refers to the characteristics of the rock units that reflect the processes and environments of deposition. The facies may be built up of a combination of subfacies, each subfacies being defined based on a distinctive rock unit feature, such as grain size, sedimentary structures, fossil content, or other descriptive properties that reflect the conditions and environment of sedimentation. A facies association is composed of several facies and subfacies that reflect the environment of deposition and characterize a depositional system. A facies sequence may be recognized where there is a progressive change in the depositional environment with time, such as the common Bouma sequence in turbidite facies. The purpose of this study was to establish a thorough understanding of the facies associations and facies sequences within the upper Middle Devonian and Upper Devonian Ravendale Interval section of the Bancannia Trough and to identify prospective areas for reservoir potential. This paper presents a re-interpretation and re-evaluation of the lithostratigraphy in part of the study area using the three available petroleum exploration wells (Bancannia South-1, Bancannia North-1 and Jupiter-1), as shown in Fig. 1. Furthermore, recent discoveries of hydrocarbon potential have confirmed the Bancannia Trough to be of interest in the Darling Basin, although its sedimentary petroleum reservoir stratigraphy is relatively unknown.

The application of wireline log interpretation, integrated with core and cutting analysis, is used to define electrofacies and trends in depositional environments. An electrofacies is an expression of facies that reflects lithology derived from wireline logs in the subsurface geology. The Bancannia Trough is a case study highlighting some of the problems in estimating petroleum potential using lithostratigraphic principles. The results of this study may be compared with coeval siliciclastic facies records from other basins worldwide.

All descriptions of core used in this study are archived and available for public access in the DIGS database (see company reports from the three wells; Baarda 1968a, b; Wiltshire 1969), and the cores are publicly available for viewing in the Core Library of the Geological Survey of NSW. In the discussion below, measured core descriptions will be referred to with a well location and a figure. If a well location is referred to, but there is no figure, the core description is found in Baarda (1968a, b) and Wiltshire (1969) [unfortunately the representative core images are not available for public access in the DIGS database (Digital Imaging Geological System) from Geological Survey of New South Wales (GSNSW)].

Recently, however, numerous studies on geochemical and geophysical properties, sedimentology and stratigraphy of significant upper Middle Devonian and Upper Devonian reservoir rocks of the Ravendale Interval have provided valuable information on non-marine depositional sequence correlation and subdivision on a regional scale across the Darling Basin (e.g. Bembrick 1976; Brown et al. 1982; Byrnes 1985; Mullard 1995; Sinelnikov 1995; Willcox et al. 2003; Neef and Larsen 2003; Neef 2004, 2009; Cooney and Mantaring 2007; Khalifa and Ward 2009, 2010).

The present paper has no methodology and interpretation techniques using sequence stratigraphic concepts based on the identification of systems tracts (e.g. LST, TST and HST), key stratigraphic surfaces (e.g. SB, TS, and MFS), depositional sequences, parasequences and parasequences sets. This is because the aim of this paper was to illustrate the use of sedimentological concepts to interpret both facies and facies association relationships, and the distribution of lithostratigraphic architecture to predict reservoir potential of the Devonian Ravendale Interval in the subsurface of the Bancannia Trough, western Darling Basin. It is our objective to emphasize that wireline log interpretation, integrated with core and cutting analysis, can be used to define electrofacies and trends in depositional environments, as discussed in the database and methodology sections below.

The objectives of this paper on the Bancannia Trough are to (1) document the stratigraphic boundaries within the Ravendale Interval based on regional wireline log correlation; (2) demonstrate that conventional wireline logs, calibrated carefully against core and cutting-defined facies and subfacies, can be compared to a paleoenvironment, using a re-examination of core data (lithology, sedimentary structures, palaeontological evidence and other sedimentary features). The integration of gamma-ray and sonic log records provides an electrofacies scheme of resolution much higher than what would be achieved through traditional methods; (3) to determine the extent and geometry of each of the proposed new lithostratigraphic units within the Ravendale Interval; and (4) integration of sedimentary facies/subfacies and electrofacies with depositional environments and other features identified from cores, cutting and wireline log data, to develop a lithostratigraphic-facies association model in the Bancannia Trough. This geologic information will increase knowledge about the history of the Ravendale Interval in the Darling Basin.

Geological background of the Ravendale Interval

Stratigraphic and depositional environment framework

The Darling Basin is an onshore back-arc basin with an areal extent of about 90,000 km² and is situated in western

Time Scale (Ma)	Period	Epoch	Age	West ----- Correlation of the Lithostratigraphic Units and Equivalents ----- East				- Whole Darling Basin Region -	
				----- Kanimblan - Alice Springs Events ~ Regional Unconformity ~ Seismic Marker (Horizon-D) -----					
355	Devonian	Late	Famennian	Ravendale Formation (762 m)	Nundooka Sandstone (1070 m)	Unit-C (375 m)	Crowl Creek Formation (2000 m)	Upper part of the Mulga Downs Group	
360			Frasnian	Rose (1969) Packham (1969)	Ward <i>et al</i> (1969)	Unit-B (120 m)	Bundycoola Formation (300 m)		Ravendale Interval (Outcrop and Subsurface) Bembrick (1997a, 1997b)
365		Middle	Givetian			Unit-A (600 m)	Glen (1982)		
370			Eifelian			Carroll (1982)			
375				----- Tabberabberan Event ~ Regional Unconformity ~ Seismic Marker (Horizon-C) -----					
380									

Fig. 2 Simplified lithostratigraphic subdivisions and equivalents of the upper Middle Devonian through Upper Devonian formations in the Darling Basin, western NSW (modified after Khalifa and Ward

2009, 2010; Khalifa *et al.* 2016), including seismic marker unconformities (c, d) as used by Evans (1977) and the Ravendale Interval defined by Bembrick (1997a)

New South Wales (Fig. 1). The basin was an active area of Palaeozoic deposition from the late Cambrian until the early Carboniferous, contemporaneous with the development of the adjacent Lachlan Fold Belt to the east. Several fault-bounded troughs within the Darling Basin preserve up to 10 km of predominantly mature siliciclastic sediments, mostly brought in by major river systems draining the large Gondwana land mass to the west. Several stratigraphic breaks within the sedimentary succession, reflecting distinct orogenic events in the adjacent Lachlan Fold Belt, enable division into four stratigraphic intervals; the Ravendale Interval is the topmost of these intervals.

Generalised schemes of Ravendale Interval stratigraphy in the Darling Basin were summarized in Ward *et al.* (1969), Packham (1969), Conolly *et al.* (1969), Carroll (1982), Glen (1982) and Neef *et al.* (1995, 1996b) and were modified by Bembrick (1997a, b). Figure 2 incorporates these and other references into an abridged lithostratigraphic framework for the upper Middle Devonian and Upper Devonian Ravendale Interval. This interval has a Givetian–Famennian age, as documented by Neef *et al.* (1996a) and is present throughout the Darling Basin. The sparse but predominant fossils in the Ravendale Interval and its equivalents are: *Lepidosigillaria yalwalensis*, *Phyllolepis? Bothriolepis* and *Spirorbis*. These species indicate that the Ravendale Interval is of late Devonian (late Givetian–Famennian) age, as discussed by Packham (1969), Evans (1977), Glen *et al.* (1996), Neef *et al.* (1995), Young and Turner (2000), and Neef and Larsen (2003).

The upper Middle Devonian and Upper Devonian Ravendale Interval lies between seismic Horizons ‘C’ and ‘D’, which have been correlated by wireline logs through most wells within the Darling Basin (Fig. 2). Seismic Horizon ‘C’ probably represents the Tabberabberan event, a regional unconformity of late Middle Devonian (Givetian age), and seismic Horizon ‘D’ probably represents the Kanimblan-Alice Springs events that produced a regional unconformity of Early

Carboniferous time as originally described by Evans (1977). Furthermore, the upper part of the exposed Mulga Downs Group is equivalent to the subsurface Ravendale Interval proposed by Bembrick (1997a, b). General lithostratigraphic subdivisions and equivalents of the Ravendale Interval in the Darling Basin are shown in Fig. 2. The interval is equivalent to the Ravendale Formation named by Rose (1968). Conolly *et al.* (1969) have described the Ravendale Formation on the eastern side of the Bancannia Trough. The unit is synonymous with units A, B and C mapped by Carroll (1982) in the Mutawintji National Park on the eastern side of the Bancannia Trough. The Ravendale Formation is equivalent to the Nundooka Sandstone exposed on the western side of the Bancannia Trough to the north and east of Fowler’s Gap by Ward *et al.* (1969). The upper part of the Mulga Downs Group is also equivalent to lower part to the Bundycoola Formation and the upper part to the Crowl Creek Formation in the Buckambool area, west of Cobar within the Darling Basin (Glen 1982).

The depositional environment of the Ravendale Interval is summarized in Fig. 3. In general, the Ravendale Interval is initiated by an influx of coarse siliciclastic sediments in both the western and eastern parts of the basin (Ward *et al.* 1969; Conolly *et al.* 1969; Neef *et al.* 1996b). Few coarse clastic sediments reached the central regions of the basin (Neef *et al.* 1995; Bembrick 1997a, b). The depositional environment of the Ravendale Interval is dominantly fluvial but closes with a Famennian marine episode encountered in the structural troughs where the thicker Upper Devonian section is preserved (Glen 1979; Bembrick 1997b; Alder *et al.* 1998; Neef and Larsen 2003).

Overview of previous work on Bancannia Trough stratigraphy

Most workers agree that the Ravendale Interval and its equivalents are extensively present from the Bancannia Trough to the Dunlops Range in the eastern Darling Basin

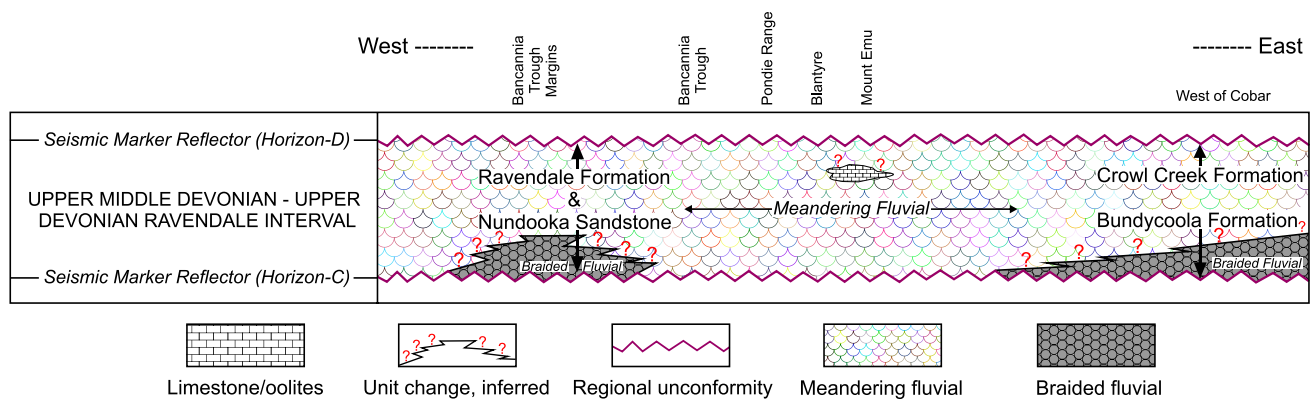


Fig. 3 Idealized, schematic representation of a general sedimentary environment framework for the Devonian Ravendale Interval in the Darling Basin, showing correlation of the various lithostratigraphic units (adapted from Bembrick 1997a; Alder et al. 1998; Khalifa and Ward 2010)

