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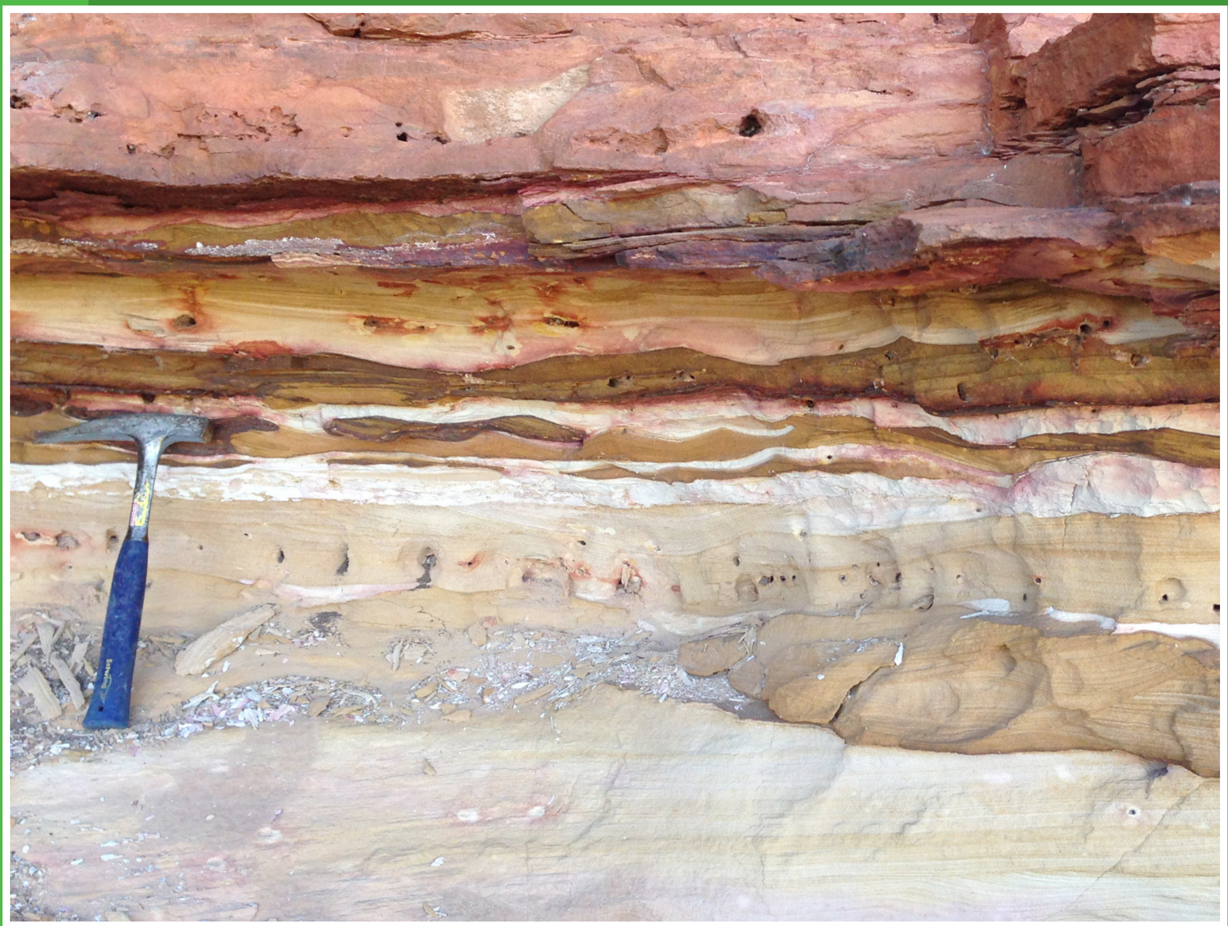
REPORT 173

THE LIVERINGA GROUP, CANNING BASIN: CORRELATING OUTCROP TO SUBSURFACE

by LM Dent



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Cover photograph: Outcrop section of the Lightjack Formation on the Balgo Terrace, southeastern Canning Basin

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The Liveringa Group, Canning Basin: correlating outcrop to subsurface

by

LM Dent

Abstract

The middle to late Permian Liveringa Group has been identified and mapped in outcrop across large areas of the northern Canning Basin in the Gregory Sub-basin, Fitzroy Trough and Balgo and Betty Terraces. Previously, the group was divided into three formations; however, the application of this subdivision to the subsurface Liveringa Group is limited. This Report presents a two-part subdivision for the subsurface Liveringa Group that can be correlated across the northern Canning Basin.

Historically, the Liveringa Group was divided, in ascending order, into the Lightjack Formation, the Condren Sandstone and the Hardman Formation. In some regions, the Hardman Formation was further divided into three members: the Kirkby Range, Hicks Range and Cherrabun Members. This study identified nine facies associations in outcrops of the Lightjack Formation, Condren Sandstone, Kirkby Range Member and Hicks Range Sandstone Member. These associations record a broad regression during the deposition of the Lightjack Formation that culminated in maximum regression marked by the fluvial facies identified in the Condren Sandstone. This was followed by a transgressive phase with a return to shallow-marine conditions recorded in the Kirkby Range Member of the Hardman Formation. The regressive trend observed in outcrop correlates with an overall coarsening-up trend observed in gamma ray logs from subsurface wells and a broadly negative or regressive trend in the Dynamic-INPEFA curve.

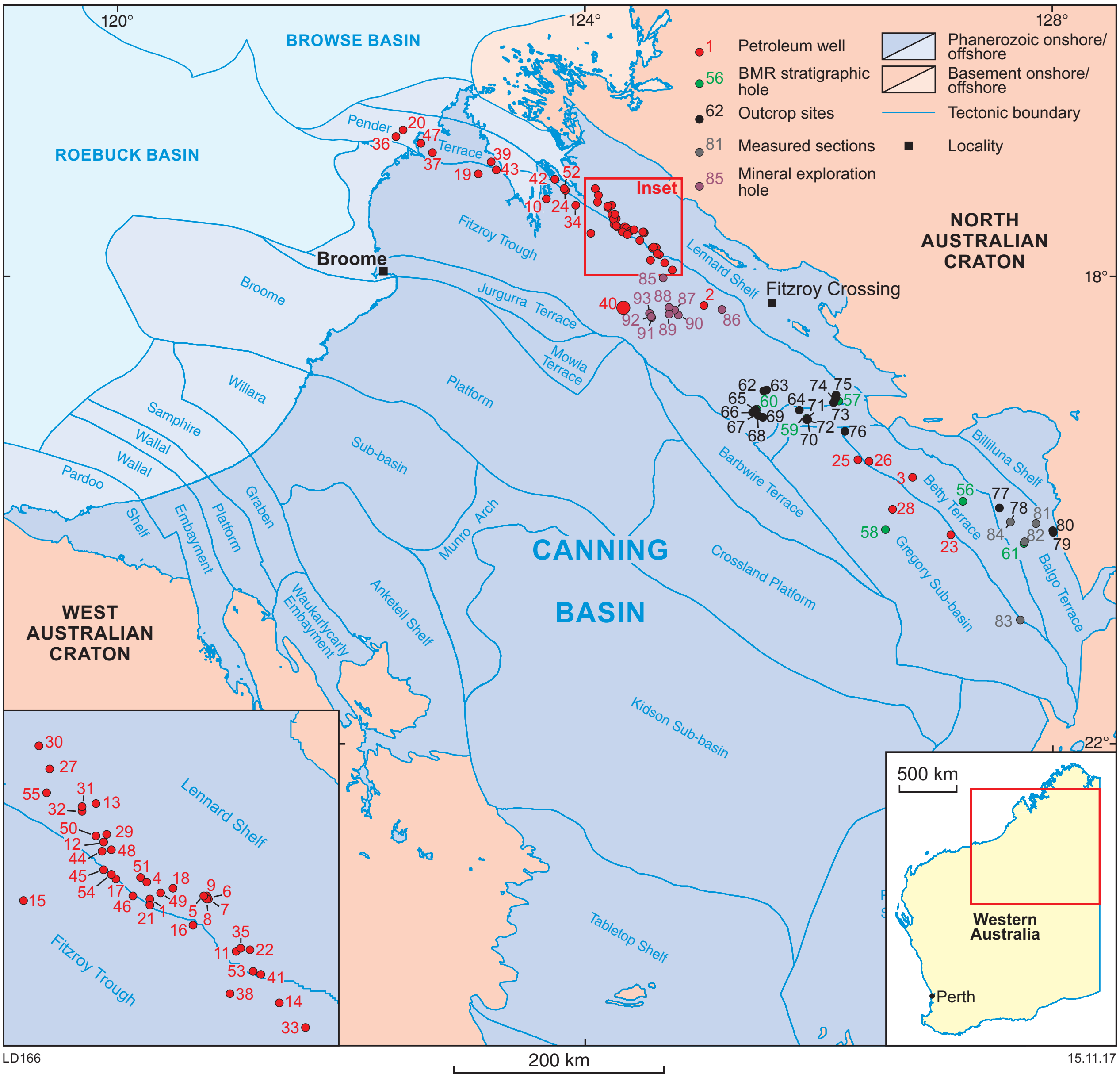
The proposed two-part division of the Liveringa Group is based on the identification of these two trends: the older Lightjack Formation and Condren Sandstone together exhibit a regressive trend, while the younger Hardman Formation comprises the change from regressive to transgressive depositional facies within the Canning Basin. Individual members of the Hardman Formation could not be definitively identified from subsurface gamma ray logs or in the Dynamic-INPEFA curves; however, the three members were identified locally where good outcrop and well data were available in close proximity.

KEYWORDS: facies analysis, outcrop, stratigraphic correlation, well log interpretation

Introduction

The Canning Basin, in northwestern Australia, hosts an Ordovician to Cenozoic sedimentary fill (Forman and Wales, 1981; Yeates et al., 1984; Kennard et al., 1994). Thin coal seams in the middle Permian Lightjack Formation have enticed sporadic attention to this interval. However, since the 1:250 000 mapping and basin studies undertaken in the 1970s, the middle and upper Permian stratigraphy has received significantly less attention than the Ordovician, Devonian, Carboniferous and early Permian intervals, which have been favoured for research due to their petroleum prospectivity (Lehmann, 1984; Apak and Backhouse, 1999; Redfern and Williams, 2002; Haines, 2009). Middle–late Permian sedimentary rocks are widely distributed but discontinuous across the Canning Basin. These strata comprise the Liveringa Group and Godfrey Beds in the northeast in the Fitzroy Trough, Gregory Sub-basin and flanking Crossland Platform, Lennard Shelf and Betty, Balgo and Jurgurra Terraces; the Triwhite Sandstone in the far southwest in the Kidson Sub-basin, and Tabletop and Anketell Shelves; and the Chirup Formation in the Wallal Embayment (Fig. 1). The Liveringa Group and its equivalents are absent in central basin areas, on the Broome Platform, Jurgurra Terrace, Crossland Platform and the Willara Sub-basin (Mory, 2010). Coal prospectivity is limited to the northeastern parts of the Canning Basin, mainly the Fitzroy Trough, and the Liveringa Group stratigraphy in this area has received the most attention. Early work by Yeates et al. (1975a) divided the Liveringa Group into three formations: the lower Lightjack Formation, middle Condren Sandstone and the upper Hardman Formation. Of these, the Hardman Formation was further divided into the Kirkby Range, Hicks Range Sandstone and Cherrabun Members (Fig. 2). These divisions were retained and incorporated into the 1:250 000 Series maps.

Insufficient interest and difficulties interpreting well logs, due to casing shoe positions, has prevented the application of formation divisions to subsurface sections of the Liveringa Group (Mory, 2010). As a result, there is still a poor understanding of the subsurface stratigraphy that impedes detailed definition and correlation of the strata. The Liveringa Group and equivalents have been intersected in 61 petroleum wells and stratigraphic holes, although cored sections are limited; most of the wells are located in the northwestern Fitzroy Trough and adjacent Lennard Shelf (Fig. 1). However, the majority of outcrops are located in the southeastern Fitzroy Trough, Gregory Sub-basin and Balgo Terrace. Outcrops, wells and well log data are sparsely distributed in basin areas south of the Fitzroy Trough and Gregory Sub-basin. Limited core data and the large distances between outcrop and wells make



1 Aquanita 1	**21** Katy 1	**41** Philydrum 1	**61** BMR Lucas 14	**81** Lightjack 1 (Gumbo Point)
2 Asgard 1	**22** Kennedia 1	**42** Point Torment 1	**62** Shore Range 1	**82** Lightjack 2 (Micha Bore)
3 Bindi 1	**23** Kilang Kilang 1	**43** Puratte 1	**63** Shore Range 2	**83** Lightjack 3 (Stretch Range)
4 Blackstone 1	**24** Kora 1	**44** Scrubby 1	**64** Beefwood Park	**84** Condren Pinnacles
5 Blina 3	**25** Lake Betty 1	**45** Sundown 2	**65** Millyit Range 1	**85** ARCMR045
6 Blina 4	**26** Lanagan 1	**46** Sunup 1	**66** Millyit Range 2	**86** ARCMR054
7 Blina 5	**27** Langoora 1	**47** Tappers Inlet 1	**67** Millyit Range 3	**87** ARCMR069
8 Blina 7	**28** Lawford 1	**48** Terrace 1	**68** Millyit Range 4	**88** ARCMR070
9 Blina 8	**29** Lloyd 2	**49** Thompsons 1	**69** Millyit Range 5	**89** ARCMR071
10 Booran 1	**30** May River 1	**50** Wattle 1	**70** Hicks Range 1	**90** ARCMR072
11 Boronia 1	**31** Meda 1	**51** West Blackstone 1	**71** Hicks Range 2	**91** SR01
12 Boundary 1	**32** Meda 2	**52** West Kora 1	**72** Hicks Range 3	**92** SR02
13 Canegrass 1	**33** Metters 1	**53** West Philydrum 1	**73** Christmas Creek 1	**93** SR04
14 Crimson Lake 1	**34** Millard 1	**54** Whitewell 1	**74** Christmas Creek 2	
15 East Yeeda 1	**35** Mimosa 1	**55** Yarrada 1	**75** Christmas Creek 3	
16 Hakea 1	**36** Minjin 1	**56** BMR Mt Bannerman 1	**76** Boundary Hill	
17 Hangover 1	**37** Moogana 1	**57** BMR Mt Bannerman 2	**77** Durbai Creek 1	
18 Janpam 1	**38** Nemile 1	**58** BMR Cornish 1	**78** Condren Pinnacles 1	
19 Jum Jum 1	**39** Padilpa 1	**59** BMR Crossland 1	**79** Namalook 1	
20 Kambara 1	**40** Petaluma 1	**60** BMR Crossland 2	**80** Namalook 2	

Figure 1. **Structural subdivisions of the Canning Basin with the location of petroleum wells, outcrop sites, measured sections, stratigraphic holes and mineral exploration holes used in this study**

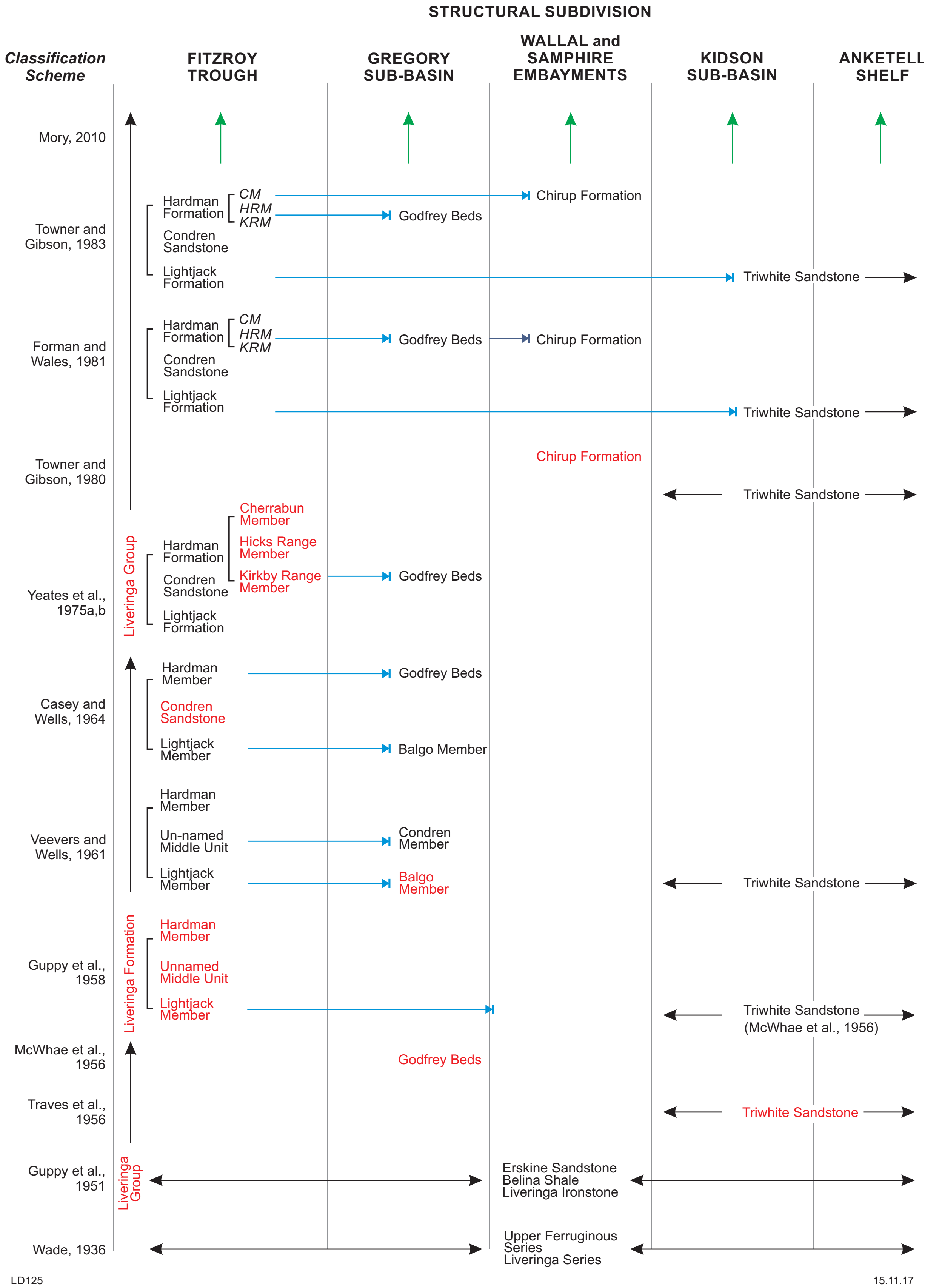


Figure 2. Evolution of stratigraphic nomenclature of the Liveringa Group across the Canning Basin, arranged using structural subdivisions of Martin et al. (2015); red text indicates the initiation of a new classification, reclassification or subdivision; blue arrows indicate laterally equivalent strata with different names; black arrows indicate consistent nomenclature across multiple structural subdivisions of the basin; green arrows indicate consistent use of most recent nomenclature in Mory (2010)

it difficult to correlate outcrop facies to well logs, and challenging to subdivide the subsurface Liveringa Group into its component formations and members. Interpreting individual datasets independently is restrictive as there is limited information for each. However, a significantly more robust dataset was produced by combining outcrop facies and well logs, historical log data (e.g. BMR drillholes), palynozones, and key indicators of depositional setting such as coal, glauconite and spinose acritarchs.

This Report focuses on the Liveringa Group stratigraphy in the northeastern Canning Basin within the structural subdivisions of the Fitzroy Trough, Gregory Sub-basin and Balgo Terrace (Fig. 1). These areas were selected due to extensive outcrop, and subsurface intersection in 55 petroleum wells and six stratigraphic holes drilled by the Bureau of Mineral Resources (BMR, an earlier name for Geoscience Australia; Appendix 1). The geology of the Liveringa Group was assessed at a series of outcrop sites (Fig. 1) to identify major outcrop-scale facies associations and facies trends. These data were integrated with well data and other available information to support division and correlate the subsurface succession of the Liveringa Group.

Regional geological setting

Structural and tectonic overview

The intracratonic Canning Basin is Australia's largest onshore basin, extending over 640 000 km^2 onshore, with an additional offshore area of ~100 000 km^2. Basin formation was initiated during Early to Late Ordovician rifting, with subsequent basin evolution controlled by four major tectonic events between the Devonian and Triassic, as summarized in Figure 3 (Drummond et al., 1991; Shaw et al., 1994; Parra-Garcia et al., 2014). Structurally the basin constitutes four major depocenters, flanked by a series of shelves, platforms and terraces that display a predominantly northwest structural grain (Fig. 1; Yeates et al., 1984; Shaw et al., 1994; Hocking et al., 1994). The Fitzroy Trough and Gregory Sub-basin are aligned northwest–southeast forming extensive depocenters in the northern basin (Fig. 1). The formation of the Fitzroy Trough was initiated in the Ordovician with continued development up to the Cretaceous. It also experienced significant growth during the Devonian–Carboniferous extension (Brown et al., 1984; Drummond et al., 1991; Shaw et al., 1994; Parra-Garcia et al., 2014). Ordovician–Cenozoic sedimentary units fill the basin, with thicknesses up to ~15 km estimated in the Fitzroy Trough (Forman and Wales, 1981; Kennard et al., 1994; Mory, 2010). The earliest units are Ordovician–Silurian and have not been intersected in drillcore in the Fitzroy Trough, although their presence has been interpreted from seismic sections. Parra-Garcia et al. (2014) used seismic data to suggest that the thickness of Ordovician–Silurian sedimentary rocks is significantly greater in the Fitzroy Trough than on the adjacent uplifted areas. This trend of stratal thickening into the Fitzroy Trough was also observed in the overlying Permo-Carboniferous deposits (Mory, 2010; Dent, 2016).

Sequence stratigraphic context

Kennard et al. (1994) assigned the Ordovician–Cretaceous basin fill to four first-order megasequences that comprise 15 second-order supersequences (Fig. 3). Deposition of each megasequence was correlated to a major tectonic phase in basin development. The Liveringa Group forms part of the third, the late Carboniferous – Permian megasequence, which was deposited during the Point Moody Extension event (Fig. 3). The base of this megasequence is marked by a basin-wide unconformity at the base of the Grant Group, which is related to uplift and erosion caused by the Meda Transpression (Fig. 3). The top of the megasequence is marked by an unconformity at the top of the Triassic Blina Shale that is related to extensive Triassic–Jurassic uplift and erosion associated with the Fitzroy Movement.

The late Carboniferous–Permian megasequence comprises four supersequences: G, H, I and J (Fig. 3). The Liveringa Group forms the uppermost part of Supersequence I and overlies the Poole Sandstone – Noonkanbah Formation succession (Fig. 3). These two underlying formations represent the final stage of a three-part deglaciation sequence, related to the Permo-Carboniferous Gondwanan deglaciation, that has been correlated across numerous West Australian basins (Eyles et al., 2002). Supersequence I displays a second-order transgressive–regressive character related to global eustatic sea-level rise at this time, recording inundation and the development of widespread shallow seas in the basin during the early–middle Permian. The Liveringa Group was deposited in fluvial to shallow-marine environments, including lagoonal and deltaic settings, during the regressive phase of this second-order cycle.

Lithostratigraphy

The middle to late Permian stratigraphy of the Canning Basin has been described, defined and classified in phases over the past 80 years. The Liveringa Group was first identified as the 'Liveringa Series and Upper Ferruginous Series' in the Fitzroy Trough region by Wade (1936). Subsequently, these stratigraphic units were named, renamed and revised across the basin. Nomenclature and definitions of the stratigraphy vary with structural province, the history of classification, sequence divisions and their lateral equivalents. The evolution of stratigraphic nomenclature for the Liveringa Group is summarized in Figure 2 and information about the type-section localities is summarized in Table 1.

The current stratigraphy is derived from basin studies conducted at three scales; the first and most detailed is the 1:250 000 basin mapping. Secondly, there are regional studies that investigated specific parts of the basin or structural domains. These cover both the southern Canning Basin (Traves et al., 1956; Towner et al., 1976) and the northern Canning Basin (e.g. Guppy et al., 1951; Casey and Wells, 1964; White and Yeates, 1976). In addition, there are more focused regional studies of the Gregory Sub-basin (Yeates et al., 1975b) and the Fitzroy Trough (Guppy et al.,

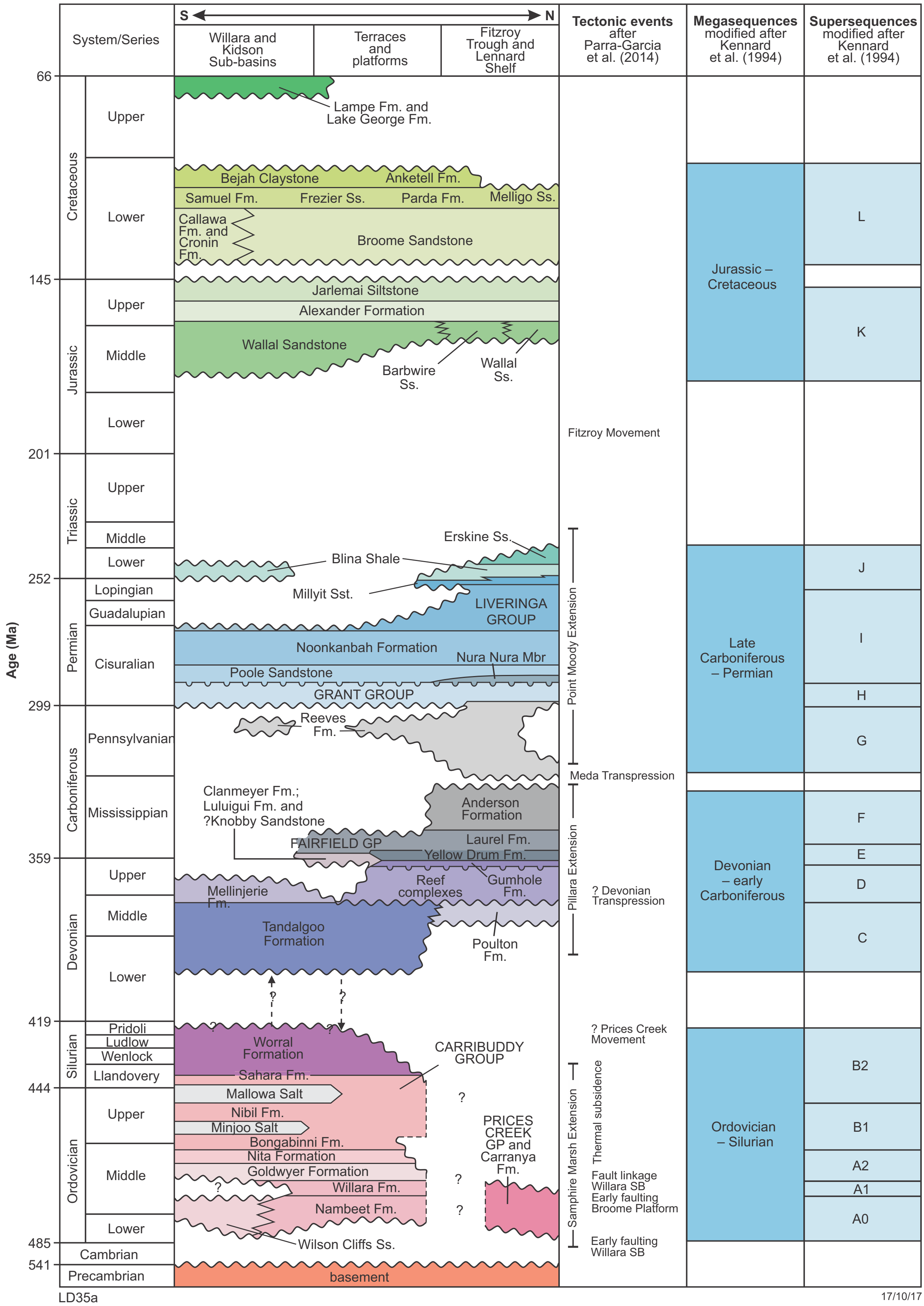


Figure 3. **Summary of the Canning Basin stratigraphy; major tectonic events after Parra-Garcia et al. (2014), stratigraphy revised from Shaw et al. (1994) and depositional megasequences and supersequences modified after Kennard et al. (1994)**

Table 1. Locations of type sections for formations and members within the Permian Liveringa Group

Formation or member	*Location of type section*	*Coordinates*	*1:250 000 Series map*	*Designated by*
Lightjack Formation	Lightjack Hill	18°59'S, 125°50'E	Noonkanbah	Guppy et al. (1958)
Triwhite Sandstone	Lake Dora	22°10'S, 123°30'E	Tabletop	Traves et al. (1956)
Chirup Formation	WAPET Chirup 1 (well)	19°51'S, 120°26'E	Mandora	Forman and Walkes (1981)
Condren Sandstone	Condren Pinnacles	20°06'01"S, 127°39'01"E	Lucas	Casey and Wells (1964), refined by Yeates et al. (1975b)
Hardman Formation	Mount Hardman	18°19'S, 124°49'E	Noonkanbah	Guppy et al. (1958)
Kirkby Range Member	Kirkby Range	19°07'S, 125°13'E	Crossland	Yeates et al. (1975b)
Hicks Range Sandstone Member	Hicks Range	19°13'48"S, 125°53'42"E	Crossland	Yeates et al. (1975b)
Cherrabun Member	Spring Creek	19°11'00" S, 125°33'06"E	Crossland	Yeates et al. (1975b)
Godfrey Beds	Godfreys Tank*	20°14'07"S, 126°32'16"E	Cornish	Casey and Wells (1964)

NOTE: * Coordinates amended by Mory (2010)

1958). Finally, at the largest scale, the Liveringa Group was evaluated in a number of basinwide studies and reviews (McWhae et al., 1956; Veevers and Wells, 1961; Towner and Gibson, 1980; Forman and Wales, 1981; Towner and Gibson, 1983; Yeates et al., 1984; Middleton, 1990; Mory, 2010; Mory and Hocking, 2011).

The work of Guppy et al. (1958) and Yeates et al. (1975a) is of particular significance in the northern half of the basin. Guppy et al. (1958) proposed a three-part division of the Group (Fig. 2) and constrained 'Liveringa' strata to those between the Noonkanbah Formation and the Blina Shale; previously Triassic strata had also been grouped under the Liveringa heading (Reeves, 1949). Later, Yeates et al. (1975a,b) re-assigned group status to the Liveringa strata and applied formation classifications to the three main constituents of the Liveringa Group in the Fitzroy Trough: the Lightjack Formation, Condren Sandstone and Hardman Formation (Fig. 2). The Condren Sandstone thins towards the northwest and wedges out at the southeastern end of the Fitzroy Trough, leaving the Hardman Formation overlying the Lightjack Formation. Yeates et al. (1975b) proposed further subdivision of the Hardman Formation into three members: the lower Kirkby Range Member, middle Hicks Range Sandstone Member and the uppermost Cherrabun Member. These divisions were consistently adopted in later works and are recognized in the currently accepted nomenclature proposed by Towner and Gibson (1983; Fig. 2).

The Godfrey Beds are locally present in the Gregory Sub-basin and on the adjacent Betty and Balgo Terraces. They are now considered laterally equivalent to the Hardman Formation and likely correlate to its basal section (Yeates et al., 1975b; Towner and Gibson, 1983). The classification 'Godfrey Beds' is still used (Mory, 2010), although direct correlation of these beds to the northern Fitzroy Trough scheme (Fig. 2) is hindered by stratal relationships. The beds were defined in McWhae et al. (1956) from a section where neither upper nor lower contacts were exposed. Furthermore, the top of the Godfrey Beds is commonly eroded and a disconformable to unconformable contact with the overlying Triassic Millyit Sandstone has been recorded (Mory, 2010).

The base of the Liveringa Group was originally defined as the Balgo Member in the Gregory Sub-basin (Veevers and Wells, 1961; Casey and Wells, 1964). The member was recognized as a lateral equivalent to the Lightjack Formation of the Fitzroy Trough, but was differentiated due to the absence of continuous strata between the two structural domains (Casey and Wells, 1964). It was later reclassified to the Lightjack Formation by Yeates et al. (1975b) and Towner and Gibson (1983). The name Balgo Member is no longer used although the term is still present on maps pre-dating the 1980s.

Stratigraphic revision is still required in some parts of the northeastern Canning Basin. On the existing 1:250 map sheets, the Condren Sandstone and Hardman Formation are each locally divided into two informal members (Mount Ramsay), and an undivided Liveringa Group is also shown (Lennard River). Informal divisions of the Lightjack Formation have also been made in areas of the Fitzroy Trough (Noonkanbah; Crowe and Towner, 1981) and Gregory Sub-basin (Mount Anderson; Gibson and Crowe, 1982).

Stratigraphic division in the southern half of the Canning Basin is less complicated. The Triwhite Sandstone, originally identified by Traves et al. (1956), has been recorded from sparse outcrop on the Anketell and Tabletop Shelves. The Liveringa Formation was identified in petroleum well Kidson 1, in the Kidson Sub-basin, where it overlies the Noonkanbah Formation and is unconformably overlain by Mesozoic sedimentary rocks (Johnson, 1966). Macrofossils indicate an early Permian age (Towner and Gibson, 1980) and lateral equivalence to the lower Liveringa Group; it is generally considered correlative to the Lightjack Formation (Fig. 2; Guppy et al., 1958; Veevers and Wells, 1961; Towner and Gibson, 1980; Forman and Wales, 1981; Towner and Gibson, 1983).

The Chirup Formation, originally defined by Towner and Gibson (1980), was delineated based on the WAPET Chirup 1 well; it has not been identified in outcrop. This formation is thought to be restricted to the Wallal and Samphire Embayments and, based on palynological data, is considered equivalent to the upper Hardman Formation (Towner and Gibson, 1980).

An interval of the stratigraphy in the Kidson Sub-basin is still assigned to 'undifferentiated Liveringa.' These sedimentary rocks, present in Corbett 1 and Patience 1 and 2, are not assigned to a particular formation and are unconformably overlain by younger Jurassic sediments.

Middle to late Permian stratigraphy and depositional setting

Lightjack Formation and equivalents

The Liveringa Group comprises a range of fluvial to shallow-marine deposits that record the regression of a widespread shallow sea that was prevalent across the Canning Basin during the early Permian. The transition from lower to middle Permian strata is commonly conformable across the basin, with both the Lightjack Formation and Triwhite Sandstone conformably to gradationally overlying the Noonkanbah Formation. The Lightjack Formation is interpreted to lie unconformably on basement in some areas at the southeastern limits of the Canning Basin (e.g. LUCAS and HELENA). Typically, the Triwhite Sandstone is unconformably overlain by the Jurassic Callawa Formation (e.g. SAHARA, PATTERSON RANGE and URAL), although locally it is unconformably overlain by the Cretaceous Anketell Sandstone (e.g. PERCIVAL and SAHARA).

The Lightjack Formation and Triwhite Sandstone are generally interpreted as regressive shallow-marine deposits within in a shallowing-up sequence conformable with the underlying Noonkanbah Formation (Veevers and Wells, 1961; Yeates et al., 1975b; Forman and Wales, 1981; Towner and Gibson, 1983). In the northern basin, the Lightjack Formation is commonly characterized by a highly fossiliferous concretionary band at its base, a sandy mid-section and the presence of coal, which has attracted economic interest (Yeates et al., 1975a; Crowe and Towner, 1976; Yeates et al., 1984). Transition to paralic conditions is interpreted towards the southeast of the basin (Yeates et al., 1975b). Typically the Lightjack Formation is conformably overlain by the Condren Sandstone and disconformably overlain by the Hardman Formation where the Condren Sandstone is absent. An unconformable relationship has been recorded locally between the Lightjack Formation and Barbwire Sandstone, the Millyit Sandstone (CROSSLAND) and Jurassic sedimentary rocks (MOUNT ANDERSON); an unconformity is also inferred between the Lightjack Formation and Godfrey Beds (e.g. LUCAS).

Condren Sandstone

The Condren Sandstone comprises predominantly fluvial sandstone facies with shallow-marine, deltaic, tidal flat and swampy environments interpreted towards its most northwestern extent (Yeates et al., 1975b; Forman and Wales, 1981; Yeates et al., 1984). A conformable to disconformable relationship is recorded between the Condren Sandstone and the overlying Godfrey Beds and Hardman Formation. Locally it is unconformably overlain by the Triassic Blina Shale (MOUNT BANNERMAN). The top of the Condren Sandstone has not been observed in outcrop in the southeastern Canning Basin (e.g. HELENA, STANSMORE and BILLILUNA) and the nature of the contact has not been described.

Hardman Formation and equivalents

The Godfrey Beds were interpreted to have been deposited in paralic to tidal flat environments, and trace fossils in the Gregory Sub-basin sections suggest shallow-marine conditions (Yeates et al., 1975b; Yeates et al., 1984). This is consistent with the low-energy, open shallow-marine and lagoonal settings proposed for its northern lateral equivalent, the Kirkby Range Member (Yeates et al., 1975b; Forman and Wales, 1981; Yeates et al., 1984). The lack of a hiatus between the Lightjack Formation and the Kirkby Range Member, where the Condren Sandstone is absent, has led to the suggestion that the uppermost Lightjack Formation in the Fitzroy Trough is equivalent to the Condren Sandstone (Yeates et al., 1984).

Within the Hardman Formation, the lowermost Kirkby Range Member is conformably overlain by the Hicks Range Sandstone Member. The Cherrabun Member generally disconformably overlies the Hicks Range Sandstone Member, although a conformable contact has been identified locally (CROSSLAND). The Hicks Range Sandstone Member is interpreted to be a regressive package recording a shallow marine to fluvial transition, with fluvial progradation from the northwest (Yeates et al., 1975b; Forman and Wales, 1981; Yeates et al., 1984). The overlying Cherrabun Member records the return of shallow-marine conditions and is characterized by abundant marine fossils. Depositional setting is interpreted to range from shallow marine to deltaic and paralic (Yeates et al., 1975b; Forman and Wales, 1981; Yeates et al., 1984).

The Cherrabun Member is disconformably overlain by the Triassic Blina Shale and unconformably overlain by Jurassic strata. This disconformable relationship is localized over the centres of the Fitzroy Trough and Gregory Sub-basin (DERBY and MOUNT BANNERMAN).

The Chirup Formation, in the Wallal and Samphire Embayments, unconformably overlies the Grant Group and is unconformably overlain by the Triassic Blina Shale and Jurassic Wallal Formation (Towner and Gibson, 1980). The depositional environment of the Chirup Formation is interpreted as coastal swamp or marsh (Towner and Gibson, 1980; Forman and Wales, 1981).

Biostratigraphy

Palynological and paleontological dating constrains the Liveringa Group to the Guadalupian–Lopingian (middle–late Permian). Finer scale dating of its formations is more challenging due to inconsistencies in formation–palynological zone correlation and general misidentification or misrepresentation of formation boundaries. A summary of available palynological data for the Liveringa Group, from wells and drillholes, and supplementary information on the spore-pollen zones relevant to correlations in this Report are provided in Appendix 2. Figure 4 displays the location of all holes that contain palynological information and the position of correlation sections that show palynozone relationships across the basin (Appendix 3). The palynological summary for each well in Appendix 2 can be opened via the link from the well location in Figure 4. The correlation sections can be viewed either in Appendix 3, or by selecting an individual correlation section in Figure 4.

Recently, tuffaceous rocks from eastern and Western Australia were dated by chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS). This dating included samples from the Lightjack Formation and has led to a significant revision and a more robust age definition of the previous (Price, 1997) Permian palynological zonation (Laurie et al., 2014; Fig. 5).

The top of the Liveringa Group is more easily defined than the base, as the overlying Blina Shale is determined to be Triassic by the presence of the zones *L. pellucidus* and *K. saeptatus* (Fig. 6; Fig. 4, Section 1; Appendix 3). Zones of Triassic age are not recorded in the Liveringa Group and its equivalents. The youngest zones recorded in the Liveringa Group are the late Permian spore-pollen zones *P. crenulata – P. microcropus* (e.g. at Mimosa 1 and Puratte 1; Fig. 4, Section 1; Appendix 3). The middle Permian zone *D. granulata* has been recorded at the base of the Liveringa Group, and the top of the underlying Noonkanbah Formation lies within the early to middle Permian *P. sinuosus* zone. The middle Permian *M. villosa* zone, between *P. sinuosus* and *D. granulata*, has only been recorded in two wells in the Canning Basin: Puratte 1 and BMR Lucas 14. Existing formation picks based on regional correlation suggest that in Puratte 1 this *M. villosa* zone is at the top of the Noonkanbah Formation (Dent, 2016), although the original formation boundaries interpreted based on lithology in BMR Lucas 14 placed the *M. villosa* zone at the base of the Lightjack Formation (Fig. 4, Section 2; Appendix 3). In Moongana 1, the zone *L. vermithola* is present at the base of the Lightjack Formation according to formation picks by Dent (2016) and Mory (2010); this zone is also named 'upper Stage 4b' by Kemp et al. (1977) and Price (1983). The upper Stage 4b zone was originally described for the Puratte 1 and BMR Lucas 14 samples, and later amended to the *M. villosa* zone (Backhouse, 2009 and Backhouse, in prep., *in* Mory, 2010). The contact between the Noonkanbah and Lightjack Formations, in both Puratte 1 and BMR Lucas 14, is ambiguous and the sparse dataset does not help define whether the *M. villos*a zone belongs to the top of the Noonkanbah Formation or the base of the Liveringa Group. Given the gradational contact between the two, the zone may be present in both units.

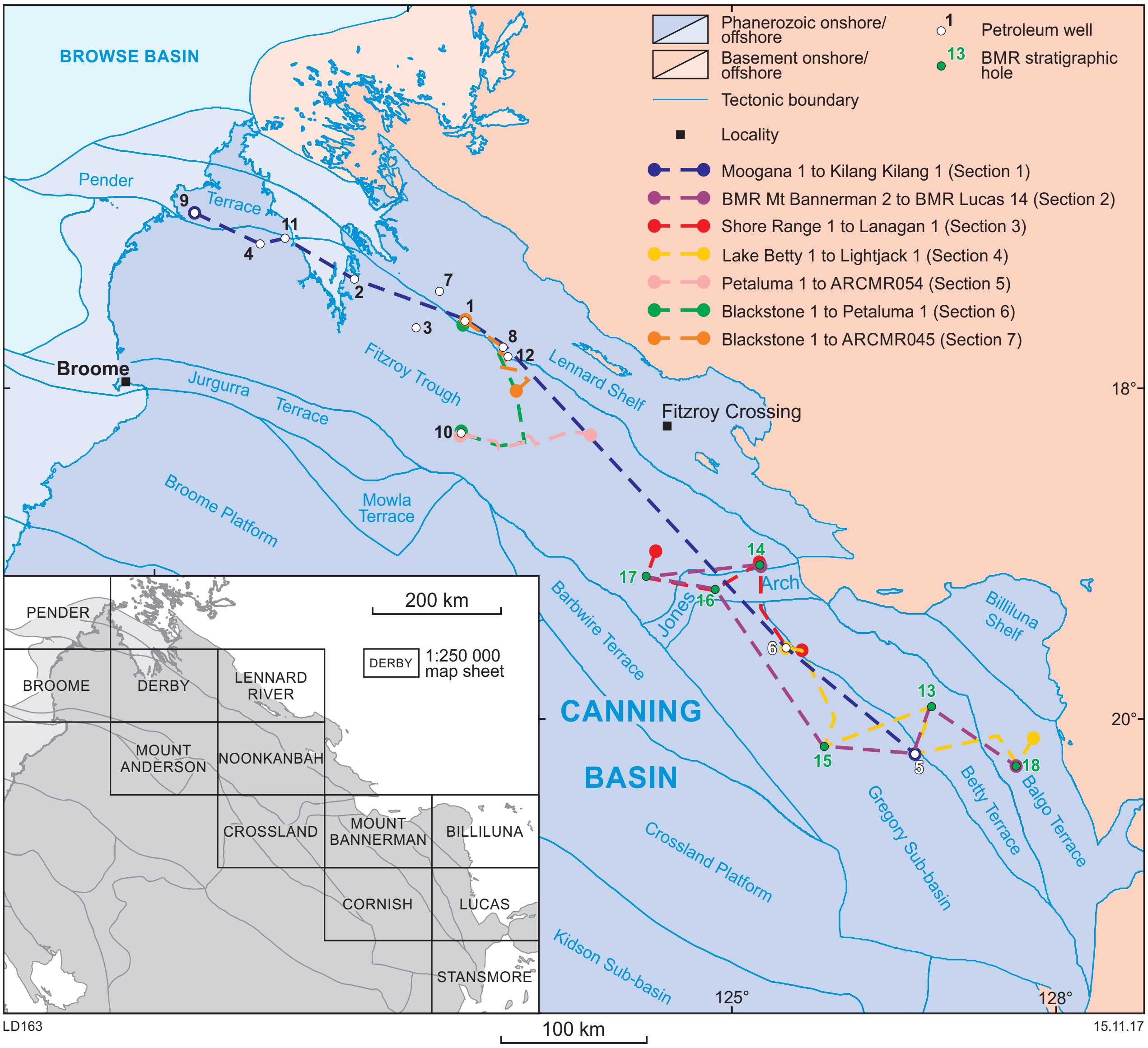
Age definition for formations within the Liveringa Group is far more ambiguous. Palynological zones follow a regular stratigraphic order but their position relative to lithologically derived formation picks is highly variable between locations. In most petroleum wells the Liveringa Group is not subdivided into formations, and the inconsistent interpretation of formation boundaries is a problem in the BMR stratigraphic holes, where both formation picks have been made and palynology samples have been taken (Appendix 3). The position of the *D. parvithola* zone is the most inconsistent with respect to lithostratigraphic formation picks. Other biostratigraphic elements affirm the general ages provided by palynology, but do not permit further refinement.

The Lightjack Formation was originally assigned a late Artinskian – early Kungurian (early Permian) age based on the presence of the bivalves *Atomodesmo exerata* and *Stutchburia muderongenses* (Yeates et al., 1975b). Early Permian ages were also assigned to the Triwhite Sandstone based on bivalve and gastropod assemblages (Dickins, in Towner et al., 1976). More recent work summarized by Archbold (2002), on a range of marine faunas including bivalves, dates the Lightjack Formation to the middle Permian (Guadalupian). Backhouse (2009, *in* Mory, 2010) records palynofloral assemblages from the *D. granulata* to *D. parvithola* zones (middle to late Permian) in the Lightjack Formation. The upper age limit of the formation is poorly constrained as *D. parvithola* is also recorded in the Condren Sandstone and in the Hardman Formation.

Glossopteris floras are present extensively throughout the Condren Sandstone, with the assemblage indicating a late Permian to early Triassic age (White and Yeates, 1976). Palynological data summarized in Mory (2010) record both the *D. dulhuntyi* (BMR Cornish 1) and Stage 5 (*D. parvithola* equivalent) zones, at the base of the Condren Sandstone (e.g. BMR Cornish 1, Kilang Kilang 1 and BMR Crossland 1; Appendix 3). The formation boundaries could be diachronous, although it is more likely that the interpreted picks are inaccurate.