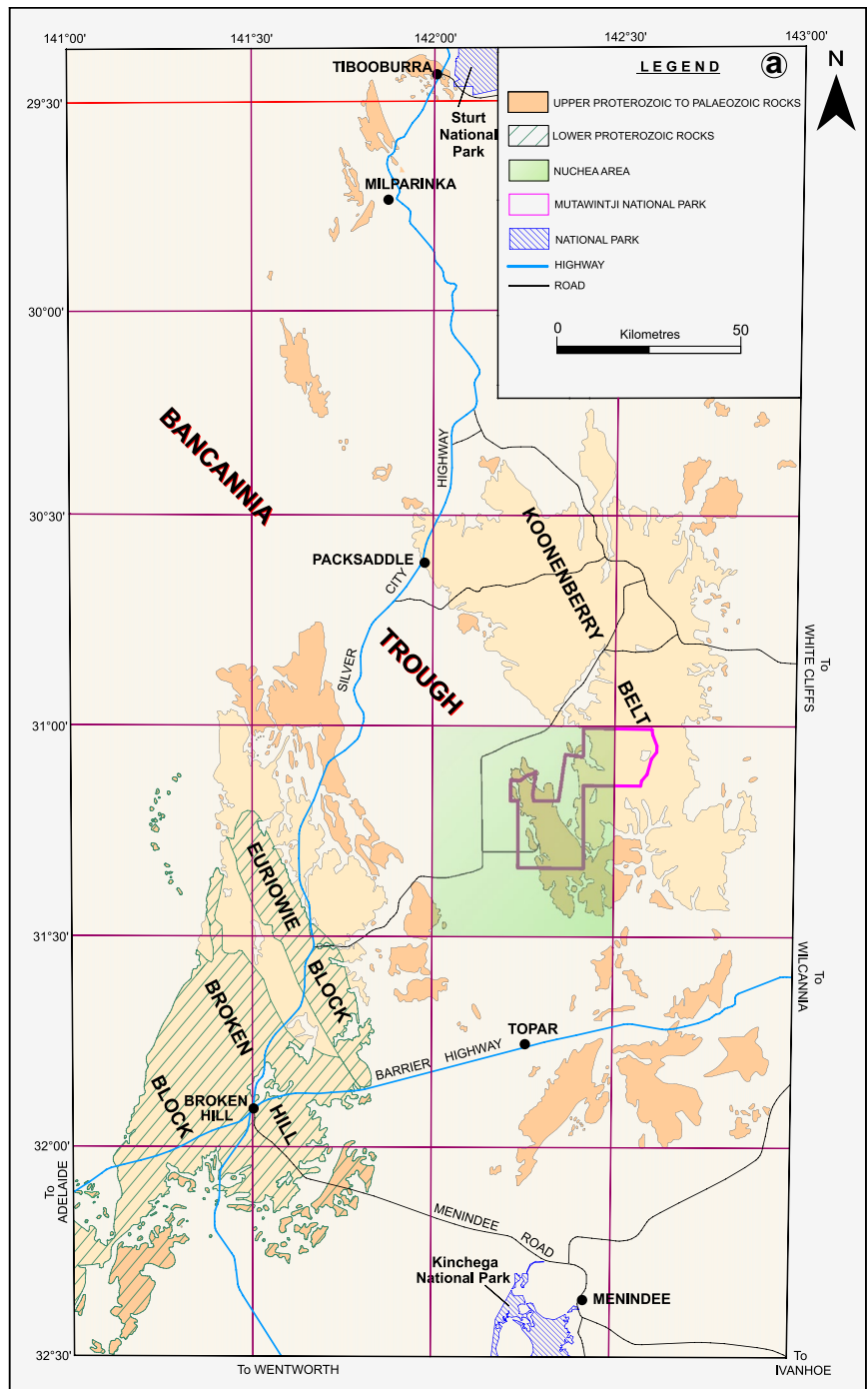
(Packham 1969, cited Khalifa 2005; Fig. 2.7, p. 51), both in the subsurface and in outcrop. The information used in the compilation of this paper includes the previous petroleum well completion reports from Bancannia South-1, Bancannia North-1 and Jupiter-1 wells, other petroleum exploration company reports, published papers, internal Geological Survey of NSW reports and mapping, palaeontological investigations, some reservoir data and sampling of core and cutting data. The aim in this paper is to review the upper Middle Devonian to Upper Devonian Ravendale Interval of the Bancannia Trough and to compile a working stratigraphic framework into which further studies could be integrated.

On the western side of the Bancannia Trough, the Ravendale Interval sediments outcrop northwest of Bancannia South-1 and west of the Jupiter-1 wells. Parts of these exposures have been described by several workers (e.g. Ward et al. 1969; Neef et al. 1995, 1996a, b) as fine to very fine-grained red-bed sub-litharenites that comprise a succession over 1420 m thick. Palaeocurrents show that sediments were derived from the west and northwest, being deposited on low-angle alluvial fans and distal braid plains (Bembrick 1997b; Alder et al. 1998). High in the sequence sediments with fossil fish have been found, which indicate a Famennian age (Neef et al. 1996b). However, this assertion appears to be based on a correlation with subsurface strata in the Bancannia South well containing Famennian spores (Bembrick 1997a; Alder et al. 1998), rather than any definitive age determined from the fish remains, which are endemic to the local area and not yet readily correlated to worldwide species. Although the basal contact with the Coco Range Sandstone is removed by localized faulting, the Nundooka Sandstone has been correlated with the upper part of the Ravendale interval in the Bancannia South well (Neef et al. 1995). Within this well, the base of the Nundooka Sandstone is interpreted to be close to seismic reflector Horizon ‘C’ of Evans (1977).

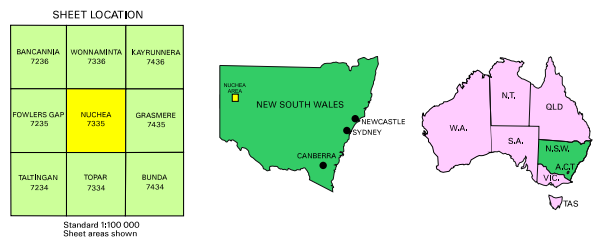
On the eastern margins of the Bancannia Trough, and adjacent to the Mutawintji National Park, there are extensive outcrops of the Ravendale Interval as mapped on the Nuchea 1:100 000 Geological Sheet by Buckley (2001) and Sharp and Buckley (2015) (Fig. 4a). Two units representing the lower and upper parts of the Ravendale Formation (the Ravendale Interval) were mapped (Buckley 2001) (Fig. 4b). Buckley’s subdivision was based on lithology, grain size and his knowledge of fluvial sedimentology of the Ravendale Formation. The lower part of the Ravendale Formation (labelled LRFM) consists of sandstone interbedded with siltstone and claystone beds. Minor shale chip conglomerate and very rare quartz pebbles form basal beds to overlying quartz sandstones. According to Buckley (2001), the upper part of the Ravendale Formation (labelled URFM) is composed of quartz sandstones and siltstones with some conglomerate at the base and the dominant sedimentary structures are assorted types of plane-laminated bedding and cross-bedding.

The type section of the Ravendale Formation is contained in the well-exposed outcrops on the eastern margin of the Bancannia Trough near the southwestern margin of the Mutawintji National Park where the Ravendale Formation overlies the Snake Cave Sandstone by gentle angular unconformity (Webby 1972). Here, the Ravendale Formation is over 1200 m in thickness and has been divided into four mapped units by Neef and Bottrill (1996). Lithologies include conglomerate, fine-grained quartz sandstone with very minor siltstone and sedimentary breccias. Palaeocurrent data indicate that these sediments were derived from the west and were deposited on alluvial fans, with currents flowing to the northeast (cf. Alder et al. 1998). A basal conglomerate containing boulders of both Snake Cave Interval sandstone and Cambro-Ordovician quartzites is attributed by Neef and Bottrill (1996) to the uplift and emergence of the adjacent Wonnaminta High to the east during structural movement on seismic reflector Horizon

Fig. 4 Location maps. **a** Simplified geographical map of the Bancannia Trough area showing Nuchea map sheet (shaded) and the Mutawintji National Park within the Western Darling Basin. **b** Condensed geological map of the Nuchea sheet showing the major stratigraphic subdivisions and surface structural elements (modified after Buckley 2001)



INDEX MAP OF THE NEW SOUTH WALES SHOWING LOCATIONS OF DIAGRAMS



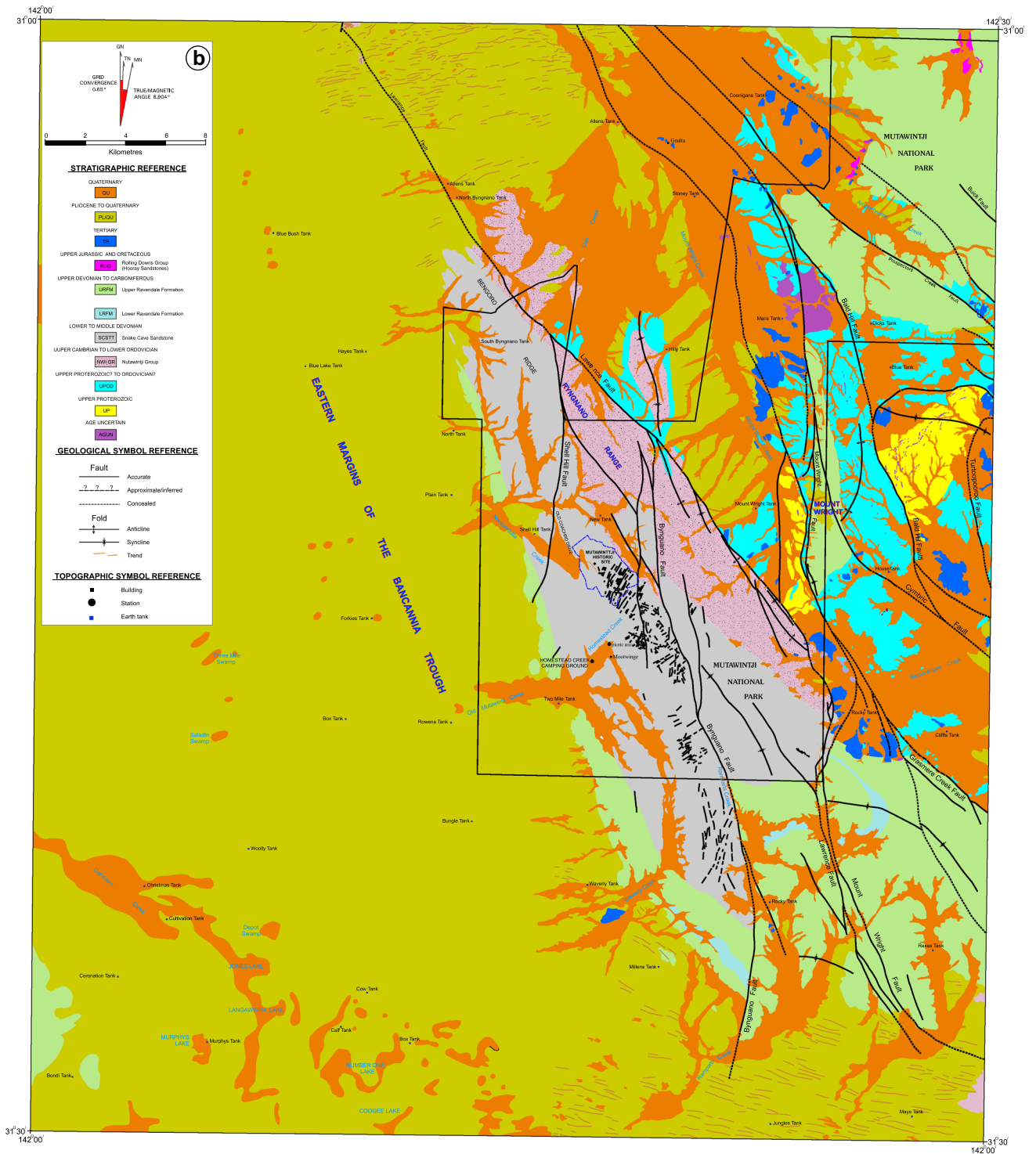


Fig. 4 (continued)

‘C’. Conglomerates containing Snake Cave Interval sandstone boulders occur on the eastern edge of the Wonnaminta High at Moona Vale and adjacent to the Mount Jack High, indicating uplifting of a similar age.