Middle to late Permian (Capitanian–Wuchiapingian) ages have been assigned to the Hardman Formation based on the presence of brachiopod zone *Liveringa magnifica* in the Kirkby Range Member and the presence of brachiopod zone *Waagenoconcha imperfect* in association with the ammonoid *Cyclolobus persulcatus* in the Cherrabun Member (Archbold, 1999). Palynological zone *D. parvithola* is recorded in the upper Liveringa Group in a number of wells including East Yeeda 1 and Blackstone 1, and the late Permian (Changhsingian) *P. crenulata – P. microcorpus* zones are recorded at the top of the Liveringa Group in Puratte 1 and Mimosa 1 (Appendix 3).

The current biostratigraphic data indicate deposition of the Liveringa Group between the middle to late Permian and provide a starting point to assist in the subdivision of subsurface sections of the Group. However, finer age definition of individual formations is hindered by a widely spaced dataset and inconsistent historical formation picks.



1 Blackstone 1	**5** Kilang Kilang 1	**9** Moogana 1	**13** BMR Mt Bannerman 1	**17** BMR Crossland 2
2 Booran 1	**6** Lake Betty 1	**10** Petaluma 1	**14** BMR Mt Bannerman 2	**18** BMR Lucas 14
3 East Yeeda 1	**7** Meda 1	**11** Puratte 1	**15** BMR Cornish 1	
4 Jum Jum 1	**8** Mimosa 1	**12** West Philydrum 1	**16** BMR Crossland 1	

Figure 4. **Location of correlation sections constructed from a combination of outcrop sections, measured outcrop sections, BMR stratigraphic holes, and petroleum well logs and mineral exploration holes; view individual correlation panels by clicking on the relevant coloured correlation line in the figure. Palynological information for numbered wells can be viewed by clicking on the well number; note the review of the palynology in this Report has led to alteration in the palynological classification for some wells**

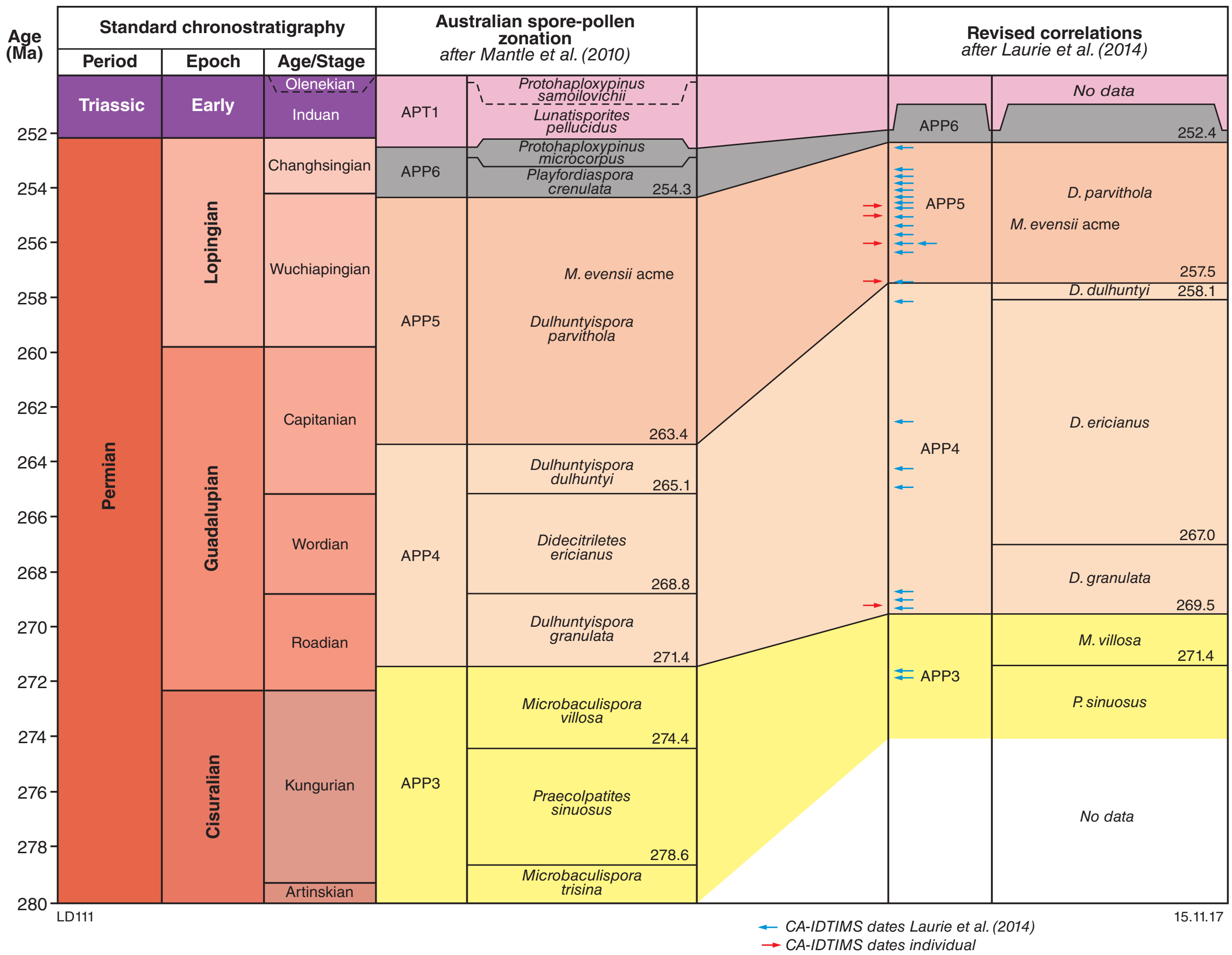


Figure 5. **Revised palynostratigraphic scheme for the middle to late Permian. On the left is the classification scheme developed by Mantle et al. (2010) that used the original palynozonations of Price (1997) calibrated to the timescale of Henderson et al. (2012). The updated scheme on the right was developed more recently by Laurie et al. (2014) and constrains the position of palynozones determined using CA-IDTIMS dates; blue arrows indicate CA-IDTIMS work undertaken as part of the research by Laurie et al. (2014) and red arrows indicate other individual dates**

Facies analysis and depositional setting of the Liveringa Group

This Report presents new data as two main components: facies analysis from outcrop, and well log interpretation and correlation. Outcrop sites in the southeastern Fitzroy Trough and Gregory Sub-basin, and on the Balgo Terrace (Fig. 1), were assessed to identify major contacts, and facies and facies associations based on lithology, sedimentary structures, and trace fossil and macrofossil assemblages (Appendix 1). The individual facies and facies associations identified for the Lightjack Formation, Condren Sandstone and lower Hardman Formation are presented in Appendix 4. Facies associations from outcrop sites were then compared with neighbouring well logs in the central and southeastern parts of the study area to assist division of subsurface strata into formations or members. These divisions were then correlated to wells in the northwestern Canning Basin where the majority of subsurface Liveringa data have been recorded but outcrop is absent.

Lightjack Formation

Outcrop lithofacies

The Lightjack Formation is present predominantly in the Fitzroy Trough, the Gregory Sub-basin, and on adjacent northern shelves and terraces. Outcrop is extensive in the southeast of this region, and subsurface sections of the formation were interpreted in numerous wells in the northwest (Fig. 1). Key outcrop localities of the Lightjack Formation examined during this study are: Shore Range, Millyit Range, Beefwood Park, Christmas Creek, Durbai Creek and Namalook (south Balgo) (Fig. 1; Appendix 1).

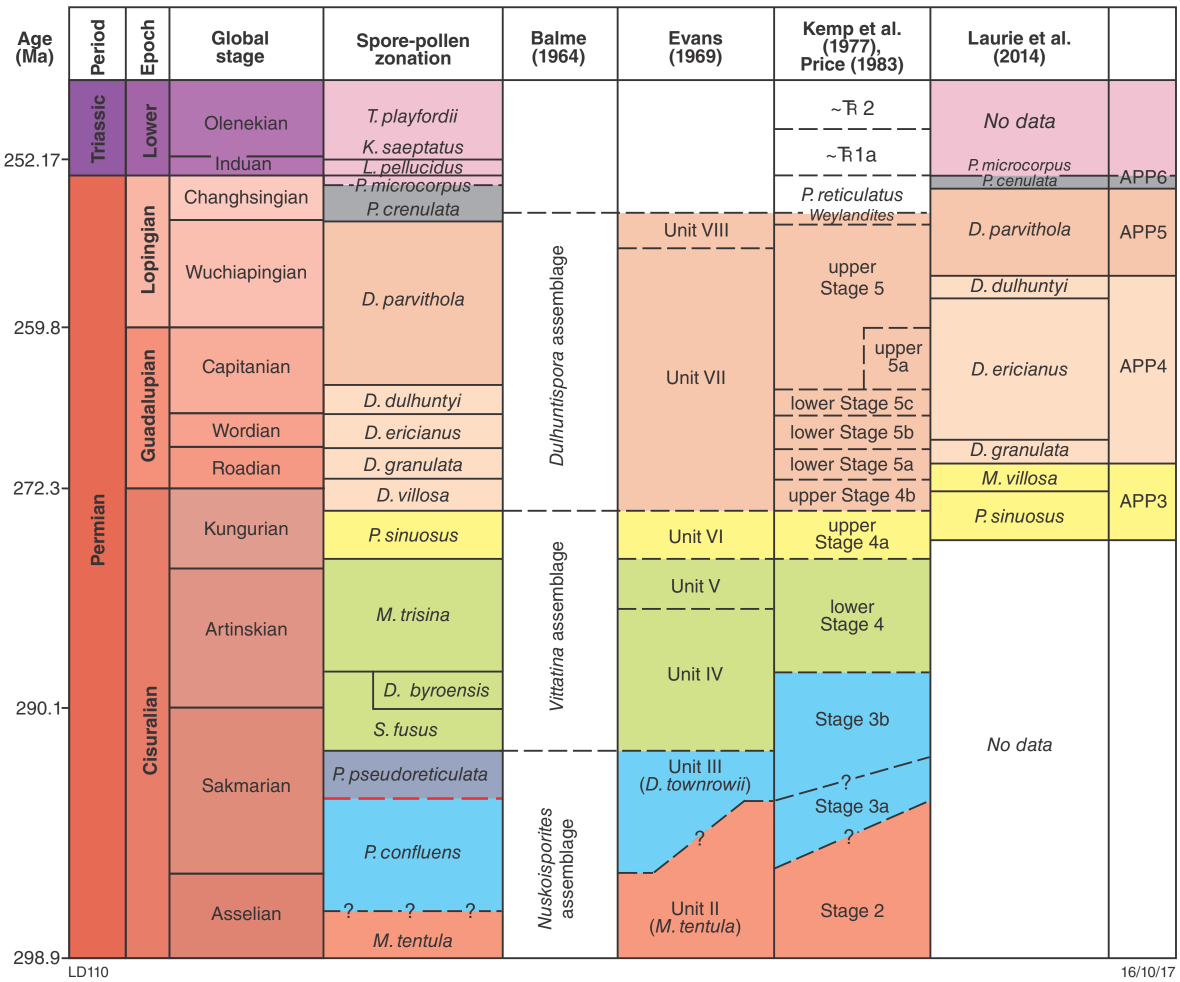


Figure 6. Palynozonation schemes applied to the Permian stratigraphy of the Canning Basin, adapted from Mory (2010); to include the most recent zones by Laurie et al. (2014); time scale according to Cohen et al. (2013)

Outcrops typically display a tabular geometry, although the rocks are friable which often results in poor exposure and scree-dominated slopes (Fig. 7a).

A ferruginous, fossiliferous concretionary layer is present at both the Shore Range 1 and Beefwood Park 1 localities. Fossil material is extremely abundant and includes bivalves, gastropods and possible scaphopods (Fig. 8a–c). At Shore Range 1, the fossiliferous concretionary layer is associated with a fine- to medium-grained, quartz-rich sandstone facies in which a low-diversity, moderate-abundance trace fossil assemblage contains *Rosselia*, *Skolithos*, *Palaeophycus* and possible *Zoophycos* (Fig. 8d–f). The concretionary layer and the overlying bioturbated sandstone facies are together identified as facies association 1 (FA1; Appendix 4). At Shore Range 1 this facies association was observed just above the Noonkanbah Formation – Lightjack Formation contact. At Beefwood Park, FA1 is present in the lower part of the formation, although the contact between the Noonkanbah and Lightjack Formations was not observed there, so the relative position of the layer cannot be precisely placed.

Thickly bedded argillaceous sandstones are present at the majority of outcrop sites: Shore Range, Millyit Range and Christmas Creek (Fig. 1). These argillaceous beds are characteristic of facies association 2 (FA2) and are distinguished from other sandstone facies by the presence of pervasive root-trace bioturbation (Fig. 9a–c). In FA2, the root-bioturbated beds are interbedded with low-angle, trough cross-stratified, ripple cross-laminated and planar-laminated sandstones (Fig. 9d,e). Straight-crested and interference ripple forms are observed in plan view on outcrop surfaces. Root-bioturbated beds are occasionally associated with zones of intense bioturbation or horizons with abundant impressions of plant material.

Facies association 4 (FA4) is also sandstone dominated, although it is easily distinguishable from FA1 and FA2 in outcrop as it forms distinct breakaways (Fig. 7a). These sandstones are commonly clean and competent, and deposits are laterally extensive with a sheet-like, tabular bedding style. Broad, low-angle trough cross-beds and interbedded bi-directional and climbing ripple cross-lamination are characteristic to FA4 (Fig. 10a–c).

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Figure 7. **(page 12) Field photos showing typical outcrops of the Liveringa Group: a) the Lightjack Formation at Christmas Creek, with scree-dominated slopes and poor exposure of FA2 (below the yellow line) overlain by abrupt breakaways and tabular geometries of FA4, above the yellow line; b) the Condren Sandstone at the Condren Pinnacles exhibits the low-profile crumbly appearance and tabular geometry associated with FA5; c) the Condren Sandstone at the Durbai Creek locality where the more massive and blocky outcrop is associated with FA6; d) the Hicks Range Member of the Hardman Formation at Hicks Range illustrating the generally massive, blocky outcrop style at this locality; e) the Kirkby Range Member of the Hardman Formation at Boundary Hill, showing the low rubbly character of the outcrop at this locality**

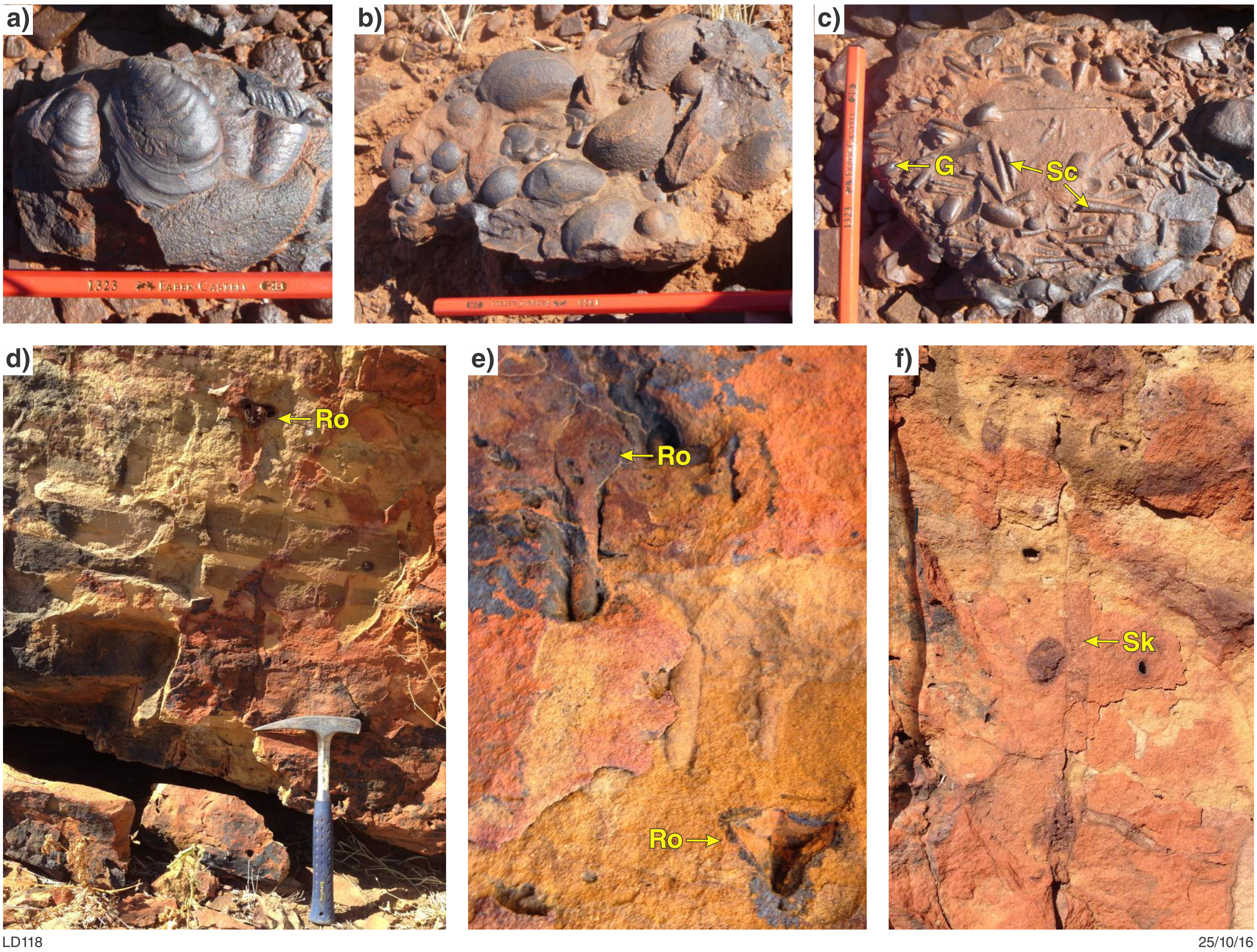


Figure 8. **Key sedimentary structures and trace fossils of FA1 from the Lightjack Formation at Beefwood Park locality (Appendix 1) containing a highly ferruginized, fossiliferous concretionary layer, features include: a) bivalves; b) abundant, high-density concretions; c) high density of fossil material including gastropods (G) and possible scaphopods (Sc). Sandstone facies associated with the fossiliferous concretionary layer at Shore Range site 1 displays: d) thinly bedded structure and a *Rosselia* (Ro) trace fossil; e) a zone of high-density *Rosselia* trace fossils; f) *Skolithos* (Sk) trace fossil**

Figure 9. **Key sedimentary features of FA2 from the Lightjack Formation: a) argillaceous root-bioturbated facies (*Rt*) overlying trough cross-bedded sandstones (*St*) at the Christmas Creek locality; b) enlarged view of *Rt* bed in a) showing a high density of vertical traces in sandstone; c) plan view of the same root-bioturbated facies at the Shore Range 2 site; d) thinly interbedded ripple cross-laminated facies (*Sr*) and horizontally laminated facies (*Sh*) at the Christmas Creek locality; e) low-angle trough cross-bedding (*St*) common to FA2**

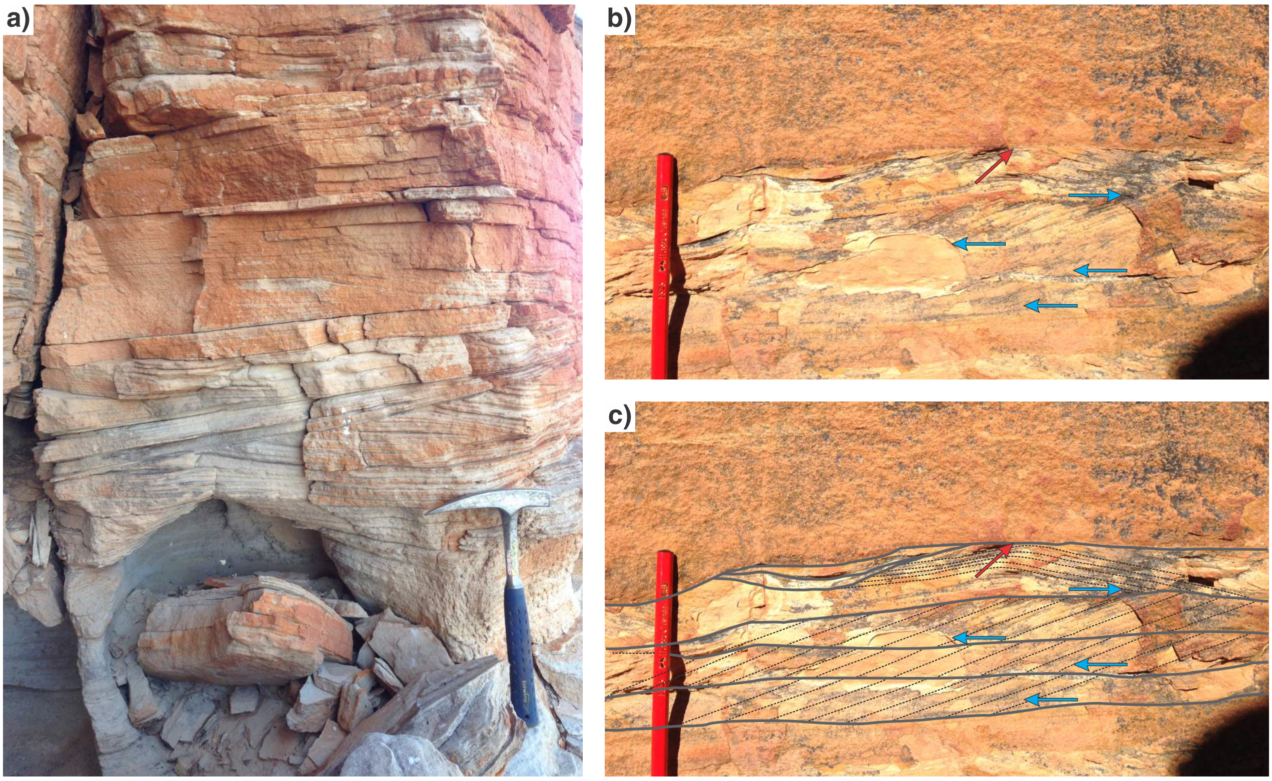


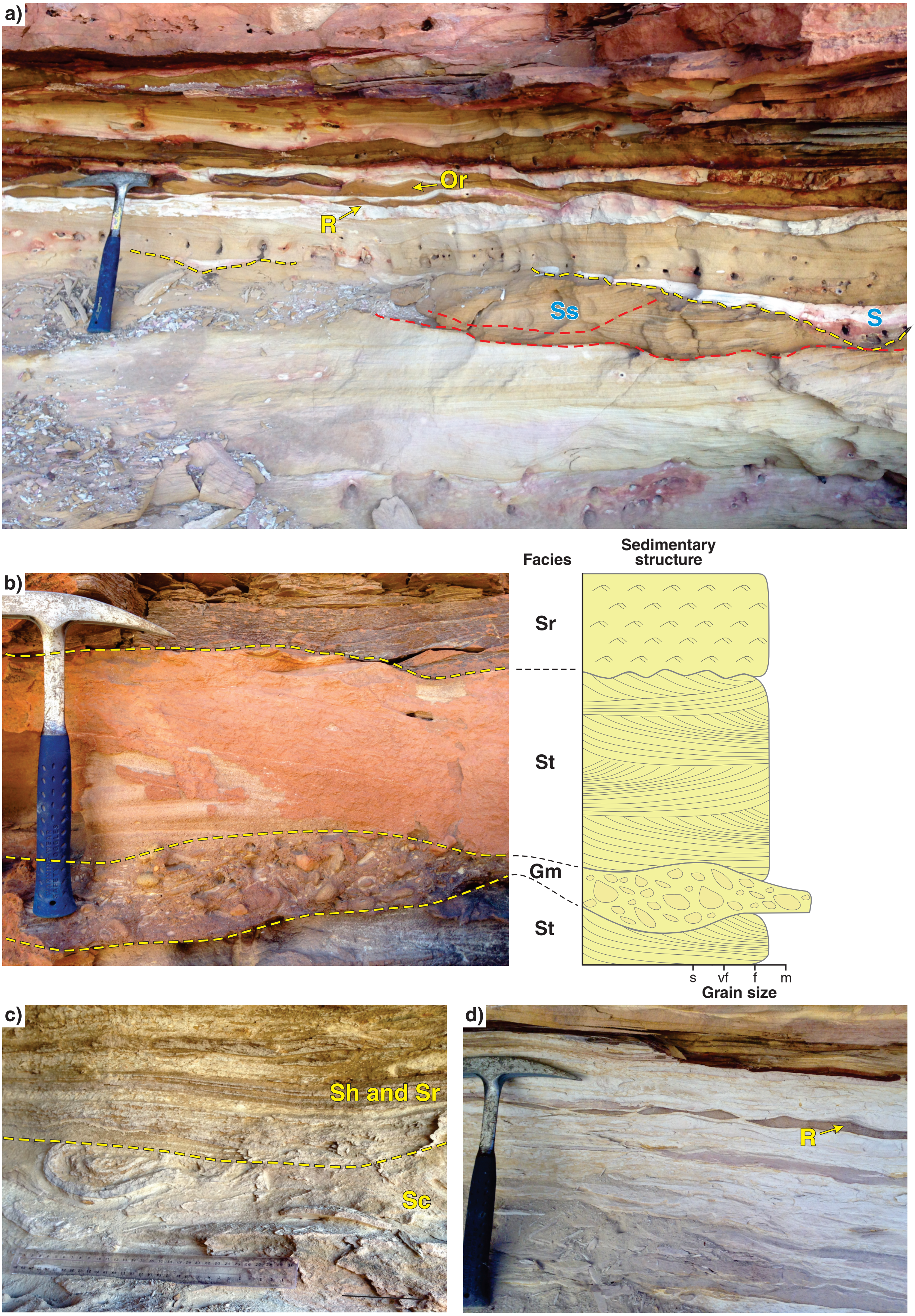
Figure 10. Key sedimentary features of FA4 from the Lightjack Formation at the Christmas Creek locality: a) low-angle trough cross-bedding amalgamated into thick sequences in sandstone; b) ripple cross-lamination, red arrow indicates climbing ripple form and blue arrows indicate current direction; c) annotated section of b) where this section highlights the presence of opposing ripple orientation, and thus flow directions, although there is a dominant flow direction towards the left. Ripple-lamination preserved in the dominant direction is erosional in form, while lamination in the opposing direction is aggradational

There is very sparse bioturbation in this association, with a bioturbation index of 1, and plant material is rare. FA4 was observed commonly at Christmas Creek and Millyit Range and appears to be laterally extensive.

Facies association 3 (FA3) is present only at the Namalook 1 site (Fig. 1). At this locality, small-scale, channel-fill sequences and scoured surfaces filled with swaley to hummocky cross-stratified sandstones are present (Fig. 11a,b). These features are found in association with convoluted, laminated sandstone and thin-to-thick amalgamated packages of ripple cross-laminated sandstones (Fig. 11c). Well-defined oscillatory ripples are present as dislocated chains and as reworked tops on current-ripple, cross-laminated sandstone intervals (Fig. 11a,d). The trace fossil assemblage preserved in FA3 is diverse and dominated by horizontal forms; the abundance of traces ranges from low to common.

Depositional sequence

Based on outcrop relationships, the ascending order of facies deposition in the Lightjack Formation is FA1, FA2 and FA4 (Appendix 3). At Shore Range 1 and 2 sites, FA1 is gradationally overlain by FA2 (Fig. 4, Section 3; Appendix 3). At the Millyit Range and Christmas Creek sections (Appendix 1), FA2 is overlain by FA4, and the contact between the two is consistently conformable although abrupt (Fig. 7a). At Shore Range 1, FA1 occurs at the base of the Lightjack Formation and overlies the interpreted contact with the Noonkanbah Formation. The basal contact of the Lightjack Formation is ambiguous at other outcrops where scree-covered slopes obscure the lower part of the sedimentary sequence. A distinct change to dark, platy, ferruginous scree was observed at the base of outcrop sections at Millyit Range and Christmas Creek. Elsewhere this type of scree is associated with weathered Noonkanbah Formation deposits, and may indicate the presence of the Noonkanbah Formation–Lightjack Formation contact at the base of these outcrops (Fig. 12a,b). A change to this dark, ferruginous, platy scree was also observed underlying FA3 in the lower valley slopes at Namalook 1 (Fig. 12a,b). FA3 is the only Lightjack Formation facies association observed at this southeasternmost locality of the study area, but is interpreted to be deposited at or near the base of the Lightjack Formation.


a)
Or
R
Ss
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Facies
Sedimentary structure
Sr
St
Gm
St
s
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f
m
Grain size
c)
Sh and Sr
Sc
d)
R

Figure 11. **(page 16) Key sedimentary features of FA3 from the Lightjack Formation at Namalook locality: a) scoured surfaces filled by swaley to hummocky cross-stratification (*Ss*) or siltstone (S) overlain by heterolithic sandstone and siltstone beds with isolated ripple trains (R) and oscillatory, reworked current-ripple lamination (Or); b) sandstone–pebble conglomerate (*Gm*) overlain by trough cross-stratified facies (*St*) and then ripple cross-laminated facies (*Sr*), with log illustrating these up-sequence facies changes; c) locally present convolute bedding (*Sc*) interbedded with planar-laminated (*Sh*) and ripple cross-laminated (*Sr*) facies; d) heterolithic sandstone and siltstone beds containing starved ripple trains (R) as sandstone lenses**

Figure 12. **Interpreted boundary between the Noonkanbah and Lightjack Formations at the Namalook locality: a) outcrop photo showing the change from flat-lying ground covered in ferrigunized platy scree, to hills of the Lightjack Formation; b) annotated image of a) with interpreted Noonkanbah Formation in the foreground shaded blue and the Lightjack Formation shaded orange (note person for scale in centre right, just below the contact)**

Depositional setting

The facies associations of the Lightjack Formation record an overall regressive marine system, commencing in a widespread shallow-marine environment that transitioned to more proximal and marginal-marine settings higher in the stratigraphic section.

In FA1 the density, abundance and preservation of macrofossils in the concretionary layers, in combination with the sedimentary structures and trace fossil assemblage, suggest a well-oxygenated, open, shallow-marine depositional setting. Minor fluctuations in water depth and flow regimes in this environment are indicated by component subfacies.

Deposition in shallow-marine settings was also interpreted for FA3 based on the association of amalgamated swaley to hummocky sandstone and heterolithic facies, local coarsening-up trends, continuous and sand-starved wave and current ripples, scoured surfaces with fine-grained fills and occasional soft-sediment deformation features. The predominantly horizontal trace fossil assemblage, including deposit feeding and dwelling traces, in combination with the abundance of clay-rich sandstone and heterolithic sandstone–siltstone facies, indicate lower energy conditions than those in which FA1 was deposited. The presence of small channel-fill sequences and associated impoverished trace fossil assemblages suggests switching between subtidal and intertidal settings (Fig. 11).

The contact between the Liveringa Formation and the underlying Noonkanbah Formation is not distinct at the Namalook 1 outcrop, although based on its position proximal to mapped Noonkanbah Formation deposits, FA3 is likely at or near the base of the Lightjack Formation. FA1 and FA3 are interpreted as laterally equivalent based on the comparable stratigraphic position and the presence of the fossiliferous concretionary band that characterizes FA1 at Balgo, just north of Namalook 1 (Fig. 1). When compared to the open marine FA1, the absence of fossils, presence of subtidal features, and trace-fossil assemblage representative of lower energy conditions suggest a more marginal-marine environment for FA3 in this southeastern outcrop. Transition from marine settings in the northwest to paralic conditions in the southeast was suggested by Yeates et al. (1975b) and later included in the depositional model of Veevers (2006), which interpreted transgression from the northwest. Dent (2016) found a similar facies trend in the early Permian Poole Sandstone, where deposition transitioned from marine to more deltaic and fluvial-type settings towards the southeast of the basin.

The change from animal-generated bioturbation in FA1 to plant-generated bioturbation in FA2, combined with the absence of fossil material in FA2, indicates a distinct change in depositional setting. Facies suggest the prevalence of shallow, subaqueous conditions during the deposition of FA2 with possible episodes of subaerial exposure. Transition from shallow-marine to fluvio-deltaic conditions is indicated by these characteristics, the increased levels of argillaceous material, and the coarsening-up sandstone facies at the top of the Shore Range 1 section.

The abundance of root-bioturbated beds, coupled with an absence of organic material or bioturbation surrounding most of these beds, is perplexing; it suggests, perhaps, the prevalence of moderate-energy flow conditions that possibly transported organic material away from its source. Such conditions would have encouraged the suspension of fine-grained sediment and created murky, biologically unfavourable conditions that may explain the absence of animal-generated trace fossils throughout most of FA2. The occasional occurrences of plant material in this association may represent marginal or cutoff areas that escaped current activity.

The abrupt transition between FA2 and FA4 signifies another distinct change in depositional setting. Ripple cross-laminations in FA4 show good evidence of bidirectional flow conditions, although the opposing flows were of unequal strength (Fig. 10b,c); together these indicate waning flows and tidal settings. The broad style of the trough cross-stratification in FA4 suggests higher energy, shallow-flow conditions. In combination with bidirectional waning-current conditions and sheet-like depositional continuity, they may be interpreted as rapid sheet-flood type deposits, potentially related to either marine ingression or rapid outflow in a fluvio-deltaic system.

Condren Sandstone

Outcrop lithofacies

The Condren Sandstone comprises predominantly quartz-rich sandstone facies, with minor to abundant proportions of silty matrix and subordinate conglomeratic facies. Two facies associations were distinguished from outcrop sites: facies association 5 (FA5) and facies association 6 (FA6). FA5 records deposition in channel, channel margin and overbank settings, and FA6 records deposition in braided fluvial environments. Outcrop style is strongly facies dependent: FA5 deposits are commonly crumbly and unobtrusive, with a planar geometry (Fig. 7b), while FA6 has a more distinct and massive appearance (Fig. 7c).

FA5 was observed at the Condren Pinnacles, the Condren Sandstone type section, and at Millyit Range. The association is characterized by thick sandstone sequences of thinly bedded planar-laminated and amalgamated ripple cross-laminated facies (Fig. 13a; Appendix 4). At both locations these facies are present in association with trough cross-bedded sandstone containing siltstone rip-up clasts aligned along the cross-bed foresets (Fig. 13b). Trough cross-bedded units at Millyit Range are coarser grained and individual sets are thicker than those at the Condren Pinnacles locality (Fig. 1). Plant material is locally abundant in FA5 and desiccation cracks were commonly observed in the scree and. Oscillatory ripples were observed at the Millyit Range site and linguoid ripples were observed at the Condren Pinnacles site (Fig. 13c,d).

FA6 was observed at only one outcrop locality. This association is distinguished by the common occurrence of large concave-up erosional scours infilled by a coarse-grained, trough cross-bedded facies (Fig. 15a; Appendix 4). Locally, trough cross-beds are thicker above scoured surfaces compared to those below them (Fig. 15a). Granular to pebbly conglomeratic beds and lags are common in this association and rounded-cobble lags are occasionally present (Fig. 15b).

Depositional sequence

There is a sharp contact between FA5 of the Condren Sandstone, at the Condren Pinnacles outcrop site, and the overlying Kirkby Range Member of the Hardman Formation. The contact is distinguished by a thin ferruginized layer and a distinct change from the sandstone of FA5 to the distinctly white–purple–yellow mottled, clay-rich sandstone of FA8 (Appendix 4) that characterizes the Kirkby Range Member. The upper contact of FA5 was not observed at the Millyit Range outcrop and the base of FA5 is obscured at the Condren Pinnacles outcrops. Neither the upper nor lower contacts of FA6 were observed at the Durbai Creek outcrop locality.

Depositional setting

Fluvial depositional settings were interpreted for both FA5 and FA6. Fluvial channel and channel margin settings are interpreted for FA5. Amalgamated trough cross-bedded sandstones with abundant rip-up clasts and thin rip-up conglomerates are indicative of channel-fill deposition. Fining-up trends and associated upwards progressions of facies, from trough cross-bedding to planar lamination to ripple cross-lamination, all indicate shallowing and lateral accretion of a point bar (Fig. 14). The combination of rip-up clasts, desiccation cracks and plant material observed indicate proximity to overbank settings. The dominance and style of current-ripple cross-lamination preserved is consistent with deposition in fluvial settings (Fig. 13a). The oscillatory ripples at Millyit Range are interpreted as wind-generated, formed in isolated pools or temporarily abandoned channel settings.

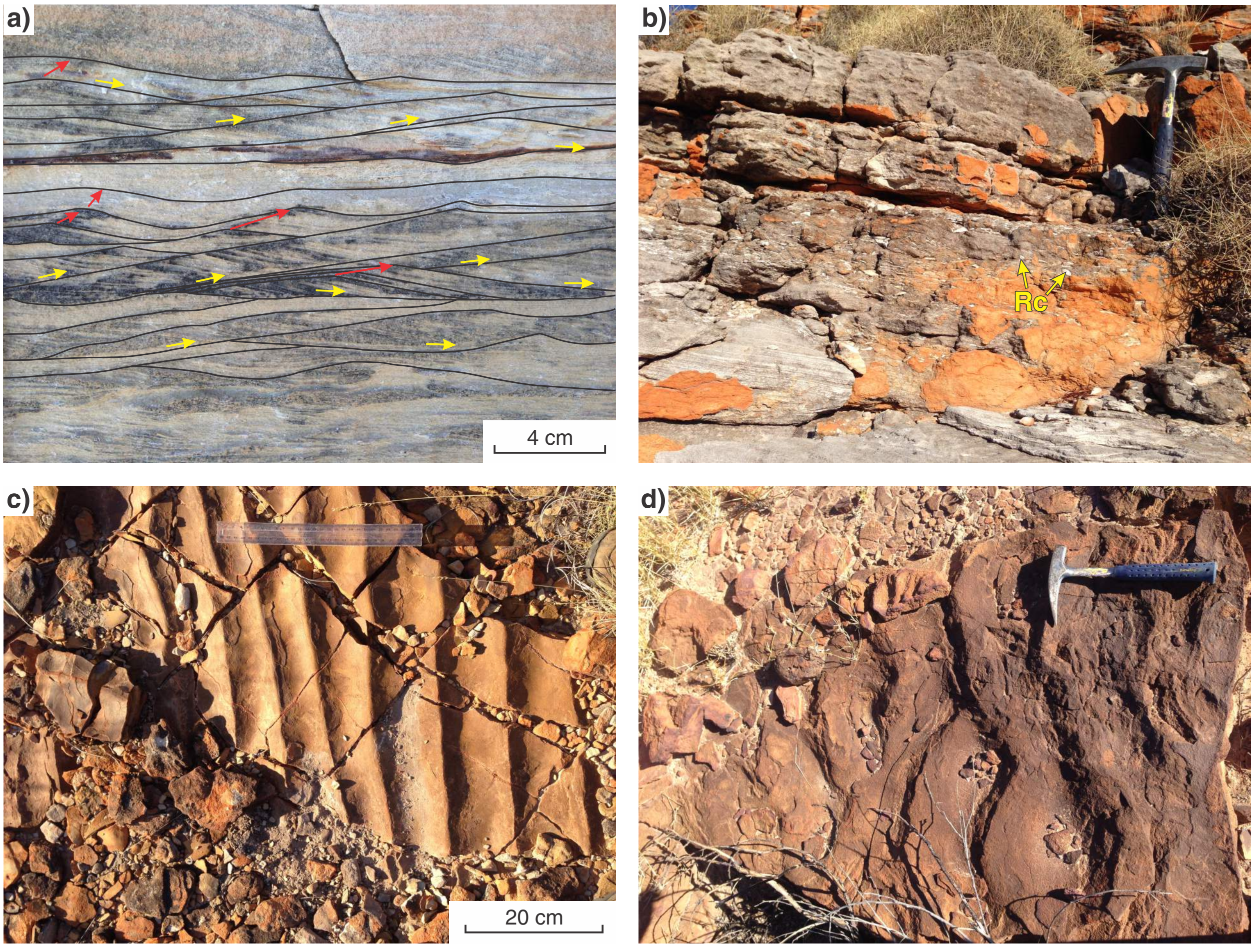

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Figure 13. Key sedimentary features of FA5 from the Condren Sandstone: a) amalgamated ripple cross-lamination at Millyit Range with both aggradational (red arrow) and erosional ripple forms (yellow arrows) that both indicate a unidirectional current; b) trough cross-bedded sandstone at Millyit Range with abundant rip-up clasts (Rc) aligned along foresets; c) plan view of oscillatory ripples preserved on the outcrop surface at Millyit Range; d) plan view of linguoid ripples preserved on the outcrop surface at the Condren Pinnacles locality

In comparison to FA5, FA6 represents much higher energy fluvial depositional settings. A fluvial environment is inferred from the erosional scours and overlying trough cross-bedded infills (Fig. 15a). Scour size, basal conglomeratic lags, cross-bed thickness and the general absence of fine-grained facies are indicative of deposition in high-energy settings. Upwards-thinning of cross-beds and regular interbedding of ripple cross-laminated and planar-laminated facies record episodic shallowing, lateral accretion and channel migration processes. A braided fluvial setting is suggested based on high-energy, multi-channel deposits and the absence of any distinct overbank, floodplain or abandoned channel features.

High-energy fluvial deposits were only recorded in the Condren Sandstone at one other location, Roberts Range (CORNISH; Yeates et al., 1984). While there is general agreement on fluvial deposition in the southeast (LUCAS, STANSMORE, CORNISH) lower energy, meandering fluvial systems were interpreted for the majority of the area (Blake and Yeates, 1976; Crowe and Muhling, 1977; Crowe, 1978). However, the lack of complete sections increases the uncertainty in this interpretation. Although the contact was not observed at Durbai Creek (BILLILUNA), the strata appear to directly overlie the Lightjack Formation, which suggests that these high-energy fluvial deposits (FA6) occur close to the base of the Condren Sandstone.

Interpretation of FA5, at the Condren Pinnacles and Millyit Range, as deposition in a meandering fluvial system is consistent with earlier interpretations (Yeates et al., 1975b; Forman and Wales, 1981). The key difference between these two localities is the localized occurrence at the Millyit Range sites of oscillatory ripples on bedding surfaces in sections otherwise dominated by current-ripple lamination. Oscillatory ripples indicate wave activity and are conventionally assigned to marine deposits for this reason; however, they may also be formed by wind-generated waves in nonmarine settings, such as cutoff pools. Transition from a fluvial to a deltaic environment was interpreted in this area by Towner (1977; CROSSLAND) and Yeates and Muhling (1977; MOUNT BANNERMAN). Similar wave-ripple features were recorded further to the southeast in the Southesk Tablelands, along with bimodal current indicators (Yeates et al., 1975b).

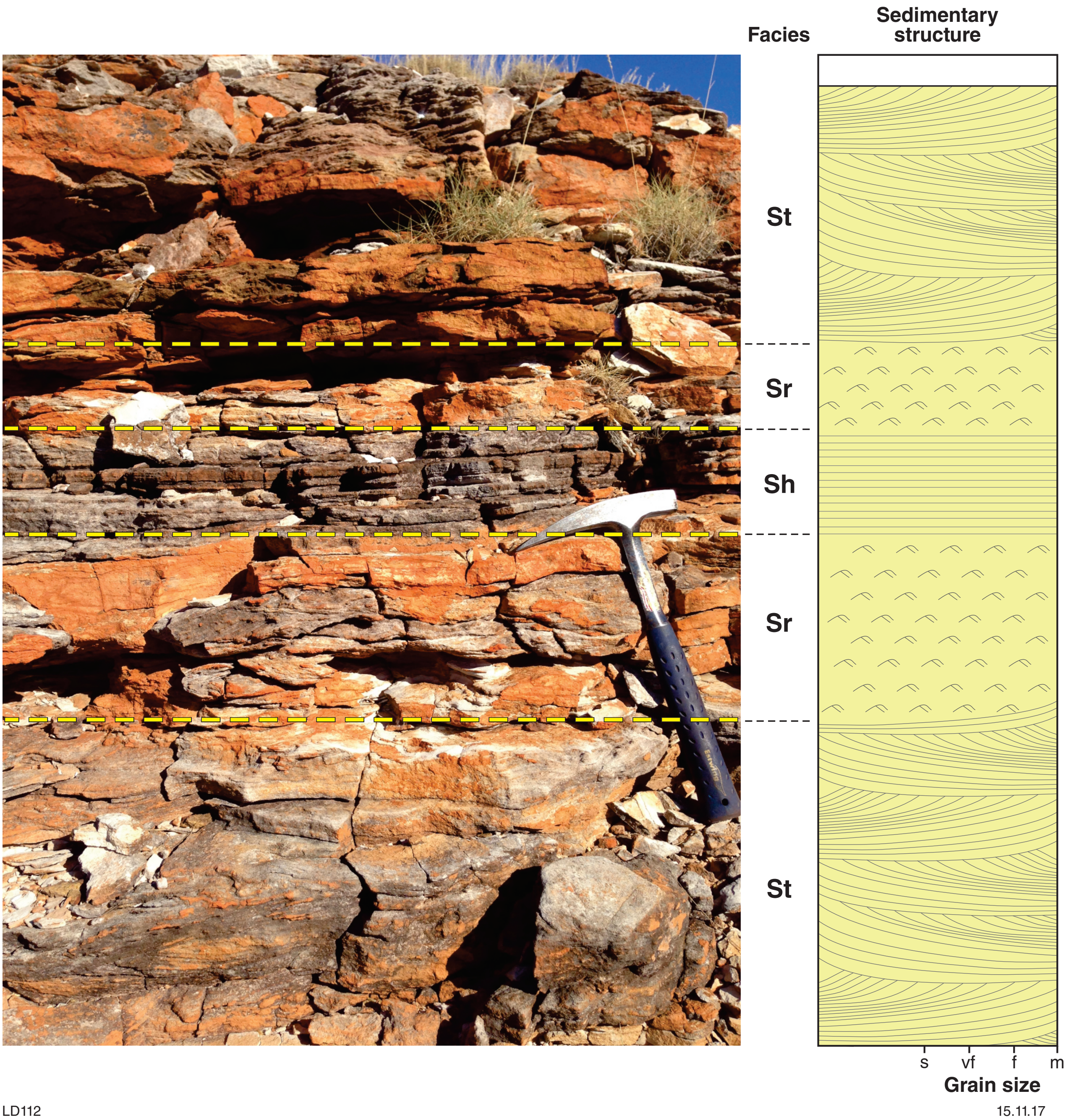


Figure 14. Representative section of FA5 from Millyit Range. The corresponding schematic log illustrates the up-section facies progressions from trough cross-bedding (*St*) to ripple cross-lamination (*Sr*) and planar lamination (*Sh*)