In 1999, the Koonenberry Deep Seismic Section was commissioned under the auspices of the Australian Geological Science Organisation and the NSW Geological Survey to traverse from the Broken Hill Block (Palaeoproterozoic) in the west across the Bancannia Trough and the Koonenberry

Fold and Thrust Belt (Early Palaeozoic) in the east. This traverse passes close to Bancannia South-1 well and provides an excellent cross-section of the Bancannia Trough, a summary of which can be found in Mills and David (2004).

Database and methodology

All data from Bancannia Trough were provided by Geological Survey of New South Wales (GSNSW). A multidisciplinary data set, including wireline logs (mainly gamma-ray, resistivity and sonic), core and cutting data, and limited biostratigraphic information in the well completion reports from three wells, was used to document sedimentary facies and build a lithostratigraphic framework for the Ravendale Interval deposits of the Bancannia Trough (Table 1). The data were interpreted in four steps.

The first step was the delineation of stratigraphic boundaries: use of geological information from wireline logs (gamma-ray and sonic), and comparison of lithological data, to identify the key stratigraphic boundaries within the Ravendale Interval and the underlying Snake Cave Interval, and the overlying Cretaceous to Cenozoic sediments in each well of the study area.

The second step was the delineation of a facies sequence in each well of the study area, designated by the sedimentological features identified in the core and cutting data and tied to wireline logs (Figs. 7, 8, 9). Furthermore, sedimentological data were interpreted in sets of vertical facies sequence logs. Detailed core and cutting descriptions of the Bancannia South-1 and Bancannia North-1 wells can be found in Baarda (1968a, b); and cutting descriptions of the Jupiter-1 well can be found in Wiltshire (1969). The gamma-ray log responses for each well show variations that reflect the facies and subfacies that are identified in the visual well logs. Facies that are determined by electric wireline log patterns are distinguished as electrofacies. The analysis of successive electrofacies within a well can distinguish facies sequences as well as sharp changes representing bounding sedimentary features. Logs examined from the three wells all show a persistent upward change in log parameters that reflect variations from fine-grained shale to coarse-grained sand intervals, including upward-fining or upward-coarsening sequences.

The third step was the definition of facies associations using all logged cores and cutting sedimentology integrated into the wireline log correlations (mainly gamma-ray data), with variations within each facies association reflecting changing depositional environments.

The final step was the division of the stratigraphic architecture of the Ravendale Interval into five units (RI1, RI2, RI3, RI4 and RI5 in ascending order) in the Bancannia

Trough. These units were described and interpreted in terms of lithostratigraphic units from wireline logs alone. Gamma-ray and resistivity logs from the three available wells (Bancannia South-1, Bancannia North-1 and Jupiter-1) were correlated to establish the lithostratigraphic units and the relative sandstone vs shale content. Also, matching of lithologic information observed in some cored samples (descriptions from Bancannia South-1 and Bancannia North-1) to specific log responses allowed recognition of a range of wireline log signatures within the Ravendale Interval and helped to provide the necessary lithostratigraphic control. Otherwise, wireline logs were calibrated with the facies associations identified in sedimentology data and subsequently correlated throughout the study area. The stratigraphic model showing the relationship between lithostratigraphic units and facies associations identified from the upper Middle Devonian to Upper Devonian Ravendale Interval allowed development of a paleogeography for the Bancannia Trough.

Description and interpretation of well data

Re-evaluation of distribution and stratigraphic relationships

The Ravendale Interval as defined here varies from the traditional stratigraphic section used for this area because we correlate wireline logs with detailed lithology by (1) re-evaluation of stratigraphic boundaries from gamma-ray and sonic logs and (2) correlation between Bancannia South-1, Bancannia North-1 and Jupiter-1 wells using wireline log signatures as discussed further below.

Re-evaluation of the positions of the stratigraphic boundaries in the available exploration wells was based on interpretation of the wireline logs (gamma-ray and sonic) and on correlation of lithology from core and cutting information (Figs. 5, 6; Table 1). Such practices have long been used to define boundaries using stratigraphic geological interpretation of wireline logs (e.g. Pirson 1983; Rider 1991). Improvement of the stratigraphic boundaries of the Ravendale Interval in the wells in the Bancannia Trough resulted in further subdivision, although this was difficult due to the limited number of available core descriptions and biostratigraphic data in the well completion reports. The bottom and top of the Ravendale Interval have been identified in the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells.

The boundary between the Snake Cave and Ravendale Intervals can be traced on the wireline log profiles through the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells (Fig. 6). This boundary is marked in the Bancannia North-1 well by a sharp decrease in the gamma-ray and sonic log values, going into the Ravendale Interval at a depth of

Table 1 Stratigraphic data of the Ravendale Intervals within the Bancannia Trough, showing well penetrations and other information used in the paper

Well name	KB (m)	TD (m)	Lithostratigraphic interval described by Bembrick (1997a, b)	“Present study” Re-evaluation of wireline logs		Types of data available	Latitude (°S)	Longitude (°E)	References	
				Top (m)	Bottom (m)					Thickness (m)
Bancannia South-1	154.2	3409	Ravendale Interval	230	1655	1425	Wireline logs: gamma-ray, sonic, resistivity and density Core and cutting data and, limited biostratigraphic information in the well completion report	– 31.05	141.41	Baarda (1968a), Byrnes (1985), Alder et al. (1998) and Bembrick (1997a, b)
Bancannia North-1	116.7	1479	Ravendale Interval	405	1150	745	Wireline logs: gamma-ray, sonic, resistivity and density Core and cutting data and, limited biostratigraphic information in the well completion report	– 30.39	141.50	Baarda (1968b), Byrnes (1985), Alder et al. (1998) and Bembrick (1997a, b)
Jupiter-1	142.9	1832	Ravendale Interval	125	1435	1310	Wireline logs: gamma-ray, sonic, resistivity Cutting data in the well completion report	– 31.30	142.09	Wiltshire (1969), Byrnes (1985), Alder et al. (1998) and Bembrick (1997a, b)

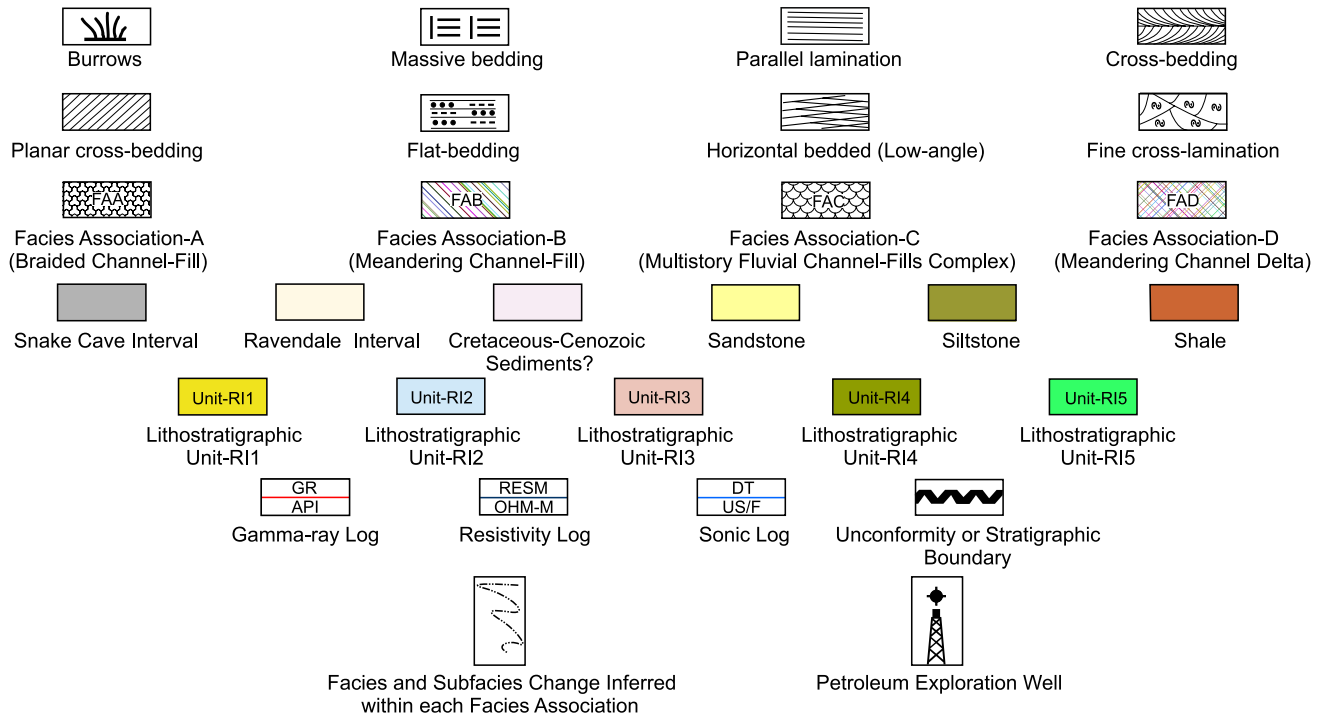


Fig. 5 Key to lithologies, sedimentary structures, sedimentological features, facies associations, depositional environments, stratigraphic units, wireline log name and other geological features and symbols used for the three wells illustrated in Figs. 6, 7, 8, 9, 10 and 11

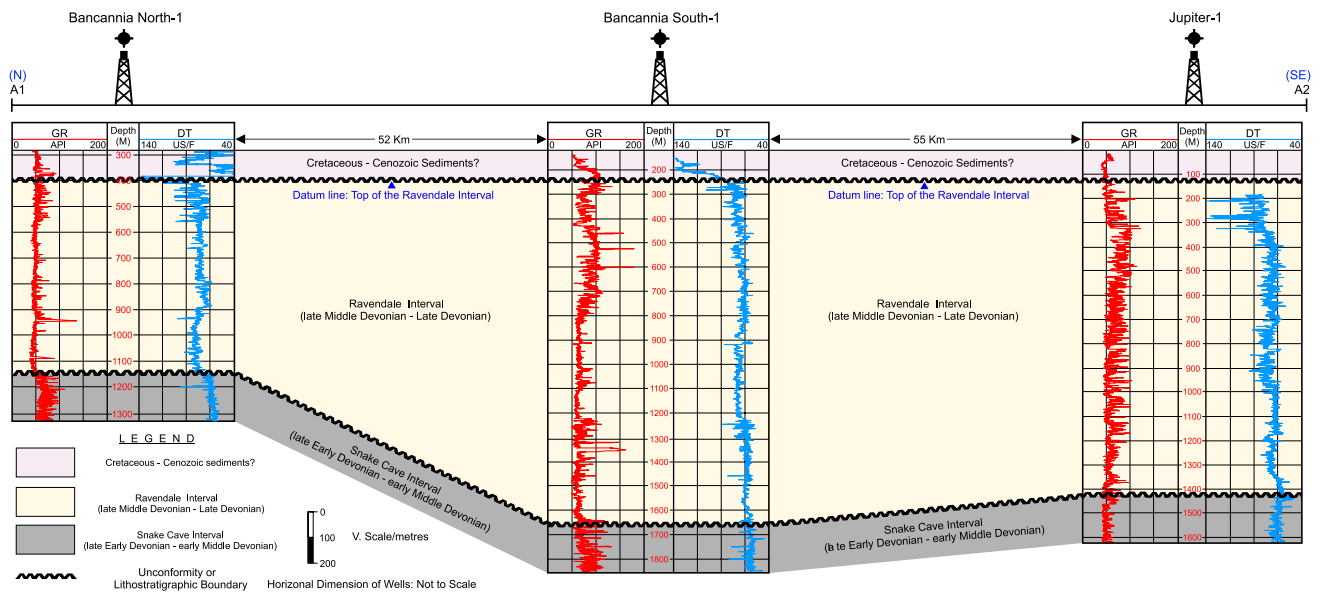


Fig. 6 Regional stratigraphic correlation showing preserved well-sections of the upper Middle Devonian to Upper Devonian Ravendale Interval through the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells in the Bancannia Trough, western Darling Basin.

Wireline log correlation is based on the gamma-ray (left) and sonic logs (right). The top of the Ravendale Interval is used as a horizontal stratigraphic datum. See Fig. 1b for well locations

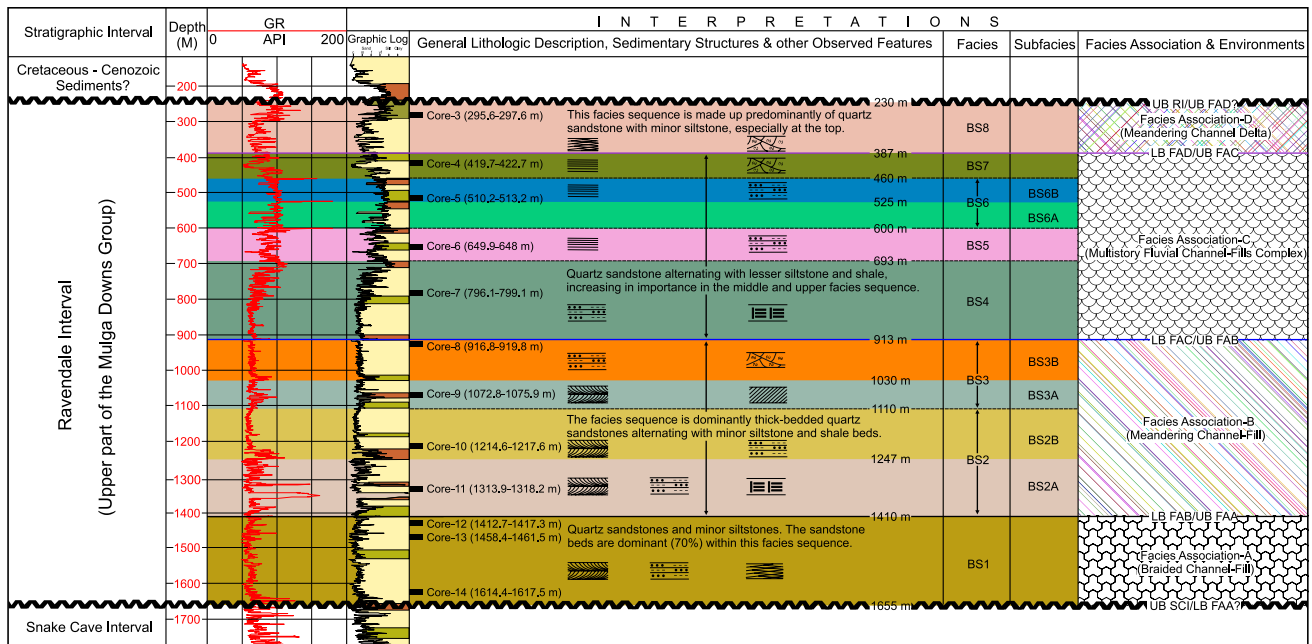


Fig. 7 Interpretive sedimentological log through the Ravendale Interval showing the distribution of major sedimentary facies/subfacies and facies associations in the Bancannia South-1 well. The well section is based on interpretation of gamma-ray signature, core/cutting descriptions, lithology and sedimentary structures, in the well com-

pletion report (refer to text for discussion). See Fig. 1b for location of the Bancannia South-1 well. See Fig. 5 for key to lithology, sedimentary structures, sedimentological features, and depositional environment symbols used in the well log

1150 m (Fig. 6), and by changes in the relevant cutting data. Figure 6 also shows a subtle drop in sharp gamma-ray and sonic values in the Bancannia South-1 well (around 1655 m depth), indicating a distinct lithological change at the Snake Cave and Ravendale boundary. In the Bancannia South-1 well, the cutting lithologic data and the reinterpreted wireline logs (gamma-ray and sonic) indicate that the lower part of the Ravendale Interval consists of interbedded sandstone and shale, whereas the upper part of the Snake Cave Interval is relatively pure sandstone (for further information see facies sequence analysis of the Bancannia South-1 well).

The boundary between the Ravendale Interval and the Cretaceous to Cenozoic strata is well defined on the wireline log profiles through the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells (Fig. 6). However, this contact is best displayed in the Bancannia South-1 well (Fig. 7). The upper part of the Ravendale Interval is relatively silty, whereas the lower part of the Cretaceous to Cenozoic strata consists of more shaly sediment with a higher gamma-ray response (Fig. 6), the transition occurring at 230 m in the Bancannia South-1 well. The boundary is also seen in the wireline log signatures (Fig. 6) in the Bancannia North-1 well at 405 m depth and the Jupiter-1 well at 125 m depth.

The correlation of log markers across the Bancannia Trough shows that revisions of the stratigraphic interval picks in the well-completion reports are necessary to improve the positions of the boundary between the top of the Snake Cave

and the bottom of the Ravendale Intervals, and the boundary between the top of the Ravendale Interval and the bottom of the Cretaceous to Cenozoic strata. Two wireline log suites (gamma-ray and sonic) were chosen for stratigraphic correlation, related to the very limited core data control from the three wells. The major correlation methods included marker beds, similarities in log motif, interval association correlation, and consideration of the regional thickness (Fig. 6).

In the Bancannia Trough, the maximum thickness of Ravendale Interval has been recorded from Bancannia South-1 well (1425 m) and Jupiter-1 well (1310 m), while it decreases towards the northeast to 745 m in the Bancannia North-1 well (Fig. 6). In the outcrop, the thickness of exposed Ravendale Formation (now Ravendale Interval, Bembrick 1997a, b) in the Mutawintji National Park area is approximately 1500 m (cf. Vickery et al. 2010). In general, the measured thicknesses of the Ravendale Interval are preserved thicknesses rather than deposited thicknesses as the top of the Ravendale Interval may have been removed by later erosion.

Geological description of facies and subfacies from well data

The facies and subfacies distinguished in the three wells are characterized by lithology, primary sedimentary structures, wireline log profile, and other features, as well as limited

paleontological information documented in the Ravendale Interval (symbols in Fig. 5). Although they are given interpretative names, each facies and subfacies (see Tables 2, 3 and 4 with references) is based on its distinctive descriptive characteristics from the three well sections (Figs. 7, 8, 9). We have used a descriptive scheme for the facies, which may be composed of various subfacies, by grouping them into major facies associations. These major facies associations were then evaluated by comparison of the features to descriptions of similar strata in the literature.

The re-interpretation of these sedimentological features differs from previous studies and is critical in developing an improved understanding of the stratigraphy in the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells. Representative sections from these three wells were analyzed in this way.

Facies sequence analysis of Bancannia South-1

The Ravendale Interval has been penetrated in the Bancannia South-1 well between 230 and 1655 m depth (Fig. 7). Twelve cores were recovered that represent approximately 25% of this interval. The sedimentological scheme defining the facies and subfacies is illustrated in a series of core logs within Bancannia South-1 well for control (Fig. 7). Core sedimentology from the Ravendale Interval enabled subdivision into intervals each characterized by gamma-ray log characteristics, together with lithological and other sedimentary features, which served as standards for correlation with the same succession in other wells (Bancannia North-1 and Jupiter-1). The eight facies and six subfacies recognized in the Ravendale Interval in this well are summarized in Table 2 (see also the sedimentological log in Fig. 7).

Facies sequence analysis of Bancannia North-1 well

This well is 52 km NE from Bancannia South-1. The Ravendale Interval has been penetrated in this well between 405 and 1150 m depth (Fig. 8). Six slabbed cores were studied that represent approximately 15% of this interval. Much of the information for this description was gathered from logs of the cores and cuttings data reported in the well completion report (Baarda 1968b). The re-interpretation of the gamma-ray log from this well is included on the vertical facies sequence through the Ravendale Interval section (Fig. 8). The gamma-ray log is described and interpreted with reference to the five facies and four subfacies defined in the Bancannia North-1 well. The facies and subfacies are summarized in Table 3 (see also the sedimentological log in Fig. 8).

Facies sequence analysis of Jupiter-1 well

This well is 55 km SE from Bancannia South-1 well, and 107 km SSE from Bancannia North-1 well (Fig. 1). The Ravendale Interval has been penetrated in this well between 125 and 1435 m depth (Fig. 8). Sedimentological description of the Ravendale Interval in the Jupiter-1 well is limited, due to the lack of core data. In the interpretation presented herein, we have attempted to integrate the sedimentological observations of the cutting data (Wiltshire 1969) with gamma-ray log signatures on the vertical facies sequence. The eight facies and nine subfacies recognized in the Ravendale Interval in this well are summarized in Table 4 (see also the sedimentological log in Fig. 9).

Integrated data analysis using electrofacies for subdivision of facies associations

The distinct gamma-ray log responses in the Ravendale Interval can be defined as electrofacies that can be correlated with actual facies and subfacies identified from cores and cuttings, based on facies association characteristics (Fig. 10; Table 5). The importance of electrofacies characterizations in facies association description and management has been widely recognized. This classification does not require any artificial subdivision of the data population but follows naturally, based on the unique characteristics of gamma-ray log measurements reflecting lithological types, grain size and sedimentary structures within the logged interval. Traditionally, electrofacies descriptions of log shapes, such as bell, funnel, serrated, serrated funnel, cylinder (block) and linear, have been used for depositional facies analysis, which help to identify size and facies profile signatures of the key stratigraphic architecture which delimit and punctuate depositional sequences (e.g. Pirson 1983; Serra and Sulpice 1975; Rider 1991; Cant 1992; Miall 2000; Mohamed et al. 2013).

Four main facies associations (FA) have been defined from the facies, subfacies and interpreted depositional environments of the Ravendale Interval (Table 5; Fig. 10) as summarized below.