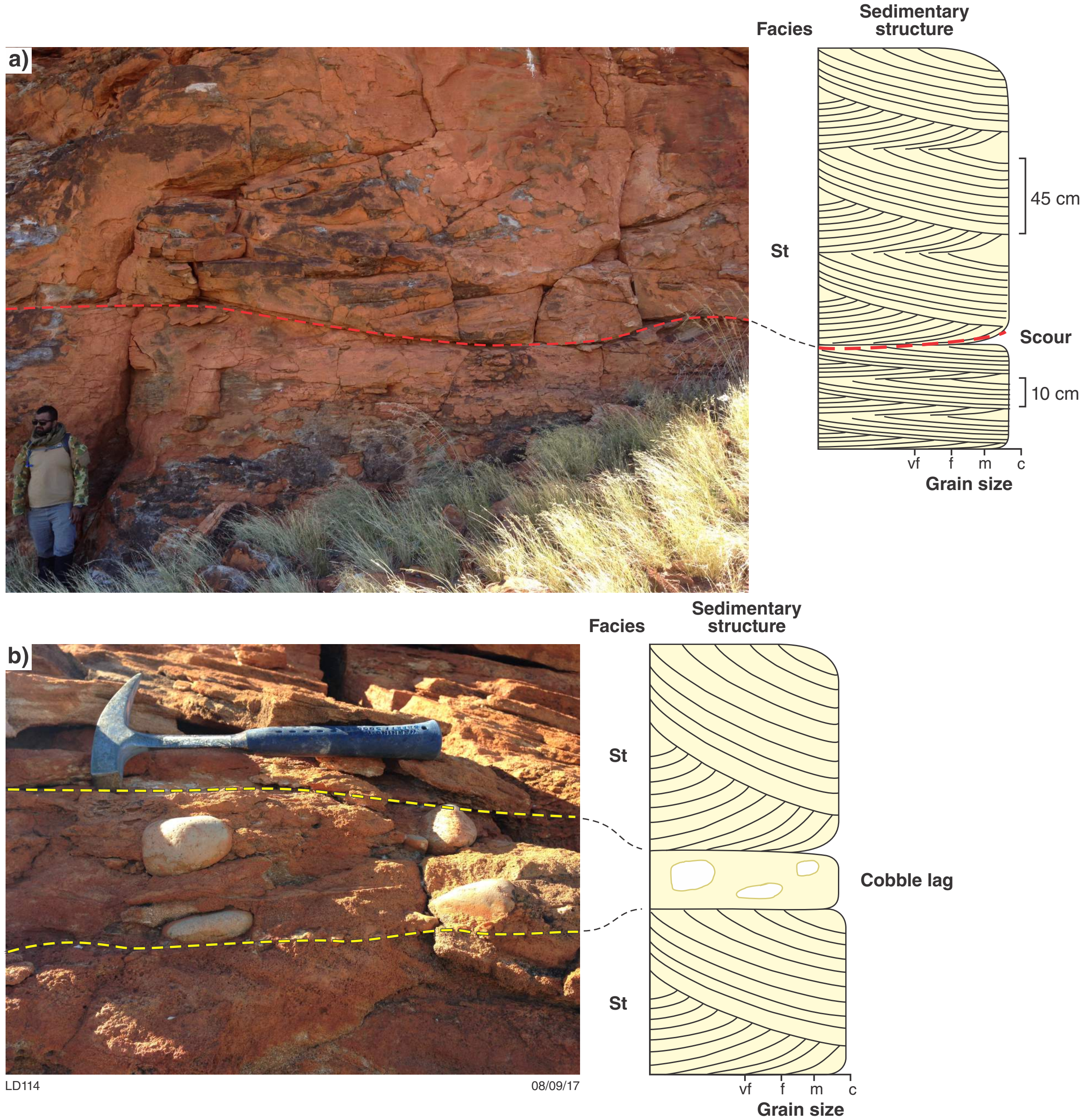


Figure 15. Key sedimentary features of FA6 from the Durbai Creek section: a) photo and corresponding schematic log showing erosional scour by thicker trough cross-bed sets (*St*, ~45 cm thick) cut into thinner trough cross-bed sets (10 cm); b) lag of rounded cobbles between trough cross-beds (*St*)

Hardman Formation: Kirkby Range Member and Hicks Range Sandstone Member

Outcrop lithofacies

The Kirkby Range Member is the oldest member of the Hardman Formation. Two shallow-marine facies associations were interpreted from the outcrop sections visited (Appendix 1). Facies association 7 (FA7) records deposition in upper to middle shoreface settings and facies association 8 (FA8) records deposition in lower shoreface or lagoonal-type settings (Appendix 4). The Kirkby Range Member shows variable outcrop styles: low rubbly outcrop is present at Boundary Hill (Fig. 7e), while the sections at Hicks Range and Millyit Range form steep breakaways from the underlying Condren Sandstone. The Hicks Range Sandstone Member is the middle member of the Hardman Formation. It was observed only at Hicks Range where massive blocky outcrop overlies the Kirkby Range Member (Fig. 7d). Facies association 9 (FA9) was identified at this outcrop site and indicates deposition in fluvial settings.

FA7 was identified only at Millyit Range. Amalgamated hummocky–swaley cross-bedding and trough cross-bedding are dominant (Appendix 4). These facies host distinct monospecific trace fossil assemblages of either *Rosselia* or *Skolithos* traces (Fig. 16a,b). These facies are interbedded with clay-rich sandstone beds containing much higher abundance and diversity trace fossil assemblages (Fig. 16c–f). In these beds, trace fossils are commonly concentrated along very fine-grained, highly oxidized bedding planes (Fig. 16e). This facies association transitions into thickly bedded, highly bioturbated facies up-section; however, interpretation of these sections is hindered by the height and steepness of outcrop faces.

FA8 was identified in outcrop at the Condren Pinnacles, Boundary Hill and Hicks Range. This association is characterized by interbedded successions of two major facies *Ba* and *Bb* (Appendix 4). Both facies are characterized by intense bioturbation that obliterates primary sedimentary structure, and distinct white and deep purple–red colouration caused by oxidation. The distinction between these facies is made on the trace fossil assemblage. In facies *Ba*, extensive *Thalassinoides* traces were found in laterally extensive box-works or high-density horizons (Fig. 17a,b) and *Diplocraterion*, *Rhizocorralium* and *Palaeophycus* are also dominant (Fig. 17c,d). The *Ba* facies is characterized by high-diversity, high-abundance horizontal traces and has a bioturbation index of 4–5. In facies *Bb*, bioturbation is observed predominantly as indistinct mottling; however, where traces are recognizable, the assemblage is dominated by small 1–2 mm diameter horizontal traces including *Chondrites* and *Phycosiphon* (Fig. 17e,f).

FA9 was identified at Hicks Range and comprises shallow trough cross-bedded sandstones amalgamated into thick beds and thick sequences (Fig. 18a). Flattened clay-clasts are common in the lower foresets of troughs. Planar-laminated and ripple cross-laminated facies are subordinate. Low-intensity, low-diversity horizontal bioturbation is common in cross-bedded facies (Fig. 18b,c). Root horizons were observed in planar-laminated facies (Fig. 18d).

Depositional sequence

FA7 of the Kirkby Range Member is interpreted to directly overlie the Condren Sandstone at Millyit Range; however, the contact is difficult to identify due to the abundance of scree on the slopes. The upper contact of FA7 was not observed due to the sheer outcrop faces, although the intensely bioturbated facies overlying it may indicate a transition to FA8. FA8 directly overlies the Condren Sandstone at the Condren Pinnacles; the lithology, mottling and bioturbation are strikingly similar to this facies as seen at Boundary Hill and Hicks Range. FA9 overlies FA8 at Hicks Range marking the boundary between the Kirkby Range and Hicks Range Sandstone Members. This boundary is gradational but distinct; intervals of facies Hm (FA8), of variable thickness, are interbedded with the trough cross-bedded facies (*St*) that dominate FA9 (Fig. 19). The upper contact of the Hicks Range Sandstone Member was not observed, nor was the uppermost Cherrabun Member of the Hardman Formation.

Depositional setting

Shallow-marine settings, above storm wave-base, are interpreted for FA7, based on the occurrence of scour and fill features, hummocky–swaley cross-bedding and the trace fossil assemblage recorded in these beds. Interbeds with more abundant bioturbation and more argillaceous lithologies indicate episodic alternation with lower energy settings. The combination and character of these two facies suggest a middle shoreface setting for FA7.

Shallow-marine settings were also interpreted for FA8 based on the identified trace fossil assemblages. The abundance and extent of bioturbation, combined with the dominance of grazing and dwelling traces, suggests well-oxygenated, low-energy conditions with abundant food sources. The variation in bioturbation styles between beds, notably the transition from larger traces in facies *Ba* to smaller traces in facies *Bb*, suggests episodic changes in conditions potentially related to less favourable, deeper water or lower oxygen levels. Based on changes in trace fossil assemblages, and the upwards progression into a fluvial facies association (FA9) at Hicks Range, a lagoonal-type setting is suggested for FA8.

Fluvial depositional settings were interpreted for FA9 based on the abundance and amalgamation of clean, trough cross-bedded sandstones into thickly bedded sequences. In addition, clay rip-up clasts, root beds, overall low diversity and abundance of bioturbation, and an absence of any distinct marine indicators are consistent with a fluvial depositional setting.

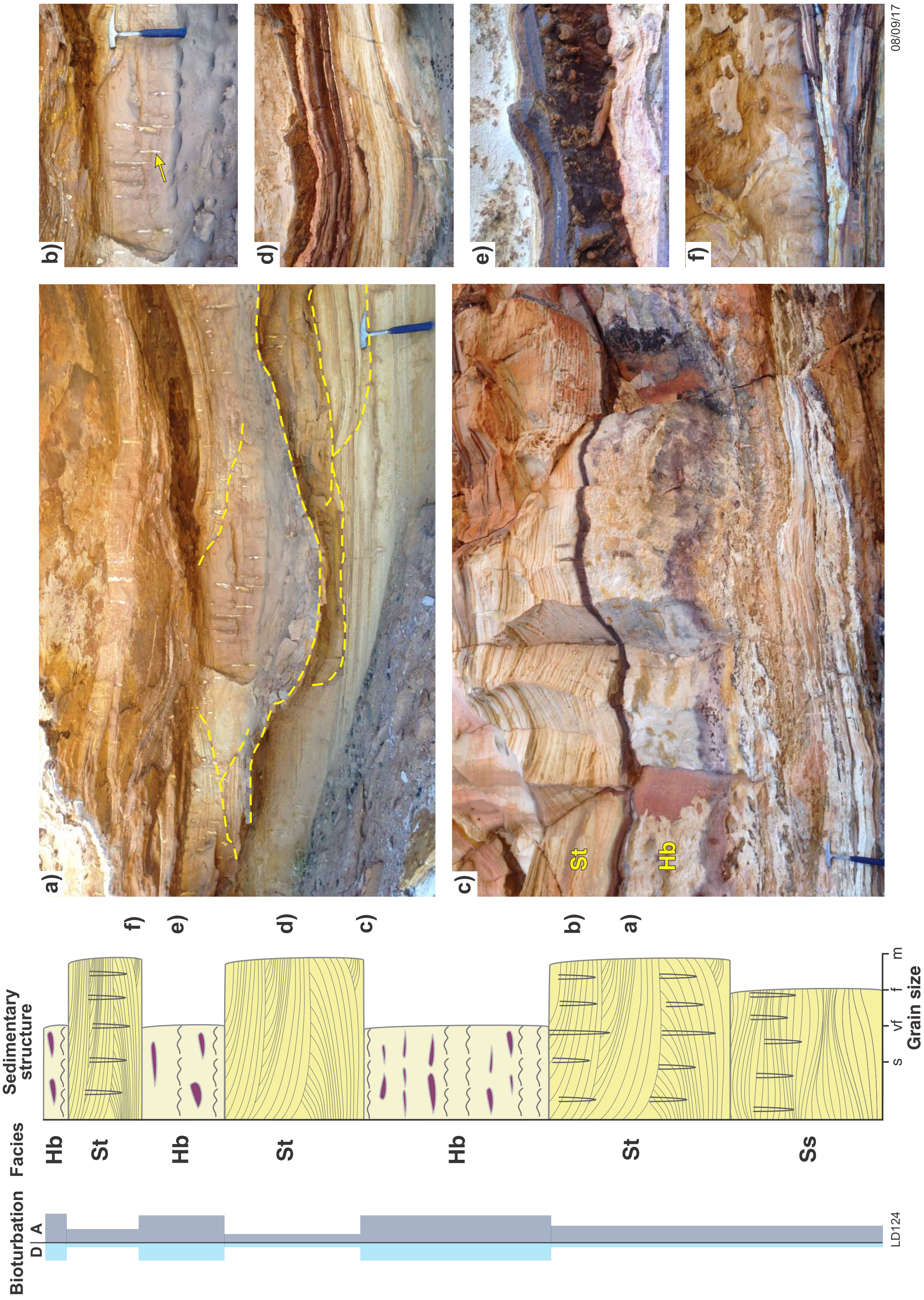


Figure 16. Key sedimentary features of FA7 seen in a representative section of the Millyit Range outcrop that illustrates interbedded swaley to hummocky cross-bedding (*Ss*), trough cross-bedding (*St*) and the bioturbated heterolithic facies (*Hb*). The shaded bioturbation log illustrates the relative levels of diversity (D) and abundance (A) of traces fossils in each facies and correlates directly to the log section. Photos a–f correspond to facies represented on the schematic log: a) sandstone facies with broad scour and fill features (scours marked in yellow) and common vertical bioturbation; b) monospecific *Skolithos* or *Rosselia* trace fossil assemblage observed in swaley and trough cross-bedded facies; c) trough cross-bedded (*St*) facies overlying a thick heterolithic bioturbated bed (*Hb*); d) clay-rich facies of *Hb* with highly oxidized (purple) layers; e) abundant bioturbation preserved in a highly oxidized layer from *Hb* facies; f) *St* facies overlying *Hb* facies

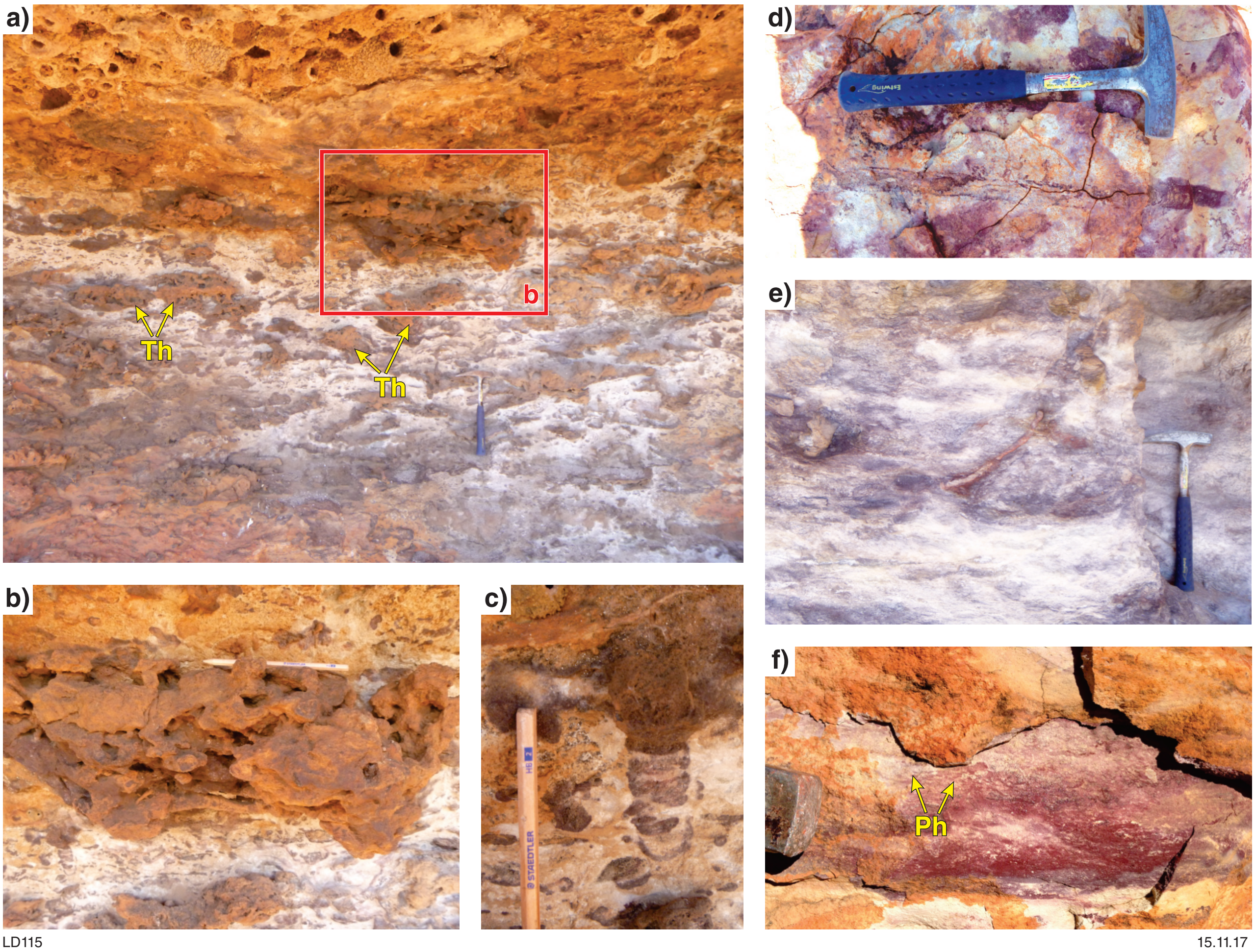


Figure 17. Key sedimentary features of FA8 from Hicks Range: a) clay-rich fine sandstone with extensive bioturbation (facies *Ba*) showing abundant *Thalassinoides* (Th) traces forming extensive boxworks; b) horizon of *Thalassinoides* burrows; c) *Diplocraterion* trace; d) *Rhizocorallium* preserved on the outcrop surface; e) extensive bioturbation in facies *Bb*, obliterating primary sedimentary structure; f) *Phycosiphon* (Ph) burrows in facies *Bb*

Correlation of outcrop to subsurface sections

Definition of the Liveringa Group

In the study area, the Liveringa Group in outcrop is defined by an abrupt, but conformable, lower contact with the Noonkanbah Formation. It is overlain both disconformably by Triassic sedimentary rocks and unconformably by Jurassic strata. The basal Liveringa Group picks used in this Report are derived from Dent (2016) and the top Liveringa Group picks are from Mory (2010). Revised boundaries for formations within the Liveringa Group are suggested in some wells, based on palynology and the regional correlation of well logs undertaken in this study (Appendix 3).

Well-log correlation

Subsurface sections of the Liveringa Group within the study area typically exhibit one of three gamma ray log profiles labelled here as Profile types A, B and C (Fig. 20). Each profile displays distinguishable elements defined by the gamma ray log signature: Profile A displays two funnel-shaped trends succeeded by a cylindrical trend (e.g. Puratte 1, Appendix 2); Profile B displays a bell-shaped trend succeeded by a cylindrical trend (e.g. Blackstone 1, Appendix 2); Profile C displays three successive funnel-shaped trends (e.g. Kilang Kilang 1, Appendix 2). Funnel-shaped trends are interpreted as coarsening-up sequences, cylindrical trends are interpreted as aggradational sequences and bell-shaped trends are interpreted as packages that change gradationally from coarsening-up to fining-up sequences.

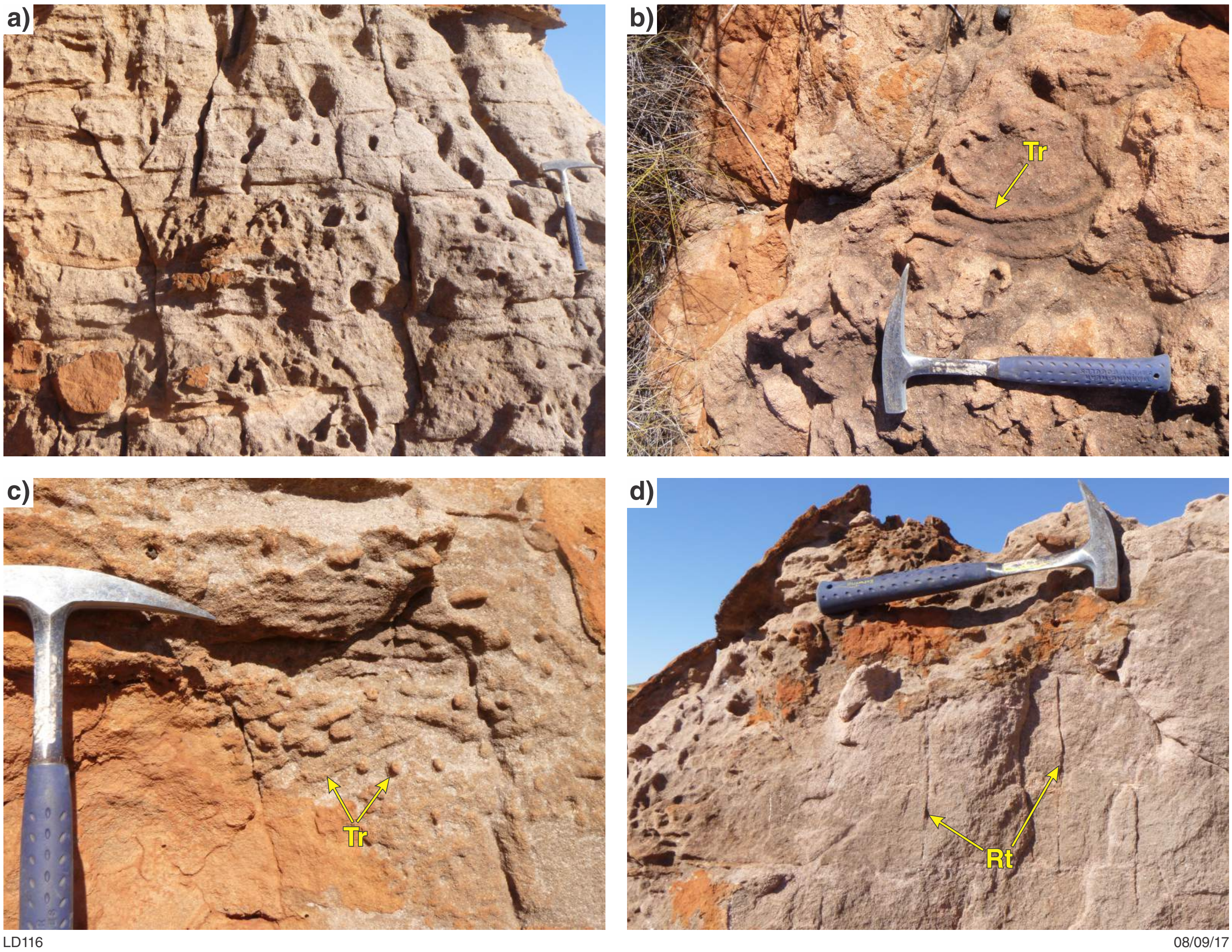


Figure 18. Key sedimentary features of FA9 from Hicks Range: a) amalgamated trough cross-bedded facies; b) plan view of horizontal, unlined sand-filled trace fossils (Tr); c) cross-sectional views of trace fossils identified as those in b) in vertical section.; d) root traces (Rt)

The wells in the study area show strong spatial trends in profile type (Fig. 21a): well logs in the southeast of the study area display a Profile C gamma ray log signature, Profile B dominates in the central Fitzroy Trough and Lennard Shelf areas, and Profile A is observed in the well logs to the far northwest (Fig. 21). Permian strata have been eroded in this far northwest section of the study region and the Liveringa Group is only partially present, or absent, in some wells (e.g. Moogana 1).