Interpretation of facies association-A (FAA): braided channel-fill system

Facies association-A (FAA), interpreted to be a braided channel-fill depositional system, generally occurs in the lower part of the Ravendale Interval and is observed over a wide area (Fig. 10). This facies association is represented by facies JR1, BS1 and BN1 (Table 5; Fig. 10) and in all three

Table 2 Summary of facies sequence and distribution in the Ravendale Interval and their sedimentological characteristics from Bancannia South-1 well

Facies	Subfacies	Thickness (m)	Re-evaluation of gamma-ray log integrated with lithological log [cuttings and cores as described by Baarda (1968a)]	Sedimentary structures
BS8		157	Facies BS8 was examined from the interval 230–387 m consisting mainly of quartz sandstone with minor siltstone beds (Fig. 7). The core sample-3 (295.6–297.6 m) is composed mainly of brown to light brown, reddish-brown, and light grey quartzose sandstones that are fine to medium grained, with subangular grains, some having subhedral to euhedral quartz overgrowths, and fair to good sorting	The sedimentary structure shows sandstone is thinly bedded with fine cross-laminations and sometime horizontal bedded (low angle). Algal biohermal was identified by Baarda (1968a)
BS7		73	Facies BS7 comprising the interval 387–460 m generally consists of sandstone with minor siltstone (Fig. 7). Quartz sandstone is medium-bedded thinning up to very thinly bedded. Core-4 (419.7–422.7 m) consists mainly of fine- to medium-grained sandstone with good to very well-sorted, sub-angular to sub-rounded quartz grains. This sandstone, ranges from grey-brownish to grey-green in colour	The sedimentary structures of the fine-grained sandstones and siltstones include parallel lamination and fine cross-laminations
BS6	BS6B	65	Subfacies BS6B (460–525 m) consists mainly of quartz sandstone with interbedded siltstone and shale (Fig. 7). Core-5 (510.2–513.2 m) is composed mainly of moderately sorted, sub-rounded pink, reddish brown and grey sandstone	This subfacies unit shows sedimentary structures that include parallel lamination and flat bedding
	BS6A	75	Subfacies BS6A examined from the interval 525–600 m is composed of fine- to medium-grained sandstone with minor shale beds up sequence (Fig. 7). Subfacies BS6A is not represented by core	
BS5		93	Facies BS5 (600–693 m) consists of medium to thick-bedded sandstone with intercalations of siltstone and shale that are variable in thickness (Fig. 7). Facies BS5 is 3.048 m thick and core sample-6 is described as light brown and grey to almost white quartz sandstone with thin interbeds of dark-grey siltstone. The shale is micaceous, silty and sandy	The sedimentary structure shows flat bedding in the fine- to medium-grained sandstone and siltstone
BS4		220	Facies BS4 (693–913 m) consists of thick-bedded sandstone alternating with siltstone and shale beds that are variable in thickness (Fig. 7). Core-7 (796.1–799.1 m) is predominantly quartz sandstone of mottled reddish brown and greenish grey colour, very fine grained, with mostly sub-angular and minor sub-rounded grains. There are minor silica-cemented micaceous siltstone beds, with minor shale beds in some parts	The sedimentary structure shows large scale flat-bedding surfaces separating the dominant massive quartz sandstone beds
BS3	BS3B	117	Subfacies BS3B (913–1030 m) is predominantly thick-bedded sandstone with minor siltstone (Fig. 7). Core sample-8 from the interval 916.8–919.8 m represents the upper part of the subfacies BS3. This core is composed mainly of red-brown quartz sandstone, very fine- to fine-grained with well-sorted sub-rounded grains	Sedimentary structures are represented by various types of flat bedding and fine cross-laminations
	BS3A	80	Subfacies BS3A, from the depth interval 1030–1110 m, are composed of interbedded sandstone, siltstone and shale (Fig. 7). Core sample-9, from the depth interval 1072.8–1075.9 m, consists of indurated, poorly to well-sorted sandstone in thin sandstone beds of 1–4 cm thickness that are vari-coloured red-brown, green and grey, varying to brick-red and light green	The dominant sedimentary structures are small-scale trough cross-beds and planar cross-bedding

Table 2 (continued)

Facies	Subfacies	Thickness (m)	Re-evaluation of gamma-ray log integrated with lithological log [cuttings and cores as described by Baarda (1968a)]	Sedimentary structures
BS2	BS2B	137	Subfacies BS2B, from the depth interval 1110–1247 m, generally consists of quartz sandstone with interbeds of minor siltstone and shale (Fig. 7). The core sample-10 from 1214.6 to 1217.6 m is mainly of sandstone, pale-brown to reddish-brown, with fine- to very fine-grained, moderately well-sorted quartz fragments in a silty clay matrix	The internal structure visible in the sandstone of the core sample is mainly bedding that is essentially flat with minor cross-bedding
	BS2A	163	Subfacies BS2A, from the depth interval 1247–1410 m, generally consists of siltstone and shale in beds 1–2 m thick, interbedded with quartz sandstone (Fig. 7). Core-11 (1313.9–1318.2 m) is mainly of pink to light red-brown quartz sandstone, very fine to fine-grained fair sorted subangular, with clear or rarely orange quartz and occasional light brown or green lithic grains	The sedimentary structure shows fine-grained sandstones that are massive, with minor cross-bedding and less common flat-bedding
	BS1	245	The depth interval 1410–1655 m in facies BS1 shows thick sandstone units with minor siltstone (Fig. 7). Facies BS1 is represented in three cores [12 (1412.7–1417.3 m); 13 (1458.4–1461.5 m); 14 (1615.4–1617.5 m)] that are quite similar lithologically. The quartz sandstone is vari-coloured from light red to brown and light pink. Individual beds show well to very well-sorted grains of fine to coarse grain size, but with some pebbly sandstone	Cross-bedding is dominant in the core, along with lesser low-angle cross-bedding and flat-bedding

wells provides the best stratigraphic control for the thickness of the lower part of the Ravendale Interval.

Two distinctive subfacies BN1A and BN1B in the Bancannia North-1 well are interpreted to have been formed as in-filled channels. They are dominantly composed of fine- to medium-grained sandstones interbedded with minor siltstone and very rare thin shale laminae. Facies BS1 and JR1 represent sediments deposited in a sandy braided channel-fill environment (cf. Cant and Walker 1978). Internally, the electrofacies of facies association-A shows a blocky profile of relatively thick sandstones with thinly interbedded siltstone and shaly siltstone that are very fine grained with thin shale interbeds (Fig. 10).

The sedimentary structures in facies association-A, interpreted as a braided channel-fill system, include cross-bedding in sand-dominant cores recorded by Baarda (1968a, b), along with lesser low-angle cross-bedding and flat-bedding, with minor fine cross-lamination and parallel horizontal lamination.

Identification of facies associations in sediments deposited in braided channel-fill depositional systems is generally based on the associated sedimentary structures, using relationships demonstrated by Miall (1977, 1996, 2000), Reineck and Singh (1980), Khalifa and Ward (2010), Weckwerth (2017), Labourdette (2011) and Noorbergen et al. (2018).

Interpretation of facies association-B (FAB): meandering channel-fill system

Facies association-B (FAB) is a major constituent of the Ravendale Interval and lies directly above deposits comprising facies association-A (FAA), as shown in Fig. 10. This facies association consists of facies BS2 and BS3 in the Bancannia South-1 well, facies BN2 and BN3 in the Bancannia North-1 well and facies JR2 and JR3 in the Jupiter-1 well (Table 5; Fig. 10). A moderately serrated funnel and blocky gamma-ray log profile indicates increasing sandstone content towards the top of this facies association, especially in the Bancannia North-1 and Bancannia South-1 wells, as shown in Fig. 10.

Facies BN2, BS2 and JR2 represent sediments that are probably similar to crevasse splay channel deposits and, as seen in cores, show fining-upward trends from generally fine-grained sandstone to siltstone. The internal structures of crevasse splay channel deposits are visible in the sandstone of core sample-10 from 1214.6 to 1217.6 m in the Bancannia South-1 well. This core shows mainly horizontal-bedded units with fine low-angle cross-laminations that are essentially flat with minor steeper cross-bedding and less common flat-bedding and parallel laminations. Likewise, facies BN3, facies BS3 and facies JR3 are characterized as likely similar small channel-fill sandstone and point bar

Table 3 Summary of facies sequence and distribution in the Ravendale Interval and their sedimentological characteristics from Bancannia North-1 well

Facies	Subfacies	Thickness (m)	Re-evaluation of gamma-ray log integrated with lithological log [cuttings and cores are described by Baarda (1968b)]	Sedimentary structures
BN5		125	Facies BN5 (405–530 m) generally consists of medium to thick-bedded sandstone units with interbedded siltstone and shale layers that are variable in thickness (Fig. 8). Facies BN5 is represented by two cores [Core-4 (420.3–421.5 m) and core-5 (480.3–481.1 m)] that are quite similar lithologically. These cores are composed mainly of very fine to fine quartz sandstones of varied colours, ranging from red to reddish-brown and pale-green to pale-brown, with poor to fair sorting. The siltstones and very fine sandstones are maroon in colour, with some brick-red clay and lustrous maroon shale. Sand-filled worm burrows are common in the clay layers	The main sedimentary structures are minor cross-bedding with lesser cross-lamination, and some massive intervals
BN4		120	Facies BN4 from the depth interval 530–650 m has thick sandstone bodies, with minor interbedded siltstone and shale that are variable in thickness (Fig. 8). Core-6 (573.1–575.7 m) consists mainly of quartz sandstone, very fine- to fine-grained, rarely medium-grained, with subangular quartz and rare traces of greenish lithic grains in a sparse white kaolinitic or red ferruginous matrix	The core sandstone has structures that include parallel laminations, fine cross-laminations, and flat-bedding, with rare horizontally deposited shale layers
BN3		71	Facies BN3 (650–721 m) generally consists of thick-bedded sandstone with very minor siltstone beds in the lower section (Fig. 8). Facies BN3 is not represented by core	
BN2	BN2B	139	Subfacies BN2B covers the depth interval from 721 to 860 m. It consists of interbedded sandstone, siltstone and minor shale (Fig. 8). The core sample-7 (725.9–727.2 m) is mainly of quartz sandstone, white and pale-brown, with coarse-grained, sub-rounded, moderately frosted quartz grains, and a trace of lithic grains, in well-cemented matrix of fine to very fine-grained quartz	Sedimentary structures include horizontal bedding, fine cross-lamination, along with bedding in thin laminae and less abundantly, small-scale cross-bedding
	BN2A	127	Subfacies BN2A covers the depth interval from 860 to 987 m. It consists of interbedded sandstone and shale, with rare to very rare thin layers of siltstone (Fig. 8). Core-8 in the interval 868.6–871.7 m consists of pinkish-brown and rare light pink sandstone, laminated with white fine to coarse-grained, poorly sorted, sub-rounded to sub-angular, partly frosted and pitted, clear and dull quartz with very rare traces of feldspar, a green mineral and very rare mica flakes	Sedimentary structures include horizontal bedding, flat-bedding, and a few parallel laminations. Some thin beds show current bedding
BN1	BN1B	98	Subfacies BN1B (987–1085 m) generally consists of thick-bedded sandstone, with minor thin beds of siltstone occurring in the lower section (Fig. 8). The core sample-9 (1039.3–1040.2 m) consists mainly of white to slightly pinkish white sandstone, fine- to medium-grained, sub-rounded to rounded and fair sorted. Clear and opaque partly frosted quartz grains, rare brown and yellow quartz grains and very rare mafic minerals are embedded in a partly calcareous matrix	Sedimentary structures include parallel horizontal lamination, and fine cross-lamination
	BN1A	65	Subfacies BN1A covers the depth interval from 1085 to 1150 m. It is made of thick-bedded sandstone (80%) with minor thin beds of shale towards the top of the subfacies (Fig. 8). Subfacies BN1A is not representing by core	

Table 4 Summary of facies sequence and distribution in the Ravendale Interval and their sedimentological characteristics from Jupiter-1 well