Palynological correlation

Correlation of trends between wells with the same gamma ray profile is easily achieved; however, the relationship between the trends in different log profiles (A, B, C) is unclear and formation names have not been formally assigned in the majority of the petroleum wells. Two broad zones can be correlated between the three profile types using the available palynology (Fig. 4, Section 1; Appendix 3). Zone 1 is the oldest unit of the Liveringa Group, based on the presence of spore-pollen zones *D. granulata* to *D. dulhuntyi*. Zone 2 coincides with a younger, thicker section of the Liveringa Group and is correlated based on the presence of palynozone *D. parvithola* (Fig. 4, Section 1; Appendix 3). The top of Zone 2 is interpreted as the appearance of the *K. saeptatus* spore-pollen zone, at the contact with the overlying Triassic Blina Shale. Near the top of Zone 2 the younger *P. crenulata* and *P. microcorpus* spore-pollen zones were recorded, although they were found only in the uppermost trend of in Puratte 1 (Profile A) and Mimosa 1 (Profile B; Fig. 4, Section 1; Appendix 3). The *P. crenulata* and *P. microcorpus* spore-pollen zones are included in Zone 2 due to the limitations of the data. The Puratte 1 and Mimosa 1 wells are about 160 km apart and the palynology of some wells between the two show an extremely short transition (~15 m) from *D. parvithola* to *K. saeptatus* (e.g. Blackstone 1; Appendix 2). There may be a very thin layer of the *P. crenulata* zone in Blackstone 1, the zone may be absent, or the palynology may be misleading; this uncertainty could result in an incorrect interpretation of the depth to the base Triassic.

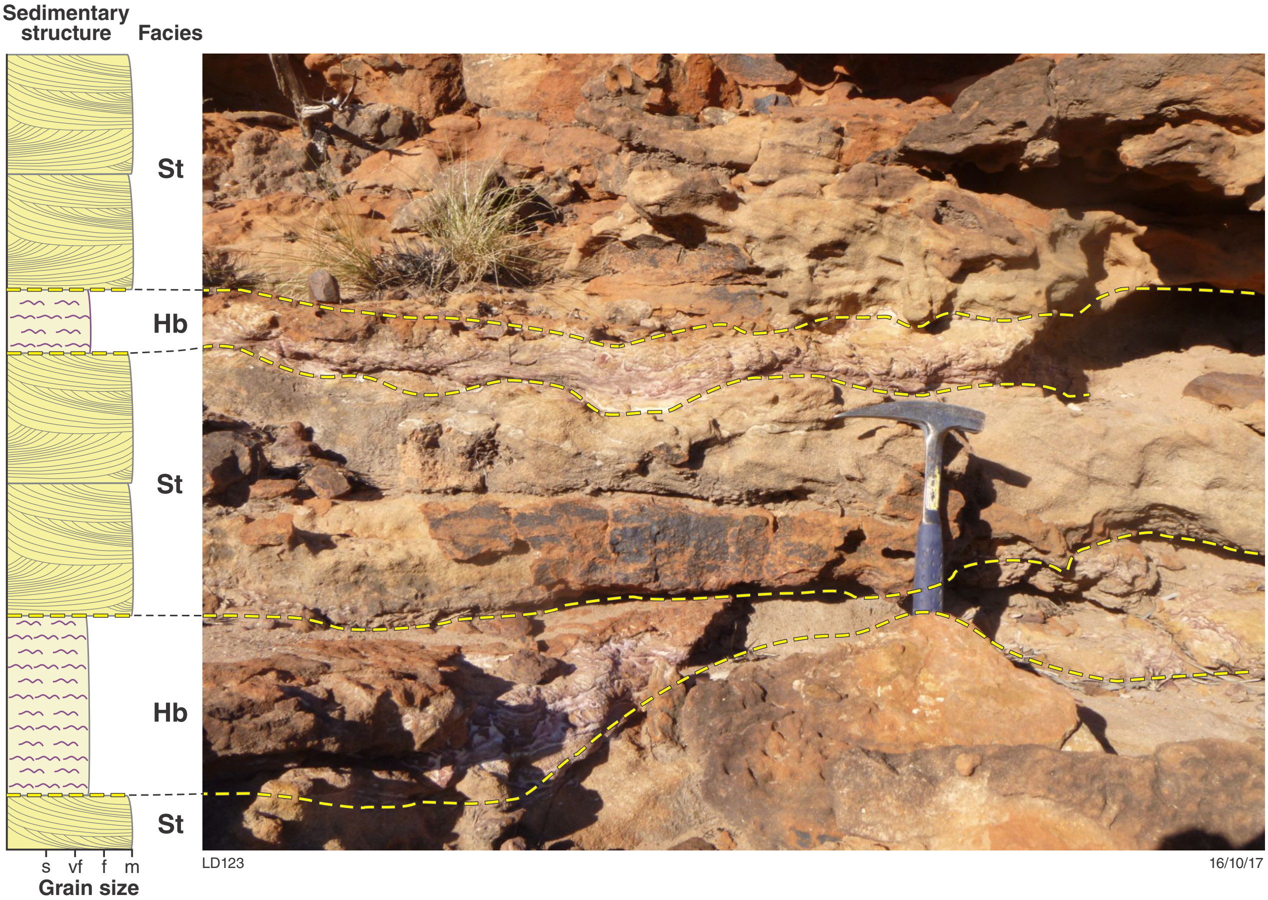


Figure 19. Intercalated contact between the Kirkby Range and Hicks Range Members at the base of the type section of the Hicks Range Member, Hicks Range, shown in outcrop and as a schematic log; the bioturbated heterolithic facies (*Hb*), typical of the Kirkby Range Member, is interbedded with trough cross-bedded sandstones (*St*), typical of the overlying Hicks Range Member

While the presence of the *P. crenulata* and *P. microcorpus* spore-pollen zones suggests that there is a younger interval overlying the *D. parvithola* zone, the data are not comprehensive enough to confidently correlate these two younger zones across the region. Foster (1982) identified that the *P. crenulata* zone is transitional and the assemblage is dominated by pollen grains that typify the underlying palynozones while also containing taxa from overlying zones. Furthermore, this *P. crenulata* zone is rarely identified in Western Australia (Mory, 2010); therefore, the identification of this zone may be problematic due to preferential preservation or lean assemblages and absence of the key taxa. A much larger dataset and finer sample spacing would be necessary to confidently establish the continuity of the *P. crenulata* zone.

The palynozone – well log relationship described is best illustrated by the wells Moogana 1, Puratte 1, Blackstone 1, Mimosa 1 and Kilang Kilang 1 (Fig. 4, Section 1; Appendix 3). Palynological data obtained from other wells are lower resolution but, in all cases, agree with the three-zone correlation. For more details see Appendix 2. Finer-scale division and correlation of the individual *D. granulata*, *D. ericianus* and *D. dulhuntyi* palynozones in Zone 1 was not attempted due to the low sampling density.

Division of the Liveringa Group

Historical lithostratigraphic formations within the Liveringa Group do not coincide with palynozone boundaries. Previously, the spore-pollen zones *D. granulata* to *D. parvithola* were recorded in the Lightjack Formation (Mory, 2010) and the *D. parvithola* zone was also recorded in the Condren Sandstone and the Hardman Formation. Due to the occurrence of *D. parvithola* in all three formations of the Liveringa Group, a combination of palynology, lithology, sedimentological features, and wireline log trends is required in order to divide it into its component formations.

In this Report well log profiles were compared to outcrop-scale facies associations, reconstructed measured-outcrop sections and well intersections (Fig. 4, Sections 1–7; Appendix 3). The dominant lithology is plotted next to each well log, where it was available from well completion reports or mud logs (Appendix 2). The study area was divided into three sectors (Fig. 21a), each with varying stratigraphic data and outcrop exposure. In the southeast sector, data from mapped outcrops of the three Liveringa Group formations were compared with wireline logs from proximal petroleum exploration wells and stratigraphic

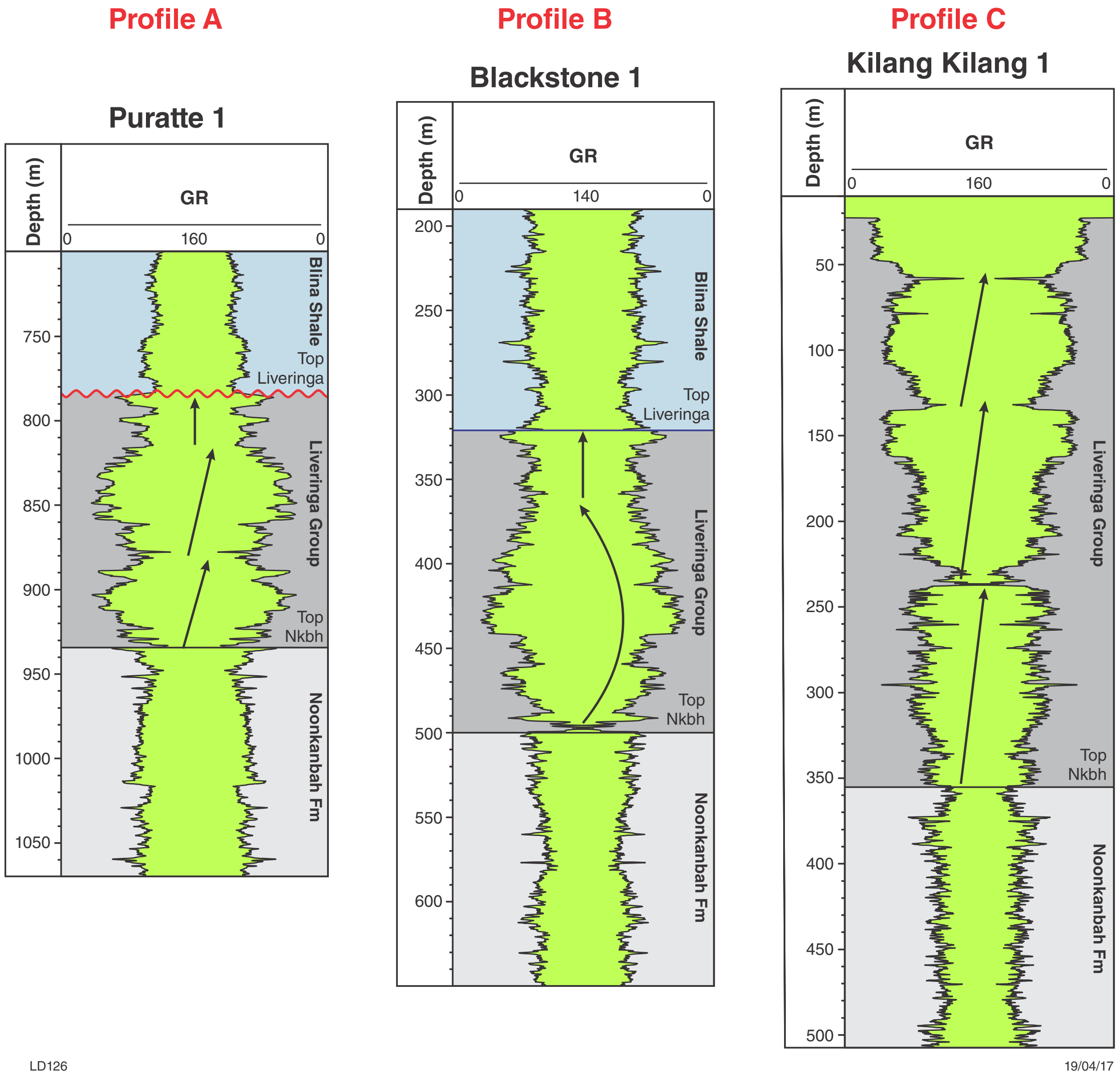


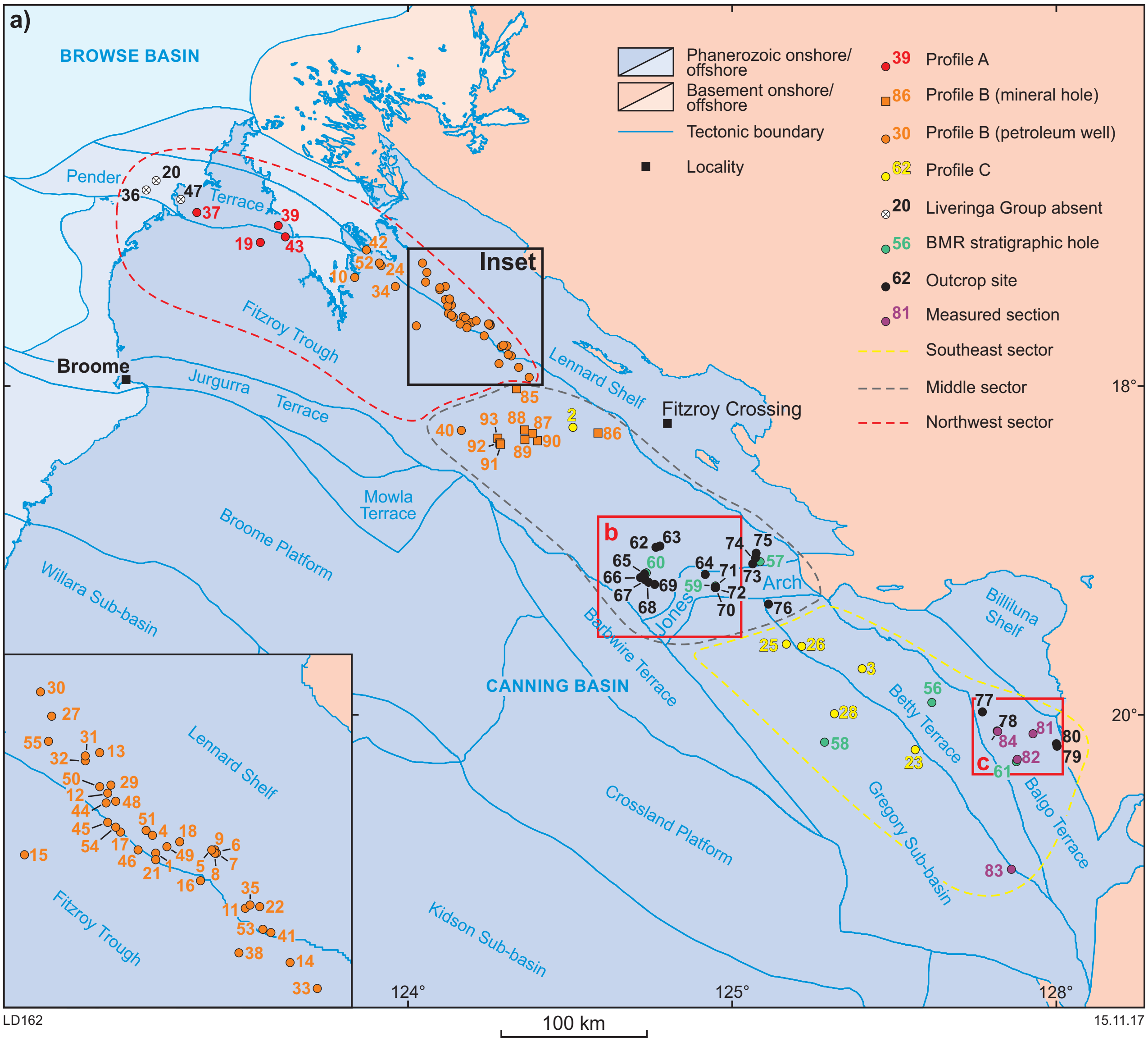
Figure 20. Gamma ray log profiles of the Liveringa Group illustrating the three main profile types exhibited in petroleum wells (traces are mirrored and filled to highlight profile shape): Profile type A constitutes two funnel-shaped trends followed by a cylindrical trend. Profile type B constitutes a bell-shaped trend followed by an aggradational trend and Profile C constitutes three successive funnel-shaped trends

holes. Definition of this sector is based on the presence of the Condren Sandstone and Profile type C in petroleum wells that each displayed stacked, coarsening-up gamma ray log trends (Fig. 21). Data for the middle sector include outcrop sections, wireline logs from petroleum wells and company drillhole data. In this area the Condren Sandstone has previously been interpreted to be ‘pinching-out’ or absent. The northwest sector contains no outcrop and historically the Condren Sandstone was interpreted to be absent; however, supplementary data including coal and glauconite were used to correlate well logs and delineate formations.

Southeast sector

Lightjack Formation

Two key features were used previously to help identify and correlate the Lightjack Formation across the Canning Basin: iron-rich concretionary bands at the base of the formation and a thick, clean, sandstone unit present between two lagoonal – shallow-marine deposits (Yeates et al., 1984). Unfortunately, neither feature was obvious in the outcrop sections visited, or in the well logs or cuttings descriptions, although the concretionary band was noted in measured section Lightjack 2 (Yeates et al., 1975b).



1 Aquanita 1
2 Asgard 1
3 Bindi 1
4 Blackstone 1
5 Blina 3
6 Blina 4
7 Blina 5
8 Blina 7
9 Blina 8
10 Booran 1
11 Boronia 1
12 Boundary 1
13 Canegrass 1
14 Crimson Lake 1
15 East Yeeda 1
16 Hakea 1
17 Hangover 1
18 Janpam 1
19 Jum Jum 1
20 Kambara 1
21 Katy 1
22 Kennedia 1
23 Kilang Kilang 1
24 Kora 1
25 Lake Betty 1
26 Lanagan 1
27 Langoora 1
28 Lawford 1
29 Lloyd 2
30 May River 1
31 Meda 1
32 Meda 2
33 Metters 1
34 Millard 1
35 Mimosa 1
36 Minjin 1
37 Moogana 1
38 Nemile 1
39 Padilpa 1
40 Petaluma 1
41 Philydrum 1
42 Point Torment 1
43 Puratte 1
44 Scrubby 1
45 Sundown 2
46 Sunup 1
47 Tappers Inlet 1
48 Terrace 1
49 Thompsons 1
50 Wattle 1
51 West Blackstone 1
52 West Kora 1
53 West Philydrum 1
54 Whitewell 1
55 Yarrada 1
56 BMR Mt Bannerman 1
57 BMR Mt Bannerman 2
58 BMR Cornish 1
59 BMR Crossland 1
60 BMR Crossland 2
61 BMR Lucas 14
62 Shore Range 1
63 Shore Range 2
64 Beefwood Park
65 Millyit Range 1
66 Millyit Range 2
67 Millyit Range 3
68 Millyit Range 4
69 Millyit Range 5
70 Hicks Range 1
71 Hicks Range 2
72 Hicks Range 3
73 Christmas Creek 1
74 Christmas Creek 2
75 Christmas Creek 3
76 Boundary Hill
77 Durbai Creek 1
78 Condren Pinnacles 1
79 Namalook 1
80 Namalook 2
81 Lightjack 1 (Gumbo Point)
82 Lightjack 2 (Micha Bore)
83 Lightjack 3 (Stretch Range)
84 Condren Pinnacles
85 ARCMR045
86 ARCMR054
87 ARCMR069
88 ARCMR070
89 ARCMR071
90 ARCMR072
91 SR01
92 SR02
93 SR04

Figure 21. Division of the study area, based on gamma ray profile types, into three sectors: southeast, middle and northwest; petroleum wells and mineral holes are coloured according to log profile type (A, B or C, as described in Fig. 20); b) and c) show the detailed geological setting, based on 1:250 000 Series maps, of outcrop sites visited in the middle and southeastern sectors, respectively

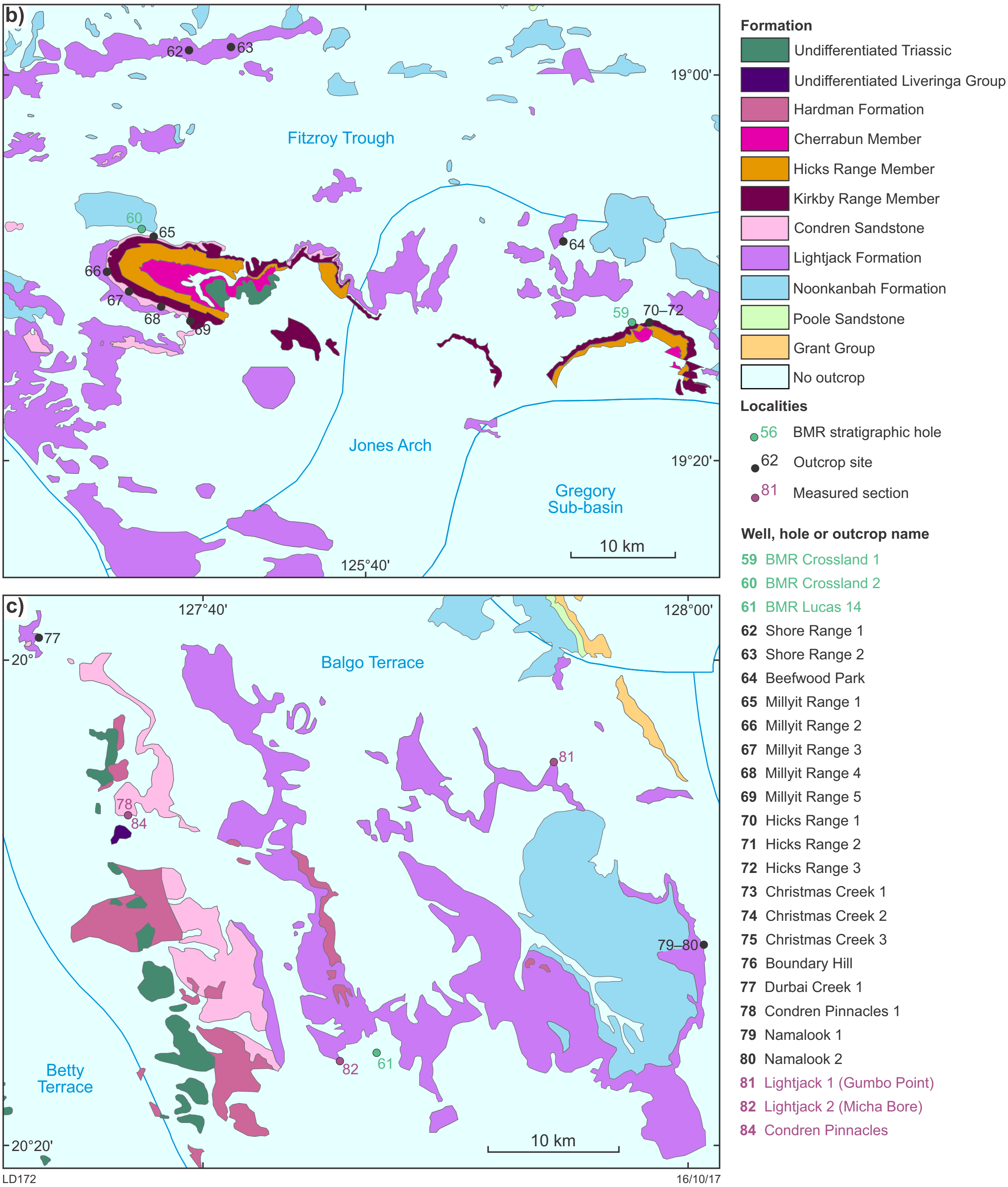


Figure 21. continued

In the absence of reliable marker beds, the Lightjack Formation was interpreted in Kilang Kilang 1 based on the presence of palynozones *D. granulata* and *D. ericianus* and the coarsening-up gamma ray log trend at the base of the Liveringa Group. These two characteristics are similar to the log signature and palynology of BMR Mt Bannerman 1 and consistent with Lake Betty 1 (Fig. 4, Section 4; Appendix 3). Interbedded sandstone and siltstone intervals were recorded in these wells, in the stratigraphic hole BMR Cornish 1, and outcrop sites Lightjack 1 and 2, and Namalook 1 and 2 (Fig. 4, Sections 2 and 3; Appendix 3). In both Kilang Kilang 1 and BMR Mt Bannerman 1 the basal coarsening-up trend is overlain by a fine-grained interval which records the *D. parvithola* palynozone; in BMR Mt Bannerman 1 this fine-grained interval is interpreted to be the Lightjack Formation and the overlying sandstone facies is interpreted to be the base of the Condren Sandstone.

The shallow-, open- to marginal-marine and possible intertidal settings interpreted from outcrop facies at Namalook 1 and 2 (Fig. 21c) are consistent with mixed fresh and saltwater indicators in outcrops at nearby Balgo (Yeates et al., 1984) and widespread shallow-marine conditions in the Gregory Sub-basin during deposition (Yeates et al., 1975b). Marginal-marine settings are interpreted from the palynology in Kilang Kilang 1 and marine settings are interpreted from the sample examined from Lake Betty 1. Palynology from BMR Mt Bannerman 1 and BMR Cornish 1 record no indicators of marine settings based on the absence of acritarchs; however, marine and particularly marginal-marine settings cannot be ruled out.