Facies	Subfacies	Thickness (m)	Re-evaluation of gamma-ray log integrated with lithological log [cuttings are described by Wiltshire (1969)]
JR8	JR8C	75	Subfacies JR8C, covering the depth interval 125–200 m, is composed of interbedded quartz sandstones and siltstones (Fig. 9). The cuttings indicate that the light grey to white medium- to coarse-grained sandstone is composed of well-sorted, well-rounded grains, generally clear, although some grains are white
	JR8B	75	Subfacies JR8B covers the depth interval from 200 to 275 m. It generally comprises thick-bedded sandstone with minor thin beds of shale occurring at the top of the subfacies (Fig. 9). Quartz sandstones are light grey to green, very fine to medium-grained, predominantly poorly sorted and containing subangular to sub-rounded quartz grains, often with a clayey and sometimes with a calcareous matrix, and rare to common accessory pyrite. Micro-micaceous shale is light green-grey and some red-brown, mottled, moderately firm, and blocky
	JR8A	50	Subfacies JR8A occurs at a drilled depth of 275–325 m. The lower part of the subfacies consists of thick-bedded sandstone with thin beds of siltstone (Fig. 9). Cuttings show generally light grey-green sandstone, ranging in grain size from medium sand to granules, with a modal size of coarse to very coarse sand. Minor hard siltstone fragments are light grey to dark grey, very sandy and clayey
JR7	JR7B	90	Subfacies JR7B from the interval 325–415 m consists of interbedded sandstone, siltstone and shale (Fig. 9). The cuttings show quartz sandstone with medium to coarse, sub-rounded to rounded grains, occasionally angular where re-crystallized, and rare green lithic grains in a sparse siliceous, partly kaolinitic matrix. The siltstone and shale interbeds are vivid-green, purplish-black and reddish brown in colour, soft, micaceous and fissile
	JR7A	85	Subfacies JR7A (415–500 m) contains interbeds of sandstones and siltstones with traces of shale (Fig. 9). The lithologies present in facies JR7A are similar to subfacies JR7B, mainly consisting of quartz sandstone, with patches of angular re-crystallized quartz grains. Interbeds of minor siltstone are very fine- to fine-grained, very hard, quartzose, and very micaceous, and there are minor black and dark grey shale layers
JR6		100	Facies IR6 occurs at a drilled depth of 500–600 m and generally consists of interbedded sandstones and siltstones with very thin beds of shale (Fig. 9). The cuttings show mainly quartz sandstone with minor siltstone and shale. The sandstone is brown to white and very fine to fine-grained, and is composed of sub-rounded to rounded quartz grains. The siltstone is red-brown, purple-brown and grey, varying to brown or brick-red. The shales are fairly hard and blocky to rarely fissile
JR5	JR5B	15	Subfacies JR5B covers the depth interval from 600 to 615 m. It consists of thick beds of quartz sandstone (70%) dominant over lesser shales (Fig. 9). The cuttings consist mainly of silicified quartzose sandstones that are generally light grey, to greenish light grey, with some white and pale pink tints. The shales are soft, micaceous and fissile
	JR5A	127	Subfacies JR5A (615–742 m) is made up predominantly of quartz sandstone, interbedded with minor siltstone and shale units (Fig. 9). The cuttings indicate that the sandstones are white and light grey to medium grey and pale to deep red brown. They are firm and friable to moderately hard and rarely very hard, with interbeds of minor siltstone and shale
JR4		127	Facies IR4 occurs at a drilled depth of 742–827 m and consists of interbedded sandstones and shales with very thin beds of siltstone in the middle part of the section (Fig. 9). Cuttings show light to medium grey and brown friable quartz sandstones with traces of green and black specks in a siliceous and calcareous matrix. The shale is hard and blocky to rarely fissile. The siltstones are firm, blocky, slightly calcareous, slightly micaceous, and commonly argillaceous
JR3	JR3B	98	Subfacies JR3B (827–925 m) is dominated by thick-bedded siltstone units alternating with quartz sandstone in the middle section (Fig. 9). The cuttings show very fine- to fine-grained siltstone, white to brownish-white, with sub-angular to rounded grains. The sandstone has well to very well-sorted grains, green and grey-green and slightly micaceous
	JR3A	132	Subfacies JR3A (925–1057 m) consists of interbeds of sandstones and shales with traces of siltstone beds that are variable in thickness (Fig. 9). The cuttings show sandstone, pale-brown to reddish-brown, with fine- to very fine-grained, moderately well-sorted quartz grains in a silty clay matrix. Shale that occurs in thin interbeds is commonly micaceous and slightly calcareous and the siltstones are very fine-grained, moderately well-sorted and soft to medium hard
JR2		168	Facies IR2 occurring at a drill depth of 1057–1225 m consists of sandstones interbedded with siltstone and shale beds that are variable in thickness (Fig. 9). The cuttings show mainly sandstone, fine- to medium-grained, with subangular to sub-rounded quartz grains. Siltstones are commonly quartzose, fine to coarse and commonly interbedded with very fine-grained shale that is hard, blocky and rarely fissile
JR1		210	Facies JR1 covers the depth interval from 1225 to 1435 m. It is composed of thick-bedded sandstone (70%) with alternating siltstone units that occur in the lower part of the section (Fig. 9). The cuttings indicate fine- to medium-grained, relatively well-sorted quartz sandstone and grey, medium to very fine-grained siltstone containing fine shale fragments and some mica in a calcareous to well-silicified, rarely kaolinitic, matrix

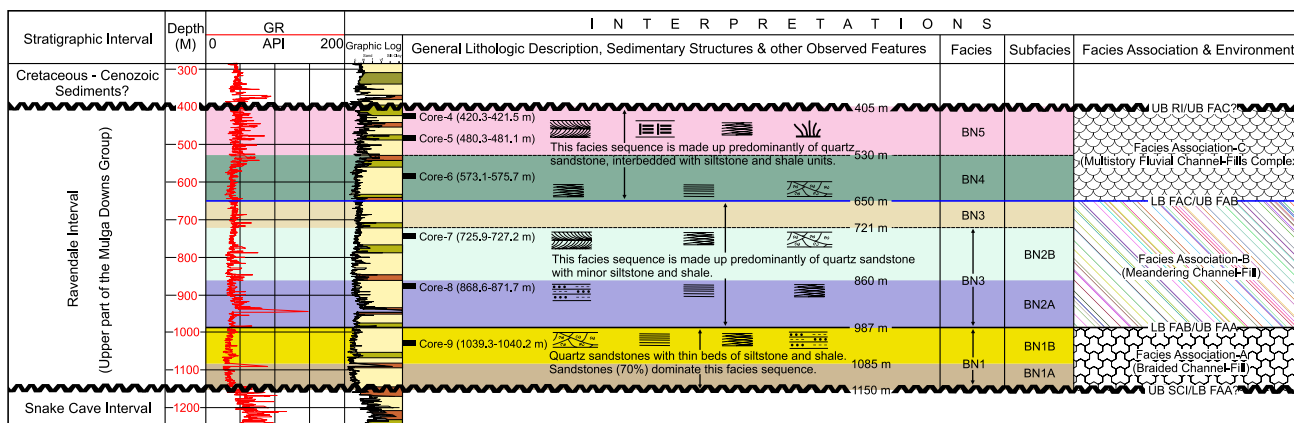


Fig. 8 Interpretive sedimentological log through the Ravendale Interval showing the distribution of major sedimentary facies/subfacies and facies associations in the Bancannia North-1 well. The well section is based on interpretation of gamma-ray log signature, core/cutting descriptions, lithology, sedimentary structures, and the well

completion report (refer to text for discussion). See Fig. 1b for location of the Bancannia North-1 well. See Fig. 5 for key to lithology, sedimentary structures, sedimentological features, and depositional environment symbols used in the well log

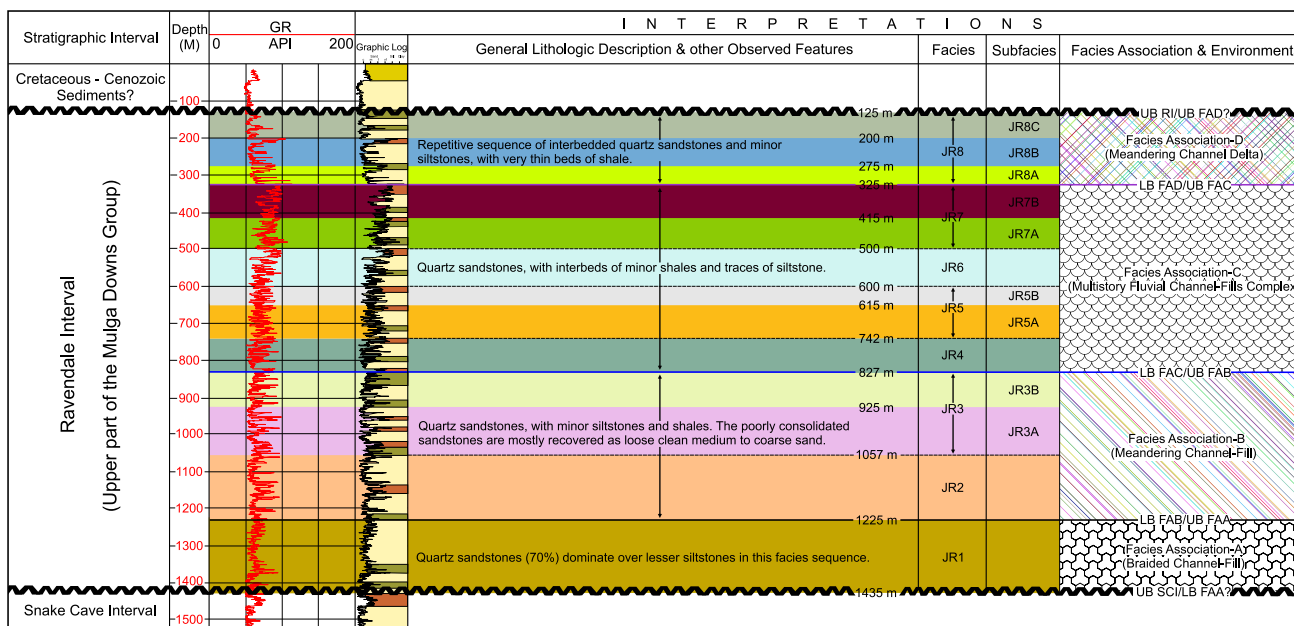


Fig. 9 Interpretive sedimentological log through the Ravendale Interval showing the distribution of major sedimentary facies/subfacies and facies associations in the Jupiter-1 well. The well section is based on the interpretation of gamma-ray log signature, cutting descriptions

and lithology, and the well completion report (refer to text for discussion). See Fig. 1b for location of the Jupiter-1 well. See Fig. 5 for key to lithological, sedimentological features, and depositional environment symbols used in the well log

environments with cores having upward-fining trends from generally fine-grained sandstone to siltstone. The ideal vertical succession of a channel-fill sandstone and point bar is characterized by a sharp base and a continuous, blocky or upward-fining gamma-ray log profile (Fig. 10). Cores from these three facies have sedimentary structures that include flat bedding and fine cross-laminations with less abundant small-scale trough cross-beds and planar cross-bedding.

Therefore, this facies association-B (FAB) is interpreted to represent a meandering channel-fill depositional system similar to those documented by Selley (1985), Reineck and Singh (1980), Miall (1992, 1996, 2000), Olariu and Bhat-tachrya (2006), Khalifa and Ward (2010) and Yao et al. (2018).

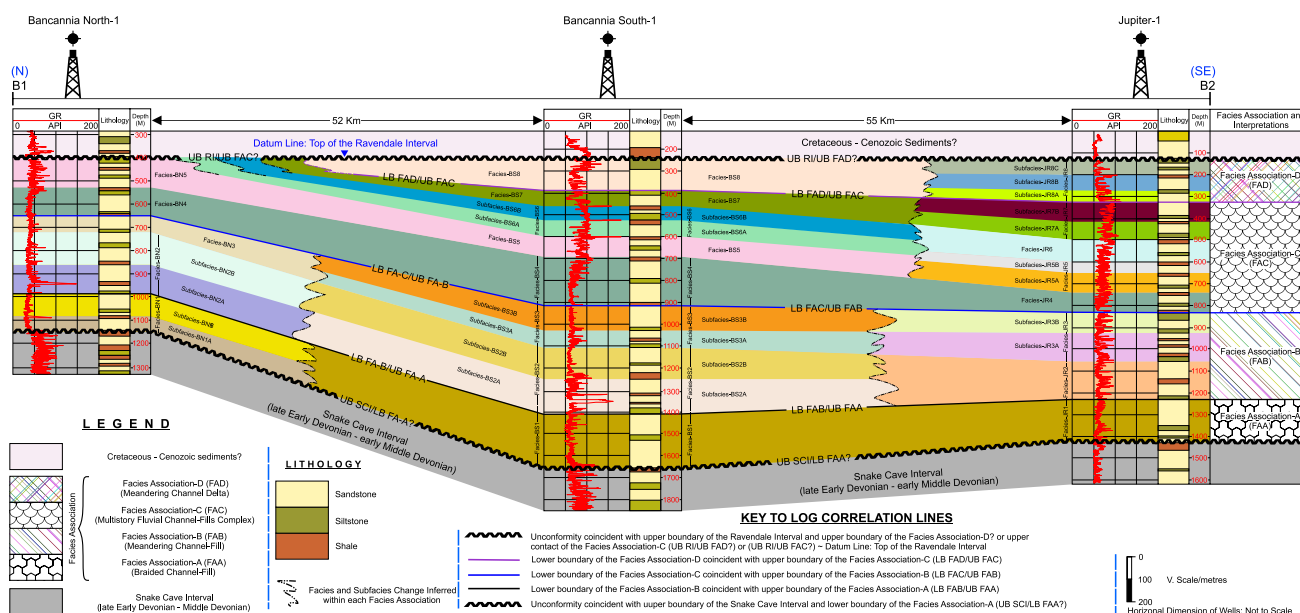


Fig. 10 Wireline log stratigraphic section showing correlation of major facies, subsfacies and inferred facies association boundaries in the three well sections through the Ravendale Interval in the Bancannia Trough. Note the top of the Ravendale Interval is used as a

stratigraphic datum. The subdivision of sedimentary facies and subsfacies is derived from general sedimentological features, lithology stacking patterns and gamma-ray values in each well. See Fig. 1b for the wireline log stratigraphic section location of the three wells

Table 5 Constituent facies and interpretation of the facies association

Facies association and depositional system	Constituent facies and main characteristics
FAA as the braided channel fill	Facies BN1 (subfacies BN1A and BN1B) are sediments of a channel-fill sands environment Facies BS1 and JR1 are sediments of a sandy braided channel-fill environment <i>In general, electrofacies of this facies association displays as a blocky pattern</i>
FAB as the meandering channel fill	Facies BN2, BS2, BS3 and JR2 are sediments of channel lag and crevasse splay sandstone environment Facies BN3, JR3 are sediments of an abundant small channel-fill sandstone and point bar environment <i>In general, electrofacies of this facies association displays as moderately serrated funnel and blocky patterns</i>
FAC as the multistory fluvial channel-fill complex	Facies BN4, BN5, BS4, BS5, BS6, BS7, JR4, JR5, JR6 and JR7 are sediments of either a single fluvial channel sandstone story or multistory fluvial channel sandstone stories environment <i>In general, electrofacies of this facies association display as serrate and serrated funnel patterns</i>
FAD as the meandering channel delta	Facies BS8 and, subsfacies JR8A and JR8C are sediments of distributary channel sands associated with crevasse splay siltstones environment Subfacies JR8B are sediments of a delta-plain complex environment <i>In general, electrofacies of this facies association display as funnel and bell patterns</i>

Interpretation of facies association-C (FAC): multistory fluvial channel-fill complex system

Facies association-C (FAC) generally occurs in the upper part of the Ravendale Interval in the Bancannia Trough (Fig. 10). This facies association contains facies BN4 and BN5 in the Bancannia North-1 well, with subordinate facies BS4, BS5, BS6 and BS7 in the Bancannia South-1 well

and JR4, JR5, JR6 and JR7 in the Jupiter-1 well (Table 2; Fig. 10).

A lithological description of sediment deposited in this facies association is given in the descriptions of facies BN4, BN5, BS4, BS5, BS6, BS7, JR4, JR5, JR6 and JR7 (Tables 2, 3, 4) and can be interpreted as various types (i.e. single and multistory) of fluvial channel sandstone bodies contained within facies association-C (FAC) as shown in Figs. 7, 8, 9 and Tables 2, 3, 4. Fluvial channel sandstone bodies in facies

association-C show a large variability of measured vertical thicknesses (Fig. 10). Maximum thicknesses recorded from the present data are about 500 m, but sandstone bodies ranging from 4 to nearly 10 m thick are by far the most common. Fine- to medium grained sandstone includes small-scale parallel lamination, horizontal bedded (low angle) and flat bedding with a few decimetres to centimetre scale massive beds as described by Baarda (1968a, b). The main feature of the electrofacies for facies association-C is a typical serrate and serrated funnel gamma-ray log profile, reflecting the interbedded sandstone–siltstone lithologies.

This facies association is believed to have been deposited in a multistory fluvial channel-fill complex depositional system like those documented by Reineck and Singh (1980), Miall (2000), Walker (2006), Olariu and Bhattacharya (2006) and Noorbergen et al. (2018).

Interpretation of facies association-D (FAD): meandering channel delta system

Facies association-D (FAD) forms a minor constituent (< 10%) of the Ravendale Interval. This facies association is represented by facies BS8 and JR8 (Table 5; Fig. 10). Facies BS8 and subfacies JR8A and JR8C represent sediments deposited as distributary channel sands associated with crevasse splay siltstone deposits, and subfacies JR8B is probably most similar to delta–plain complex deposits (Tables 4, 5). In general, electrofacies of this facies association has funnel and bell patterns on the gamma-ray log that are interpreted as upward-coarsening sandstone.

The lithology of facies association-D (FAD) is interpreted to be composed of sheet-like sand-bodies interbedded with fine-grained siltstones and well-sorted and well-rounded, medium- to coarse-grained sandstones, constituting an overall upward-coarsening stratigraphy. Shale beds ranging from a few tens of centimeters to 1 m thick are interbedded with the sandstone. The shale is light green-grey to red-brown in colour, mottled, moderately firm, blocky and slightly micaceous in this facies association. The sandstones have well-developed thin beds with fine cross-laminations and there are some horizontal-bedded siltstones. Traces of algal bioherms are common throughout these deposits. Facies association-D (FAD) is interpreted as a meandering channel delta depositional system as in the models of Reineck and Singh (1980), Miall (1978, 1985, 2000), Khalifa (2006), Walker (1984, 2006), Noorbergen et al. (2018) and Zongquan et al. (2018).

Discussion

Wireline log controlled lithostratigraphic unit correlations versus facies association

In the first model, our reference case, the lithostratigraphic architecture of the Ravendale Interval in this study area was determined using correlation of wireline logs with lithologic features in described cores from the three available wells. Most of the lithostratigraphic units in the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells, as defined from cores, cuttings and characteristic gamma-ray and resistivity log responses, provide data for facies association analysis. In these wells, thicknesses of sandstone, siltstone and shale strata range from less than 1 m to several hundred metres. In ascending lithostratigraphic order, the following lithostratigraphic units are recognized: RI1, RI2, RI3, RI4 and RI5 (Fig. 11).

Lithostratigraphic Unit-RI1, which represents strata at the base of the Ravendale Interval, unconformably overlies the Snake Cave Interval, and this is the oldest unit in the stratigraphic architecture of the Ravendale Interval in the study area. The unit shows an abrupt lithological change in both the gamma-ray and resistivity log characteristics at the unconformable lower boundary of Lithostratigraphic Unit-RI1 (LB Unit-RI1), coincident with the lower boundary of facies association-A (LB FAA?), as shown in Fig. 11.

Internally, the architecture of Lithostratigraphic Unit-RI1 is represented by stacked coarsening-upward sandstone beds with 50 m average thickness, 60% sand content and variable gamma-ray logs. The upper part of Lithostratigraphic Unit-RI1 exhibits a fining-upward changing to a coarsening-upward gamma-ray pattern with a wide distribution in the study area. The gamma-ray log patterns show blocky sandstone beds and bedsets that thicken and increase in grain size upwards. In the Bancannia South-1 well, this unit is dominated by 10–20 m thick quartz sandstone beds, with interbedded siltstones ranging from 20 to 40%, and fewer shale beds (Fig. 11). Furthermore, in places, the lower part of Lithostratigraphic Unit-RI1 is defined by the facies association-A (braided channel-fill depositional system) and the uppermost part of Lithostratigraphic Unit-RI1 as facies association-B (meandering channel-fill system), as shown in Fig. 11. In the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells, gamma-ray and resistivity log patterns of Lithostratigraphic Unit-RI1 are similar. Lithostratigraphic Unit-RI1 reaches a maximum thickness of approximately 404 m in the Bancannia South-1 well, and a minimum thickness of approximately 297 m at the southern margin of the study area, in the Jupiter-1 well (Fig. 11).

Wireline log correlation shows that Lithostratigraphic Unit-RI2 gradationally overlies Lithostratigraphic Unit-RI1

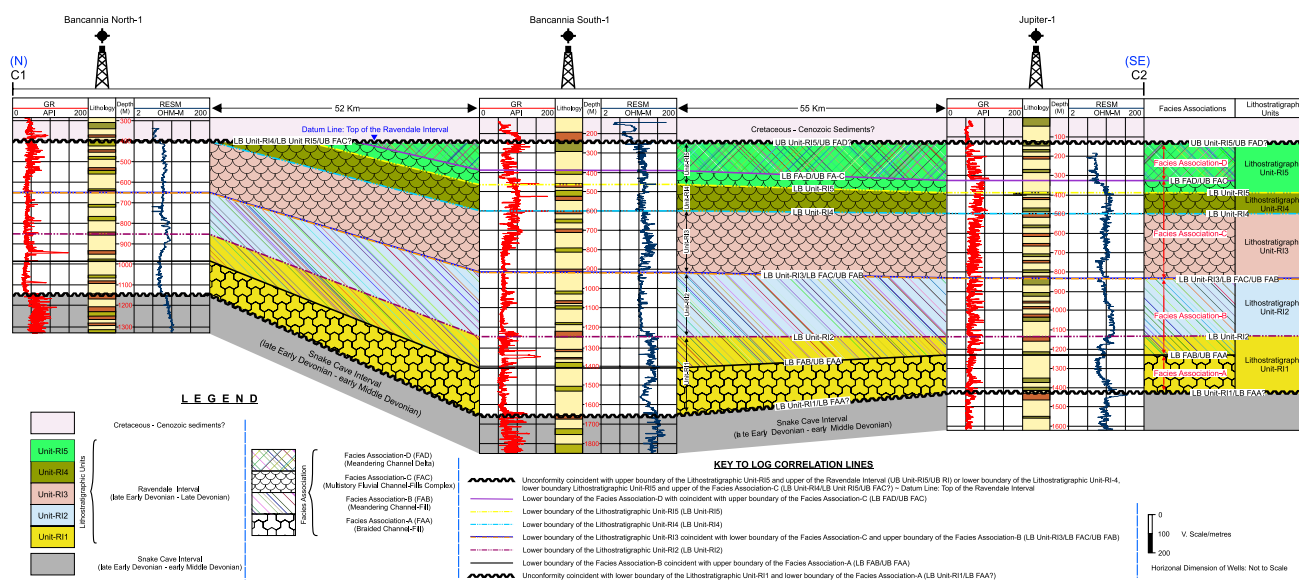


Fig. 11 Stratigraphic model showing the relationship between lithostratigraphic units and facies associations of the Ravendale Interval in the Bancannia Trough. Note the top of the Ravendale Interval is used as a stratigraphic datum. Model is based on correlation of wireline logs of the Bancannia South-1, Bancannia North-1 and

Jupiter-1 wells (Fig. 11). Wireline log characteristics in Fig. 11 show an abrupt change in the gamma-ray and resistivity log responses at the lower boundary of Lithostratigraphic Unit-RI2 (LB Unit-RI2). Note the strong, sharp, high gamma-ray values in the Bancannia South-1 well around 1251 m and log segments with relatively high gamma-ray values at 850 m in the Bancannia North-1 well and at 1135 m in Jupiter-1 well. The lower boundary of this unit (LB Unit-RI2) in the Bancannia South-1 well shows an increase in gamma-ray response and a decrease in resistivity values coinciding with a change to a dominant shale lithology.