Condren Sandstone

In the southeast sector (Fig. 21), the Condren Sandstone was deposited in a fluvial environment. High- and low-energy fluvial deposits have been interpreted both in the Balgo area and in the more southern Stansmore Range area. This variation was observed elsewhere, with high-energy fluvial deposits at Durbai Creek 1 and lower-energy fluvial deposits interpreted at the Condren Pinnacles (Fig. 21c). As is typical of meandering fluvial systems, facies are often not laterally extensive resulting in lithological variability over short distances as seen both in outcrop and in the well logs. The palynology in the southeast sector can only be used to confirm that sediment was deposited in the *D. parvithola* zone.

The original palynological report for Kilang Kilang 1 suggested that the interpreted ‘Condren Sandstone’ interval was deposited in a transgressive environment that transitioned from marginal marine to marine environments up-section. While this is inconsistent with the fluvial deposition recorded to the east and southeast, the original 1:250 000 scale mapping interpreted some marine indictors in outcrop sections in the Southesk Tablelands (CORNISH; Crowe, 1978). Deltaic (MOUNT BANNERMAN; Yeates and Muhling, 1977) and deltaic to marine (CROSSLAND; Towner, 1977) settings were also interpreted in the northwest. Considering the position of Kilang Kilang 1 in a major depocenter, marine deposits may be present in this well.

Hardman Formation

An abrupt contact and a distinct change in lithofacies were recognized where the Condren Sandstone is overlain by the Hardman Formation at the Condren Pinnacles. The overlying Hardman Formation is a finer-grained, clay-rich sandstone. The sharp increase in gamma ray log values at 135 m depth in Kilang Kilang 1 is interpreted as a flooding event and the beginning of deposition of the Hardman Formation. This interpretation is based on previous descriptions of marine indicators in the Hardman Formation (Yeates et al., 1975b), the marine setting of the strata directly below this surface as indicated by the palynology, and the notable similarity between the Hardman Formation at the Condren Pinnacles and the marine intervals observed at the Boundary Hill outcrop. The interpreted flooding event can be correlated with the other three petroleum wells in the southeast sector at Lawford 1, Lanagan 1 and Lake Betty 1 (Fig. 4, Section 4; Appendix. 3). Previous biostratigraphy from ammonoid and brachiopod faunas place the Hardman Formation as late Wuchiapingian in age (Archbold, 1999), which would equate to the *D. parvithola* palynozone. With no palynology available in the uppermost parts of the wells or measured outcrops in the southeast sector, this flooding surface is the best indicator of the base Hardman Formation.

Middle sector

The majority of outcrop sections investigated for this Report are located in the middle sector (Fig. 21b); however, since very few petroleum wells intersect the Liveringa Group in this area, correlation with subsurface data was restricted. Extensive coal exploration in the northern half of this middle sector targeted seams in the Lightjack Formation. Gamma ray logs are available from some of these holes affording a subsurface view of the Liveringa Group between the sparse petroleum well logs. Unfortunately, the intervals covered by the logs is limited and many show only incomplete parts of the Liveringa Group (Fig. 4, Section 5; Appendix 3).

Coal is easily interpreted in well logs where it produces a distinctive low gamma ray value, such as that observed between 200 and 214 m depth in Petaluma 1 (Fig. 4, Section 5; Appendix 3). Generally two coal seams have been recorded in the Lightjack Formation, referred to as the P1 and P2 seams in coal company reports. Ideally these seams could be used as marker beds for correlating well logs; however, based on the information from company well reports, the coal is not laterally continuous and many holes are too shallow to intersect the Lightjack Formation (e.g. ARCMR069-072; Fig. 4, Section 5; Appendix 3). Seams were also misidentified, with P1 interpreted at the top of the Liveringa Group in wells ARCMR069 and ARCMR070 (Fig. 4, Section 5; Appendix 3). As a consequence, the formation picks for the tops of the Liveringa Group and the Noonkanbah Formation in these wells were originally incorrect, leading to inconsistent correlation with neighbouring wells (e.g. ARCMR071) and lack of agreement with the 1:250 000 maps.

Overview of the Liveringa Group in the middle sector

The most distinct feature of the well logs in this middle sector is the contact between the Liveringa Group and the overlying Triassic Blina Shale. This contact is marked by an abrupt increase in gamma ray values, due to the change in lithology to a thick shale unit (e.g. ARCMR070; Fig. 4, Section 5; Appendix 3). This boundary can be correlated to wells in the northwestern sector and is supported by palynology (e.g. Blackstone 1; Fig. 4, Section 7; Appendix 3). In combination with formations shown on geological maps, this boundary was used to correlate well logs in this area (Fig. 4, Section 5; Appendix 3).

Gamma ray log signatures in this sector are predominantly Profile type B and record a coarsening-up trend sometimes followed by a fining-up trend; where both occur, the combined thickness is 100–150 m. This pattern was observed in the lower part of the Liveringa Group recorded in a number of wells (e.g. SR01, SR02, ARCMR054 and Petaluma 1; Fig. 4, Section 5; Appendix 3). The Profile B signature is subtly expressed in the middle-sector wells, although it is still consistent with the log signatures observed in petroleum wells from the northwestern sector (e.g. Boronia 1 and Mimosa 1; Fig. 4, Section 6; Appendix 3). The top of this trend is commonly marked by an increase in gamma ray log values and is correlated as surface BH on Sections 5 and 6 (Fig. 4). The sedimentary package from the base of the Liveringa Group to the top of BH is correlated across the middle sector and into the northwestern sector (Fig. 4, Sections 5 and 6; Appendix 3).

The gamma ray log above the BH surface shows a predominantly aggradational trend extending to the top of the Liveringa Group. This aggradational unit contains a number of thin (<10 m) low-value gamma ray bands interpreted to be sandstones that can be correlated between neighbouring wells (e.g. ARCMR070-071; Fig. 4, Section 5; Appendix 3). This aggradational package has also been correlated to wells in the northwestern sector based on log character and is illustrated in (e.g. Mimosa 1, Fig. 4, Section 6; Appendix 3)

Lightjack Formation and Condren Sandstone

Dividing the Liveringa Group into specific formations and members is difficult on wireline logs from the middle sector of the study area. At the southern end of the middle sector the Condren Sandstone is present in outcrop, although it is interpreted to pinch out in the Kirkby Range area (Towner, 1977). In the coal exploration holes and petroleum wells north of this area, the Kirkby Range Member was interpreted to directly overlie the Lightjack Formation (Yeates et al., 1984). The Condren Sandstone was not identified during the 1:250 000 scale geological mapping; however, it was interpreted to be present in some of the coal drillholes.

At Millyit Range, and in the southeast sector, fluvial facies associations FA5 and FA6 were recorded in the Condren Sandstone. The vertical progression of facies associations shows a general shallowing-up trend, from the base of the Lightjack Formation into the Condren Sandstone (Fig. 4, Section 3; Appendix 3). At Millyit Range the fluvial facies association (FA5) represents the point of maximum regression in the Liveringa Group sequence (Fig. 4, Section 3; Appendix 3), a trend that was also interpreted in the southeast sector. In outcrop, there is little variation in grain size observed between facies associations in the Lightjack Formation and Condren Sandstone. These grain-size and lithological characteristics are consistent with the gradual coarsening-up trend from silt-dominated to sand-dominated facies observed in the well logs. This is interpreted as an overall regressive trend with the point of maximum regression interpreted to be the sandstone interval at the top of the coarsening-up trend; this interval is probably within the Condren Sandstone. It is difficult to definitively interpret the presence of the Condren Sandstone in this sector because of the gradational transition and absence of definitive changes in lithology or depositional environment from the underlying Lightjack Formation.

In the Fitzroy Trough, the Lightjack Formation is commonly subdivided into three informal members, including a middle sandy member which is associated with coal deposits and interpreted as an intertidal barrier bar or beach deposit (Yeates, 1975a; Crowe and Towner, 1976; Yeates et al., 1984). The P1 coal zone recorded in Petaluma 1 is correlated to a decreased gamma ray log signature in SR02 at ~210 m depth. In SR02 this decrease is interpreted as a possible sandy unit (Fig. 4, Section 5; Appendix 3) that may represent the aforementioned middle sandy zone.

Hardman Formation

The general bell-shaped log trend observed in wells in the middle sector is consistent with the transition from the base of the Lightjack Formation into the Condren Sandstone observed in outcrop. The overlying sedimentary unit, represented by an aggradational trend, would then belong to the Hardman Formation. SR01, SR02 and SR04 are all interpreted to have spud into the base of the Hicks Range Sandstone Member, which directly overlies the Kirkby Range Member (Fig. 4, Section 5; Appendix 3). In these three well logs a thin sedimentary package was observed between the top of the hole and the increase in gamma ray values at the top of the Lightjack–Condren package (Fig. 4, Section 5; Appendix 3). The contact between the Hicks Range Sandstone Member and the underlying Kirkby Range Member is not distinct on the gamma ray log, which is as expected given that a gradational contact was observed between the two in outcrop at Hicks Range (Fig. 19).

The Kirkby Range Member consists of shallow-marine facies association (FA8) at the Hicks Range, Millyit Range and Boundary Hill outcrop localities (Fig. 4; Section 3; Appendix 3). The Kirkby Range Member is interpreted to record a transgressive event, evidenced by the sequence of facies associations observed at Millyit Range where the member overlies fluvial facies of the Condren Sandstone (Fig. 4, Section 3; Appendix 3). A significant increase in gamma ray log values in the drillholes, interpreted as a possible flooding surface, is correlated to the base of the Hardman Formation (Fig. 4, Section 5; Appendix 3). The high gamma ray log values observed are consistent with the fine-grained Kirkby Range Member, as recorded both in outcrop sections and in the base of BMR Crossland 1 which are interpreted to represent the onset of a marine transgression.

A series of coal drillholes to the east of SR01, SR02 and SR04 were spud into Triassic sedimentary rock and intersect the Liveringa Group, here interpreted to be the Cherrabun and the Hicks Range Sandstone Members (e.g. ARCMR069–072; Fig. 4, Section 5; Appendix 3). The Hicks Range Sandstone Member is locally regressive at Hicks Range, where a fluvial facies association (FA9) is recorded overlying the shallow-marine association of the Kirkby Range Member (Fig. 4, Section 3; Appendix 3). This regressive trend is not obvious in the well logs and the older units of the Liveringa Group were not penetrated in these drillholes. Both factors make it difficult to identify the Hicks Range Sandstone and Kirkby Range Members; as a result, the pale blue zone in the correlation section is interpreted as Hardman Formation with the striped pattern indicating where the Kirkby Range Member could be confidently identified.

Northwest sector

Data from the northwest sector is drawn exclusively from petroleum exploration well logs (Fig. 21). Well logs exhibit two profile types: Profile A and Profile B (Fig. 20). Profile type A is restricted to four wells in the far northwest of the sector and Profile B was identified in all other wells and is present across most of the sector (Fig. 21). As in the middle sector, the contact of the Liveringa Group with the overlying Triassic Blina Shale is easily distinguished on well logs by the abrupt increase in, and sustained, high gamma ray log values.

Based on the palynology available for Moogana 1, Puratte 1, Blackstone 1 and Mimosa 1 (Fig. 4, Section 1; Appendix 3), the upper coarsening-up trend of Profile A is equivalent to the turning point in Profile B, where the trend changes from coarsening to fining upwards (Fig. 20). The uppermost package in Profiles A and B, interpreted as aggradational in each case, shows a relatively constant gamma ray trend and can be correlated with confidence. This aggradational trend is interpreted to represent the Hardman Formation, based on the presence of the *P. microcorpus* and *P. crenulata* zones in Puratte 1 and the good correlation of this palynozone to Moogana 1. The gamma ray log signature corresponding to this aggradational zone in Puratte 1 and Moongana 1 can be correlated to wells in the northwest sector and in the middle sector, where the position of the Hardman Formation is more certain due to proximity of studied outcrops. Differentiation of the three members of the Hardman Formation in wells in the northwest sector has not been attempted due to data limitations. As in the middle sector, there is no distinct trend in the gamma ray logs to suggest the presence of the regressive middle Hicks Range Sandstone Member despite suggestions by Forman and Wales (1981) and Yeates et al. (1975a) that the member prograded from the northwest.

Unfortunately no information on depositional setting is available from the palynology for wells that exhibit log Profile type A; however, glauconite is common throughout the Liveringa Group strata in Moongana 1. It is also present at the top of the second coarsening-upwards trend in Puratte 1, where it is associated with coaly deposits. In both Booran 1 and Blackstone 1, marine depositional environments have been interpreted from biostratigraphic information above the point of maximum regression; this could indicate that marine conditions were present throughout the sequence.

Dynamic Integrated Prediction Error Filter Analysis (D-INPEFA)

Dynamic Integrated Prediction Error Filter Analysis (D-INPEFA; Nio et al., 2006) was performed on wireline gamma ray logs in this study. D-INPEFA analysis and the resulting D-INPEFA curve are utilized to highlight broad trends and variations in the sedimentary sequence and assist in well correlation. Coarsening-up, shallowing and falling base-level conditions are interpreted from negative trends, e.g. from 1 towards 0 up-section. Fining-up, deepening and rising base-level conditions are interpreted from positive trends, e.g. from 0 toward 1 upsection. Typically the D-INPEFA curve has a positive trend throughout the Noonkanbah Formation, followed by a broad peak or turning point, after which it switches to a negatively trending curve between the uppermost Noonkanbah Formation and the lower Liveringa Group (Fig. 4, Section 7; Appendix 3). There is a steady negative trend until the base of the aggradational log trend, seen in both log Profiles A and B where it becomes neutral. In wells of Profile type A the turning point occurs lower in the stratigraphic section, in the upper Noonkanbah Formation, with a distinct negative trend starting from the base of the Liveringa Group (e.g. Puratte 1; Fig. 22). In wells of Profile type B this turning point occurs higher in the stratigraphy, at the Noonkanbah Formation – Liveringa Group contact, or within the lower Liveringa Group (e.g. Blackstone 1; Fig. 22). Within Profile B wells, this turning point was identified progressively higher in the wells located farther toward the southeast. In contrast, this turning point in Kilang Kilang 1 (Profile type C) is significantly higher in the Liveringa Group stratigraphy (Fig. 22). With the exception of Kilang Kilang 1, Profile C wells display anomalous D-INPEFA signatures, which is likely due to the absence of overlying strata and the presence of casing shoes. As such, the D-INPEFA curves in these wells are considered unreliable.

The D-INPEFA trends observed in all wells is consistent with the interpreted depositional settings. The continuation of the positive trend from the Noonkanbah Formation into the lower Lightjack Formation is consistent with the conformable contact between the formations. Similarly, the broad turning point from the Noonkanbah Formation into the Condren Sandstone, or its equivalent, is consistent with the gradual regression of facies and return to marine settings as observed in outcrop. In the northwest, where the regression and transgression sequences all occur within marine settings, the point of maximum regression is less pronounced in the gamma ray log due to less lithological variation. Correspondingly, there are only subtle variations

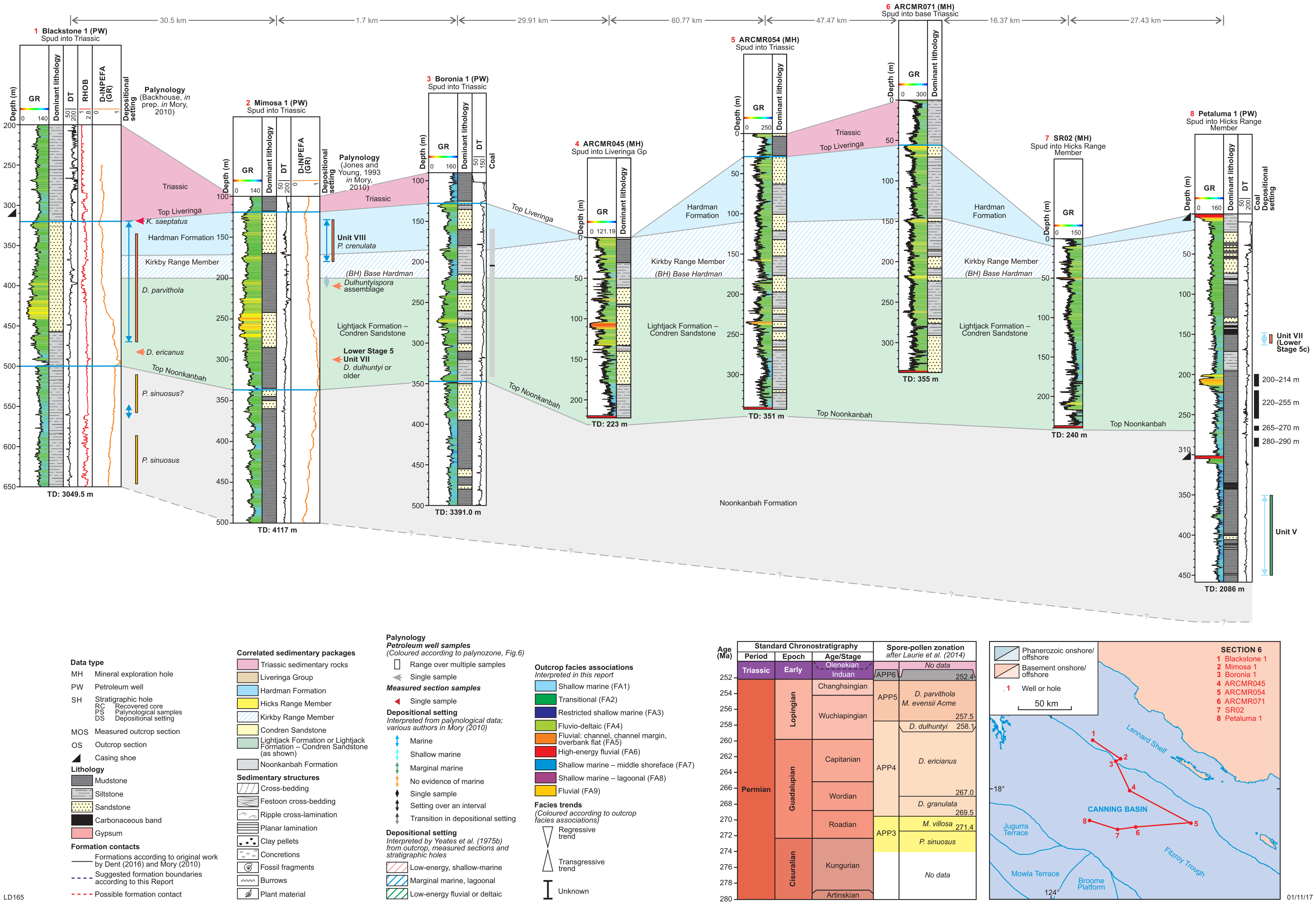


Figure 22. Correlation of the Lightjack Formation – Condren Sandstone package and the Hardman Formation package (Liveringa Group) across the gamma ray profile type (A, B and C); Dynamic–INPEFA curves illustrate the change, from northwest to southeast, in the position of the turning point, where the D-INPEFA log-trend changes from a positive to negative (see Fig. 21 for well locations)

in the D-INPEFA logs. The neutral trend observed in the interpreted Hardman Formation may reflect the consistent marine conditions at this time, although it is also possible that the trend is strongly biased by the lack of data at the top of these wells.

Regional correlation

Correlation across the three sectors and three different well log Profile types for the Liveringa Group is displayed in Figure 22. In Profile types A and B, the Lightjack Formation and postulated Condren Sandstone are shown as a continuous package equivalent to the individual formations identified in Profile C. The sedimentary package in these well logs shows a progression that is comparable with that observed in outcrop where the Condren Sandstone has been identified; on this basis, it is reasonable to suggest that this formation is also present in the wells. The lack of any definitive feature at or near the contact of the two formations makes it difficult to identify the contact in the well logs. The upper part of the Liveringa Group can be correlated across the basin and is defined as the Hardman Formation in this Report. The individual members of the Hardman Formation are not delineated in this correlation. The Hicks Range Sandstone Member and Cherrabun Member were not identified in the southeast sector, and identification of the three members is only possible locally in the middle sector where there are enough data available.

Conclusions

This Report refines the understanding of the Liveringa Group of the Canning Basin by integrating outcrop-scale facies analysis with data extracted from stratigrahic logs and subsurface gamma ray logs. Nine facies associations were recognized from outcrop section ranging from braided fluvial to shallow-marine systems. Shallow-marine, restricted shallow-marine, deltaic and fluvio-deltaic facies associations were identified in the Lightjack Formation. Fluvial facies associations were identified in the Condren Sandstone, and shallow-marine, lagoonal and fluvial facies associations were identified in the Hardman Formation. The stacking pattern of these facies associations indicates an overall regressive trend throughout deposition of the Lightjack Formation with the Condren Sandstone representing the point of maximum regression within the Liveringa Group. This was followed by a gradual return to shallow-marine conditions during deposition of the Hardman Formation.

The trends in depositional setting observed in outcrop are also evident in well logs and can be correlated across the basin to areas where outcrop is not present. In the southeast sector, well-log data enable the Liveringa Group to be divided into its three component formations: the Lightjack Formation, Condren Sandstone and Hardman Formation. In the middle and northwestern sectors, the Liveringa Group strata in well logs can be divided into two packages: the Lightjack Formation with probable Condren Sandstone in one package and, the Hardman Formation, in the other. In the middle sector, tentative identification of the Kirkby Range Member is possible in some wells, depending on the data available; however, separation of the overlying Hicks Range Sandstone Member and Cherrabun Member is currently not possible. Separation of the Hardman Formation into its component members was also not feasible in the northwest sector due to insufficient data.

References

Apak, SN and Backhouse, J 1999, Stratigraphy and petroleum exploration objectives of the Permo-Carboniferous succession on the Barbwire Terrace and adjacent areas, northeast Canning Basin, Western Australia: Geological Survey of Western Australia, Report 68, 30p.

Archbold, NW 1999, Permian Gondwanan correlations: the significance of the western Australian marine Permian: Journal of African Earth Sciences, v. 29, no. 1, p. 63–75.

Archbold, NW 2002, Peri-Gondwanan Permian correlations: the meso-Tethyan margins, *in* The sedimentary basins of Western Australia 3 *edited by* M Keep and SJ Moss: Petroleum Exploration Society of Australia; Petroleum Exploration Society of Australia Symposium, Perth, WA, 20 October 2002, p. 223–236.

Blake, DH and Yeates, AN (compilers) 1976, Stansmore, Western Australia (2nd edition): Bureau of Mineral Resources and Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 20p.

Brown, SA, Boserio, IM, Jackson, KS and Spence, KW 1984, The geological evolution of the Canning Basin: implications for petroleum exploration, *in* The Canning Basin, WA *edited by* PG Purcell: Geological Society of Australia and Petroleum Exploration Society of Australia; Canning Basin Symposium, Perth, Western Australia, p. 85–96.

Casey, JN and Wells, AT 1964, The geology of the north-east Canning Basin, Western Australia: Australian Bureau of Mineral Resources, Report 49, 61p.

Cohen, KM, Finney, SM, Gibbard, PL and Fan, J-X 2013, The ICS International Chronostratigraphic Chart (v 2015/01 update): Episodes, v. 36, no. 3, p. 199–204.

Crowe, RWA (compiler) 1978, Cornish, Western Australia (2nd edition): Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 19p.

Crowe, RWA and Muhling, PC (compilers) 1977, Lucas, Western Australia (2nd edition): Bureau of Mineral Resources and Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 23p.