In the Bancannia North-1 well, on the north-eastern side of the Bancannia Trough, the upper part of Lithostratigraphic Unit-RI2 is similar in lithology to the equivalent sections in the Bancannia South-1 well (Fig. 11). The upper part of Lithostratigraphic Unit-RI2 is composed of interbedded sandstone and siltstone with fining-upward trends. The interbedded sandstones are approximately 5–10 m thick and are separated by thin-bedded shales that occur repeatedly in the middle part of the unit. Figure 11 shows that the Lithostratigraphic Unit-RI2 is mainly dominated by facies association-B (FAB) interpreted as a meandering channel-fill system, while the principal lithology in the lower part of this unit is quartz sandstone with minor siltstone and rare shale in all three wells. Lithostratigraphic Unit-RI2 is widespread throughout the study area (Fig. 11). The maximum known thickness of Lithostratigraphic Unit-RI2 (337 m) has been recorded in the Bancannia South-1 well and the

minimum thickness (200 m) in the Bancannia North-1 well on the north-eastern of the Bancannia Trough (see location in Fig. 1).

Lithostratigraphic Unit-RI3 presents stratal architecture in the middle part of the Ravendale Interval as defined in the study area (Fig. 11). The lower boundary of Lithostratigraphic Unit-RI3 (LB Unit-RI3) is also coincident with the lower boundary of facies association-C (LB FAC) and the upper boundary of facies association-B (UB FAB), as shown in Fig. 11.

The gamma-ray log patterns of Lithostratigraphic Unit-RI3 show both upward coarsening and thickening sandstone/siltstone beds and fining and thinning siltstone/shale beds (Fig. 11). Overall, this lithostratigraphic unit averages 30 m thick and has an average sandstone content of 50–60%. Interbedded siltstones are 5–10 m thick, with an average of 10% thin-bedded shale. Figure 11 shows that Lithostratigraphic Unit-RI3 is mainly dominated by facies association-C (FAC) “multistory fluvial channel-fill complex depositional system” in all three wells. Lithostratigraphic Unit-RI3 is widely distributed in the Bancannia Trough in all wells drilled in the Ravendale Interval section. Unit-RI3 attains a maximum thickness of about 327 m in the Jupiter-1 well, is recorded as 313 m thick in the Bancannia South-1 well and has a minimum thickness of 212 m in the Bancannia North-1 well (Fig. 11).

Lithostratigraphic Unit-RI4 forms the upper part of the stratigraphic architecture of the Ravendale Interval in the Bancannia South-1 and in the Jupiter-1 wells (Fig. 11), but

it is absent in the Bancannia North-1 well on the north-eastern side of the Bancannia Trough, where it has possibly been eroded away. The thickness ranges from a maximum of 137 m in the Bancannia South-1 well in the central part of the Bancannia Trough to a minimum of about 113 m in the Jupiter-1 well in the southern part of the Bancannia Trough (Fig. 11).

The lower boundary of Lithostratigraphic Unit-RI4 (LB RI4) is seen clearly in the wireline log patterns (Fig. 11), with a sharp change to a relatively high gamma-ray pattern and relatively low resistivity values in Bancannia South-1 well. Two log markers can be identified in both wells, one at about 600 m depth in the Bancannia South-1 well showing a relatively high gamma-ray value corresponding to a thick shale bed, and the other at a depth of 500 m in the Jupiter-1 well where the boundary is also marked by a relatively high gamma-ray value.

Furthermore, wireline logs showing similar gamma-ray and resistivity curve patterns, confirmed by the cuttings from both the Bancannia South-1 and Jupiter-1 wells, indicate that Lithostratigraphic Unit-RI4 is dominantly composed of quartz sandstone beds with interbedded 5–10 m thick siltstones, making up from 20 to 60%, and minor shale beds (Fig. 11). The whole of Lithostratigraphic Unit-RI4 belongs to Facies association-C (FAC) “multistory fluvial channel-fill complex system” in both the Bancannia South-1 and Jupiter-1 wells, as shown in Fig. 11.

Lithostratigraphic Unit-RI5 forms the uppermost part of the stratigraphic architecture of the Ravendale Interval in the Bancannia South-1 and Jupiter-1 wells (Fig. 11), but it is absent in the Bancannia North-1 well on the north-eastern side of the Bancannia Trough, possibly due to subsequent erosion (see location in Fig. 1).

The lower boundary of Lithostratigraphic Unit-RI5 (LB Unit-RI5) was identified at a depth of 463 m in the Bancannia South-1 well, where a relatively high gamma-ray and relatively low resistivity value indicates a shale bed, and the other at a depth of 387 m in the Jupiter-1 well, where the boundary is also marked by a relatively high gamma-ray and relatively low resistivity value.

In both the Bancannia South-1 and the Jupiter-1 wells, the lower part of Lithostratigraphic Unit-RI5 is defined by the facies association-C (multistory fluvial channel-fill complex depositional system) and the middle to upper parts of this unit fall within facies association-D (FAD) corresponding to a meandering channel delta depositional system (Fig. 11). The boundary between facies association-C (UB FAC) with facies association-D (LB FAD) is well defined within Lithostratigraphic Unit-RI5 in Fig. 11. Lithostratigraphic Unit-RI5 demonstrates lateral continuity of similar lithology types in both the Bancannia South-1 and Jupiter-1 wells. The maximum preserved thickness of Lithostratigraphic Unit-RI5 (262 m) has been recorded in the Jupiter-1 well and the

minimum thickness (233 m) in the Bancannia South-1 well, as shown in Fig. 11.

Implications for facies sequences and reservoir properties

The upper Middle Devonian to Upper Devonian Ravendale Interval contains the main potential reservoir units within the facies sequences in the Bancannia Trough. Within these quartz sandstones, five potential reservoir units are distinguished based on wireline log correlation. The sedimentological characteristics identified in the lithology data and tied to gamma-ray log profiles, together with the petrophysical properties of potential reservoir units, are summarized in the following paragraphs (after internal company reports from the three wells; Hus et al. 2006; Blevin et al. 2007). The identification and correlation of these units relies on wireline log ‘breaks’ and log signatures.

Furthermore, in the Bancannia Trough the wells Bancannia South-1, Bancannia North-1 and Jupiter-1 all contain at least one reservoir unit. The Bancannia South-1 well completion report identifies the Ravendale Interval in that well as a “major potential sandstone reservoir facies” for the area. Two reservoir units are present in the Bancannia South-1, totaling more than 550 m. The major reservoir unit depth interval is from 830 to 1222 m and has a thickness of 392 m. This unit includes quartz sandstone, some cross-bedded and thinly interbedded siltstone (Fig. 7). The depositional environment included probable fluvial channel lag and channel-fill sandstone bodies, with single and multistory channels. This unit has fair to good porosity and permeability characteristics. Robertson Research Australia (2001) record petrographic descriptions of mature massive quartz sandstones from a depth of 1074 m with good intra-granular porosity ranging from 5 to 20%, and < 50 to 150 mD permeability. Another 175 m thick reservoir unit representing a sandy braided channel-fill environment occurs at 1448–1623 m. This reservoir unit is composed mainly of quartz sandstone with minor siltstone. The porosity of this unit average 5% and average permeability values is around 20 mD. The petrographic study of the samples from a depth of 1616 m by Robertson Research Australia (2001) revealed a moderately to well-sorted quartz-rich arenite, with disseminated very fine iron oxide along detrital grain margins (black), and minor primary intergranular porosity.

Two potential reservoir units are also present in the Jupiter-1 well. The porosities of these reservoir units are in general good to excellent (cf. Blevin et al. 2007). These reservoir facies units are present as a lower section (1173–1371 m) and an upper section (122–323 m), with an aggregate thickness of 399 m (cf. Bembrick 1997b; Blevin et al. 2007). The lower reservoir unit has a thickness of 198 m; it consists of high energy fluvial quartz sandstone with minor siltstone.

This unit has poor to fair porosity (10–20%). The upper reservoir unit is 201 m thick and is made up predominantly of quartz sandstone having a grain size ranging from medium to coarse, with fair to good sorting and associated minor shale and siltstone (Fig. 9). The porosity is good at 20–25% and the average permeability is excellent at 40 mD (cf. Bembrick 1997b; Hus et al. 2006). These properties suggest distributary channel sands in a delta-plain complex environment (cf. Blevin et al. 2007).

Results reported in the Bancannia North-1 well completion report identify a potential reservoir unit 195 m thick at the depth interval 935–1130 m (Fig. 8). This unit, consisting of quartz sandstone with fair sorting and minor shale through the section, has poor to fair porosity (20–25%) as documented by Bembrick (1997b) and Blevin et al. (2007). A high energy meandering channel-fill system with abundant fine-grained channel-fill sandstone is suggested as the depositional environment.

The subsurface data reveal that the dominant lithology present in the Ravendale Interval is well-sorted quartz sandstone, with minor interbeds of siltstone and shale. The sandstone units are commonly cross-bedded and are considered to record fluvial depositional environments. Some overall similarities in the sequence of reservoir unit lithologies can be seen in the wireline log signatures between the three wells. In nearly all cases, the reservoir units occur towards the base of the Ravendale Interval. In general, the porosities are fair to good—ranging from 10% to nearly 25% and the permeabilities ranging from 20 mD up to 140 mD. These environments probably consisted of channel sands in a braided channel-fill system with some input from a meandering channel-fill system. Reineck and Singh (1980), Miall (1992, 2000) and Olariu and Bhattacharya (2006) provide recent reviews of the literature on braided and meandering fluvial deposits. Figure 11 compares the lithologies and wireline log signatures between the three wells—Bancannia North-1, Bancannia South-1 and Jupiter-1 in the Bancannia Trough. Shale units up to 30 m thick are common in the middle part of the Ravendale sequence and could potentially provide good seals over underlying reservoir sandstones.

Conclusions

This paper presents a new interpretation of wireline log signatures (gamma-ray, resistivity and sonic), combined with core and cutting descriptions and limited petrophysical property data, that have enabled the construction of lithostratigraphic unit architecture using facies associations and related depositional environment models for the Ravendale Interval in the Bancannia Trough, western Darling Basin, New South Wales, Australia.

The present study distinguished 20 sedimentary facies and 19 subfacies, which were grouped into four facies associations defined by core and cutting descriptions combined with wireline log (gamma-ray) signatures of the Ravendale Interval in the Bancannia Trough. Electrofacies analysis has proved to be essential in attempting to understand better the architecture and to distinguish the facies associations (FA) interpreted here as follows: (FAA), a braided channel-fill system; (FAB), a meandering channel-fill system; (FAC), a multistory fluvial channel-fill complex system; and (FAD), a meandering channel delta system.

The internal stratigraphic architecture and geometry of the Ravendale Interval within the Bancannia South-1, Bancannia North-1 and Jupiter-1 wells in the study area can be divided into five lithostratigraphic Units RI1, RI2, RI3, RI4 and RI5. This study, in addition to providing the basis for a predictive sandstone facies sequence framework, can also be used to re-enforce Darling Basin petroleum exploration as there are significant variations in the local and regional stratigraphic sequence setting.

Lithostratigraphic unit correlation versus sedimentary facies association models indicate that there may be productive sand-rich intervals within the major upper Middle Devonian–Upper Devonian Ravendale Interval in the Bancannia Trough, where currently there are little available borehole data or outcrop information. Therefore, this area is recommended for future hydrocarbon-bearing reservoir exploration.

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