Crowe, RWA and Towner, RR 1976, Environmental interpretation of the Permian Nura Nura Member of the Poole Sandstone, Noonkanbah sheet area, Canning Basin: a gradation between fluviate and shallow-water marine facies, *in* Annual report for the year 1975: Geological Survey of Western Australia, p. 59–62.

Crowe, RWA and Towner, RR (compilers) 1981, Noonkanbah, Western Australia (2nd edition): Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 51p.

Dent, LM 2016, Characterization and correlation of lower Permian strata, Canning Basin, Western Australia, and implications for CO_2 sequestration: Geological Survey of Western Australia, Report 149, 104p.

Drummond, BJ, Sexton, MJ, Barton, TJ and Shaw, RD 1991, The nature of faulting along the margins of the Fitzroy Trough, Canning Basin, and implications for the tectonic development of the trough: Exploration Geophysics, v. 22, p. 111–116.

Eyles, N, Mory, AJ and Backhouse, J 2002, Carboniferous–Permian palynostratigraphy of west Australian marine rift basins: resolving tectonic and eustatic controls during Gondwanan glaciations: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 184, p. 305–319.

Forman, DJ and Wales, DW 1981, Geological evolution of the Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Bulletin 210, 91p.

Foster, CB 1982, Spore-pollen assemblages of the Bowen Basin, Queensland (Australia): their relationship to the Permian/Triassic boundary: Review of Palaeobotany and Palynology, v. 36, no. 1–2, p. 165–183.

Gibson, DL and Crowe, RWA (compilers) 1982, Mount Anderson, Western Australia (2nd edition): Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 42p.

Guppy, DJ, Linder, AW, Rattigan, JH and Casey, JN 1951, The stratigraphy of the Mesozoic and Permian sediments of the Desert Basin, Western Australia: Bureau of Mineral Resources Geology and Geophysics, Record 1951/60, 16p.

Guppy, DJ, Lindner, AW, Rattigan, JH and Casey, JN 1958, The geology of the Fitzroy Basin, Western Australia: Bulletin of the Bureau of Mineral Resources, Australia, no. 36.

Haines, PW 2009, The Carribuddy Group and Worral Formation, Canning Basin, Western Australia: stratigraphy, sedimentology, and petroleum potential: Geological Survey of Western Australia, Report 105, 60p.

Henderson, CM, Davydov, VI and Wardlaw, BR 2012, The Permian Period, *in* The Geologic Time Scale 2012, Volume 2 *edited by* FM Gradstein, JG Ogg, MD Schmitz and GM Ogg: Elsevier, Amsterdam, p. 653–679.

Hocking, RM, Mory, AJ and Williams, IR 1994, An atlas of Neoproterozoic and Phanerozoic basins of Western Australia, *in* The Sedimentary Basins of Western Australia *edited by* PG Purcell and RR Purcell: Petroleum Exploration Society of Australia, Western Australian Branch, Perth, Western Australia, p. 21–43.

Johnson, NEA 1966, Kidson 1 well completion report; West Australian Petroleum Pty Ltd: Geological Survey of Western Australia, Statutory petroleum exploration report, W244 A1 (unpublished).

Kemp, EM, Balme, BE, Helby, RJ, Kyle, RA, Playford, G and Price, PL 1977, Carboniferous and Permian palynostratigraphy in Australia and Antarctica: a review: BMR Journal of Australian Geology and Geophysics, v. 2, p. 177–208.

Kennard, JM, Jackson, MJ, Romine, KK, Shaw, RD and Southgate, PN 1994, Depositional sequences and associated petroleum systems of the Canning Basin, WA, *in* The Sedimentary Basins of Western Australia *edited by* PG Purcell and RR Purcell: Petroleum Exploration Society of Australia, Western Australian Branch, Perth, Western Australia, p. 657–676.

Laurie, JR, Bodorkos, S and Smith, TE 2014, Recalibrating the Permian palynostratigraphic scheme via U–Pb zircon CA-IDTIMS dating of tuffs in eastern Australian Basins, in 01SBD — 39th Symposium on the advances in the study of the Sydney Basin: Australian Earth Sciences Convention (AESC) 2014, Newcastle, New South Wales, 7 July 2014-10 July 2014, p. 3–7.

Lehmann, PR 1984, The stratigraphy, palaeogeography and petroleum potential of the Lower to lower Upper Devonian sequence in the Canning Basin, *in* The Canning Basin, WA *edited by* PG Purcell: Geological Society of Australia and Petroleum Exploration Society of Australia; Canning Basin Symposium, Perth, Western Australia, 27 June 1984, p. 253–275.

Mantle, DJ, Kelman, AP, Nicoll, RS and Laurie, JR 2010, Part 1: Australian and selected international biozonation schemes tied to the GTS 2004 geological timescale: Geoscience Australia, Australian Biozonation Chart 2010.

Martin, DMcB, Hocking, RM, Riganti, A and Tyler, IM 2015, 1:500 000 tectonic units of Western Australia, 2015: Geological Survey of Western Australia, <www.dmp.wa.gov.au/geoview>.

McWhae, JRH, Playford, PE, Lindner, AW, Glenister, BF and Balme, BE 1956, The stratigraphy of Western Australia: Australian Journal of Earth Sciences, v. 4, no. 2, p. 1–153, doi:10.1080/00167615608728471.

Middleton, MF 1990, Canning Basin, in Geology and mineral resources of Western Australia: Geological Survey of Western Australia, Memoir 3, p. 425–457.

Mory, AJ 2010, A review of mid-Carboniferous to Triassic stratigraphy, Canning Basin, Western Australia: Geological Survey of Western Australia, Report 107, 130p.

Mory, AJ and Hocking, RM 2011, Permian, Carboniferous and Upper Devonian geology of the northern Canning Basin — a field guide: Geological Survey of Western Australia, Record 2011/16, 36p.

Nio, SD, Böhm, AR, Brouwer, JH, De Jong, MGG and Smith, DG 2006, Climate stratigraphy, principals and applications in subsurface correlation: European Association of Geoscientists and Engineers, Short Course Series 1, 130p.

Parra-Garcia, M, Sanchez, G, Dentith, MC and George, AD 2014, Regional structural and stratigraphic study of the Canning Basin, Western Australia: Geological Survey of Western Australia, Report 140, 215p.

Price PL 1983, A Permian palynostratigraphy for Queensland, in Permian Geology of Queensland: Proceedings of the Symposium on Permian Geology of Queensland: Geological Society of Australia, Queensland Division: Brisbane, Queensland, 14 July 1982, p. 155–211.

Price, PL 1997, Permian to Jurassic palynostratigraphic nomenclature of the Bowen and Surat Basins, in The Surat and Bowen basins, south-east Queensland edited by PM Green: Queensland Department of Mines and Energy, p. 137–178.

Redfern, J and Williams, BPJ 2002, Canning Basin Grant Group glaciogenic sediments: part of the Gondwanan Permo-Carboniferous hydrocarbon province, *in* The Sedimentary Basins of Western Australia 3 *edited by* M Keep and SJ Moss: Petroleum Exploration Society of Australia; Western Australian Basins Symposium, Perth, Western Australia, 20 October 2002, p. 851–871.

Reeves, F 1949, Geology and oil prospects of the Desert Basin: Western Australia: Vacuum Oil Company, 103p. (unpublished).

Shaw, RD, Sexton, M and Zeilinger, I 1994, The tectonic framework of the Canning Basin, WA, including 1:2 million structural elements map of the Canning Basin: Australian Geological Survey Organisation, Record 1994/48, 89p.

Towner, RR (compiler) 1977, Crossland, Western Australia: Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 19p.

Towner, RR, Crowe, RWA and Yeates, AN 1976, Notes on the geology of the southern part of the Canning Basin: Bureau of Mineral Resources, Geology and Geophysics, Record 1976/95, 166p.

Towner, RR and Gibson, DL 1980, Geology of Late Carboniferous and younger rocks of the onshore western Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Record 1980/3, 67p.

Towner, RR and Gibson, DL 1983, Geology of the onshore Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Bulletin 215, 51p.

Traves, DM, Casey, JN and Wells, AT 1956, The geology of the south-western Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Report 29, 76p.

Veevers, JJ 2006, Updated Gondwana (Permian–Cretaceous) earth history of Australia: Gondwana Research, v. 9, p. 231–260.

Veevers, JJ and Wells, AT 1961, The geology of the Canning Basin: Bureau of Mineral Resources, Geology and Geophysics, Bulletin 60, 323p.

Wade, A 1936, The geology of the West Kimberley District of Western Australia: 82p. (unpublished).

White, ME and Yeates, AN 1976, Plant fossils from the northeastern part of the Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Record 1976/18, 60p.

Yeates, AN, Crowe, RWA, Passmore, VL, Rowner, RR and Wyborn, LAI 1975a, New and revised stratigraphic nomenclature, northeast Canning Basin, *in* Annual report for the year 1974: Geological Survey of Western Australia, p. 49–51.

Yeates, AN, Crowe, RWA, Towner, RR, Wyborn, AI and Passmore, VL 1975b, Notes on the geology of the Gregory Sub-basin and adjacent areas of the Canning Basin, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Record 1975/77, 268p.

Yeates, AN, Gibson, DL, Towner, RR and Crowe, RWA 1984, Regional geology of the onshore Canning Basin, WA, *in* The Canning Basin, WA *edited by* PG Purcell: Geological Society of Australia and Petroleum Exploration Society of Australia; Canning Basin Symposium, Perth, Western Australia, p. 24–55.

Yeates, AN and Muhling, PC (compilers) 1977, Mount Bannerman, Western Australia (2nd edition): Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 24p.

Appendix 1

Summary of well, hole and outcrop data for the Liveringa Group used in this Report

Table 1.1 summarizes the data sources used to construct correlations and make interpretations for this Report. All BMR stratigraphic holes and petroleum wells with recorded Liveringa Group strata were analysed, as were available mineral exploration holes with well logs. Nineteen outcrop localities were also described and analysed and are shown as 'outcrop' in Table 1.1; multiple sites at the same location are numbered individually (e.g. Millyit Range 1, 2, 3, …). The table also includes details of selected outcrop sites visited and measured by Yeates et al. (1975b). The original records of these outcrop sites often did not include specific locations, but rather relative distances from particular landmarks. Based on these descriptions, approximate coordinates are given in Table 1.

Table 1.1. Summary of well, hole and outcrop data for the Liveringa Group used in this Report

Data type	*Name*	*1:250 000 Series map*	*Latitude*	*Longitude*	*Top Liveringa (m)*	*Base Liveringa (m)*	*Depth of casing shoe (m)*	*Total depth (m)*	*Palynology available*
Outcrop	Shore Range 1	NOONKANBAH	18°58'55.50"S	125°31'45.70"E	–	–	–	–	–
Outcrop	Shore Range 2	NOONKANBAH	18°58'28.59"S	125°33'17.83"E	–	–	–	–	–
Outcrop	Beefwood Park	CROSSLAND	19° 8'46.51"S	125°49'58.75"E	–	–	–	–	–
Outcrop	Millyit Range 1	CROSSLAND	19° 8'26.70"S	125°27'42.29"E	–	–	–	–	–
Outcrop	Millyit Range 2	CROSSLAND	19° 9'53.19"S	125°25'56.76"E	–	–	–	–	–
Outcrop	Millyit Range 3	CROSSLAND	19°10'50.36"S	125°27'54.69"E	–	–	–	–	–
Outcrop	Millyit Range 4	CROSSLAND	19°11'51.43"S	125°29'3.56"E	–	–	–	–	–
Outcrop	Millyit Range 5	CROSSLAND	19°12'25.73"S	125°31'10.11"E	–	–	–	–	–
Outcrop	Hicks Range 1	CROSSLAND	19°13'15.05"S	125°53'56.02"E	–	–	–	–	–
Outcrop	Hicks Range 2	CROSSLAND	19°13'29.31"S	125°53'40.32"E	–	–	–	–	–
Outcrop	Hicks Range 3	CROSSLAND	19°13'28.64"S	125°53'55.50"E	–	–	–	–	–
Outcrop	Christmas Creek 1	MOUNT BANNERMAN	19° 4'51.10"S	126° 7'31.01"E	–	–	–	–	–
Outcrop	Christmas Creek 2	MOUNT BANNERMAN	19° 2'52.49"S	126° 8'43.64"E	–	–	–	–	–
Outcrop	Christmas Creek 3	MOUNT BANNERMAN	19° 0'55.37"S	126° 9'2.42"E	–	–	–	–	–
Outcrop	Boundary Hill	MOUNT BANNERMAN	19°19'46.74"S	126°13'27.03"E	–	–	–	–	–
Outcrop	Durbai Creek 1	BILLILUNA	19°59'2.12"S	127°32'53.51"E	–	–	–	–	–
Outcrop	Condren Pinnacles 1	LUCAS	20° 6'11.12"S	127°38'21.09"E	–	–	–	–	–
Outcrop	Namalook 1	LUCAS	20°11'36.41"S	128° 0'29.49"E	–	–	–	–	–
Outcrop	Namalook 2	LUCAS	20°10'45.39"S	128° 0'21.30"E	–	–	–	–	–
Outcrop site	Lightjack 1 (Gumbo Point)	LUCAS	20° 7'2.93"S	127°51'29.54"E	–	–	–	–	–
Outcrop site	Lightjack 2 (Micha Bore)	LUCAS	20°16'30.84"S	127°45'32.95"E	–	–	–	–	–
Outcrop site	Lightjack 3 (Stretch Range)	LUCAS	20°56'39.19"S	127°43'39.50"E	–	–	–	–	–
Outcrop site	Condren Pinnacles	LUCAS	20° 6'11.12"S	127°38'21.09"E	–	–	–	–	–
BMR stratigraphic hole	BMR Mt Bannerman 1	MOUNT BANNERMAN	19°55'42.00"S	127°13'50.00"E	~63	–	–	203	Yes
BMR stratigraphic hole	BMR Mt Bannerman 2	MOUNT BANNERMAN	19°03'56.00"S	126°10'23.00"E	–	–	–	139	Yes
BMR stratigraphic hole	BMR Cornish 1	CORNISH	20°09'56.00"S	126°34'05.00"E	–	–	–	164	Yes
BMR stratigraphic hole	BMR Crossland 1	CROSSLAND	19°12'57.00"S	125°53'35.00"E	–	–	–	262	Yes
BMR stratigraphic hole	BMR Crossland 2	CROSSLAND	19°08'09.00"S	125°28'06.00"E	–	–	–	138.7	Yes
BMR stratigraphic hole	BMR Lucas 14	LUCAS	20°16'36.00"S	127°46'44.00"E	–	–	–	102.1	Yes
Petroleum well	Aquantia 1	DERBY	17°37'39.07"E	124°21'31.19"S	333	545	538.66	3000	–

Data type	Name	1:250 000 Series map	Latitude	Longitude	Top Liveringa (m)	Base Liveringa (m)	Depth of casing shoe (m)	Total depth (m)	Palynology available
Petroleum well	Asgard 1	Noonkanbah	18°14’49.233” E	125°01’51.054”S	68	350	30 and 549	3550	–
Petroleum well	Bindi 1	Mount Bannerman	19°43'14.79"E	126°48'02.22"S	338	475.6	223 and 849.5	2507	–
Petroleum well	Blackstone 1	Derby	17°35'07.92"E	124°21'10.98"S	319	500	–	3049.5	Yes
Petroleum well	Blina 3	Derby	17°37'17.77"E	124°29'52.22"S	140	330	403	1580	–
Petroleum well	Blina 4	Lennard River	17°37'13.00"E	124°30'01.19"S	135	318.3	363.5	1526	–
Petroleum well	Blina 5	Lennard River	17°37'29.49"E	124°30'15.05"S	132	327.7	368.17	1600	–
Petroleum well	Blina 7	Lennard River	17°37'36.99"E	124°30'03.88"S	145	337.9	–	1551	–
Petroleum well	Blina 8	Derby	17°37'06.05"E	124°29'34.07"S	160	345.1	–	1550	–
Petroleum well	Booran 1	Derby	17°20'03.32"E	123°39'53.47"S	519	703.2	–	2800	Yes
Petroleum well	Boronia 1	Lennard River	17°45'24.64"E	124°34'22.43"S	124	348	–	3391	–
Petroleum well	Boundary 1	Derby	17°29'09.14"E	124°14'42.72"S	370	547.5	–	1670	–
Petroleum well	Canegrass 1	Derby	17°23'24.95"E	124°13'36.62"S	134	275.9	367.2	2006.5	–
Petroleum well	Crimson Lake 1	Lennard River	17°53'00.17"E	124°40'40.18"S	0	277	463	1980.9	–
Petroleum well	East Yeeda 1	Derby	17°37'54.17"E	124°02'54.59"S	405	661.7	–	3556	Yes
Petroleum well	Hakea 1	Derby	17°41'32.27"E	124°27'55.09"S	40	166	–	1703	–
Petroleum well	Hangover 1	Derby	17°34'34.09"E	124°16'36.47"S	207	432.5	488.5	1655	–
Petroleum well	Janpam 1	Derby	17°36'02.94"E	124°24'56.62"S	320	509.4	544	2263	–
Petroleum well	Jum Jum 1	Derby	17°07'15.70"E	123°05'02.05"S	919	1110	–	2600	Yes
Petroleum well	Kambara 1	Pender	16°44'29.82"E	122°26'19.92"S	–	655	724	3147	–
Petroleum well	Katy 1	Derby	17°38'34.92"E	124°21'33.97"S	30	330	458.13	1952	–
Petroleum well	Kennedia 1	Lennard River	17°45'10.34"E	124°36'23.93"S	110	303	–	3387.5	–
Petroleum well	Kilang Kilang 1	Cornish	20°12'41.91"E	127°07'41.64"S	10	354	569	2300	Yes
Petroleum well	Kora 1	Derby	17°15'33.37"E	123°49'47.14"S	443	615.8	–	3100	–
Petroleum well	Lake Betty 1	Mount Bannerman	19°34'05.88"E	126°19'57.34"S	0	257.7	457.2	3145.8	Yes
Petroleum well	Lanagan 1	Mount Bannerman	19°35’00.00” S	126°25’36.00”E	0?	185*	24 and 739	1530	–
Petroleum well	Langoora 1	Derby	17°18'06.00"E	124°06'53.00"S	127	245.1	580	1617	–
Petroleum well	Lawford 1	Mount Bannerman	19°15'38.00E"	126°37'50.00"S	4.3	320*	28 and 760	1313	–
Petroleum well	Lloyd 2	Derby	17°28'06.22"E	124°15'10.98"S	335	528.2	–	1580	–
Petroleum well	May River 1	Derby	17°14'44.02"E	124°05'10.94"S	37	201	89.6	1677.9	–
Petroleum well	Meda 1	Derby	17°23'51.12"E	124°11'36.91"S	218	357.1	126.5	2685	Yes
Petroleum well	Meda 2	Derby	17°24'30.08"E	124°11'28.81"S	254	420.5	–	2325	–
Petroleum well	Metters 1	Lennard River	17°56'36.42"E	124°44'36.04"S	5	182.25	495.7	1505	–

Data type	Name	1:250 000 Series map	Latitude	Longitude	Top Liveringa (m)	Base Liveringa (m)	Depth of casing shoe (m)	Total depth (m)	Palynology available
Petroleum well	Millard 1	DERBY	17°23'32.02"E	123°55'09.67"S	575	751.4	229	1680	–
Petroleum well	Mimosa 1	LENNARD RIVER	17°44'52.58"E	124°35'04.99"S	119	336.4	–	4117	Yes
Petroleum well	Minjin 1	PENDER	16°48'02.74"E	122°22'49.38"S	?	745*	746	1850	–
Petroleum well	Moogana 1	PENDER	16°56'11.98"E	122°41'31.69"S	713?	820	918	2213	Yes
Petroleum well	Nemile 1	LENNARD RIVER	17°51'32.05"E	124°33'29.94"S	5	261.8	304	1601	–
Petroleum well	Padilpa	DERBY	17°00'57.67"E	123°11'39.18"S	560	669.72	688	2184.3	–
Petroleum well	Petaluma 1	MOUNT ANDERSON	18°16'00.59"E	124°19'34.83"S	4	274	309	2086	Yes
Petroleum well	Philydrum 1	LENNARD RIVER	17°48'54.49"E	124°38'00.90"S	30	208.6	460	1608	–
Petroleum well	Point Torment 1	DERBY	17°09'52.77"E	123°44'19.50"S	370?	525	290	2130	–
Petroleum well	Puratte 1	DERBY	17°05'11.10"E	123°14'22.05"S	784	935.1	–	3750	Yes
Petroleum well	Scrubby 1	DERBY	17°30'35.70"E	124°14'29.50"S	390	586	173	1250	–
Petroleum well	Sundown 2	DERBY	17°33'12.93"E	124°14'46.17"S	222	444	483.88	1965	–
Petroleum well	Sunup 1	DERBY	17°37'08.14"E	124°19'02.40"S	73.5	319.4	389	1500	–
Petroleum well	Tappers Inlet 1	PENDER	16°51'32.79"E	122°35'26.79"S	?	618.9	535.2	2856.3	–
Petroleum well	Terrace 1	DERBY	17°30'18.30"E	124°15'55.00"S	360	538	537	2389	–
Petroleum well	Thompsons 1	DERBY	17°36'36.40"E	124°23'14.97"S	351	539	–	2009	–
Petroleum well	Wattle 1	DERBY	17°28'08.81"E	124°13'39.56"S	409	578	613	3056	–
Petroleum well	West Blackstone 1	DERBY	17°34'26.61"E	24°20'16.89"S	303	483.1	521.27	1943	–
Petroleum well	West Kora 1	DERBY	17°14'42.50"E	123°49'04.74"S	428	598.9	976	2606	–
Petroleum well	West Philydrum 1	LENNARD RIVER	17°48'15.44"E	124°36'57.83"S	13	235	292	1109	Yes
Petroleum well	Whitewell 1	DERBY	17°33'56.83"E	124°15'44.64"S	197	418.9	464.4	1753.8	–
Petroleum well	Yarrada 1	DERBY	17°21'54.48"E	124°06'13.65"S	325	478.5	–	3295	–
Mineral exploration hole	ARCMR045	NOONKANBAH	18˚ 0' 49.59"S	124˚ 40' 6.9"E	–	–	–	223	–
Mineral exploration hole	ARCMR054	NOONKANBAH	18° 17' 9.6" S	125° 10' 12" E	–	–	–	351	–
Mineral exploration hole	ARCMR069	NOONKANBAH	18° 17' 24" S	124° 46' 4.8" E	–	–	–	241	–
Mineral exploration hole	ARCMR070	NOONKANBAH	18° 15' 48.47" S	124° 43' 7.70" E	–	–	–	355	–
Mineral exploration hole	ARCMR071	NOONKANBAH	18° 19' 30" S	124° 43' 19.2" E	–	–	–	355	–
Mineral exploration hole	ARCMR072	NOONKANBAH	18˚ 19' 51.2" S	124˚ 47' 49.09" E	–	–	–	209	–
Mineral exploration hole	SR01	NOONKANBAH	18° 20' 45.6" S	124° 33' 50.4" E	–	–	–	204	–
Mineral exploration hole	SR02	NOONKANBAH	18° 21' 10.8" S	124° 34' 4.8" E	–	–	–	240	–
Mineral exploration hole	SR04	NOONKANBAH	18° 19' 1.2" S	124° 33' 10.8" E	–	–	–	204	–

NOTE: * indicates where a formation contact has been derived from a well-completion report rather than Mory (2010) or Dent (2016)

Appendix 2

Summary of palynological data available for the Liveringa Group

Logs of stratigraphic holes drilled by the Bureau of Mineral Resources (BMR, now Geoscience Australia) were digitized and adapted from the originals provided in Yeates et al. (1975b) to best represent: grain size, lithology, sedimentary structures, position of palynological samples, interpreted palynozones and depositional environments (Figs 2.1 – 2.19). Palynological samples are marked on each log and coloured according to Figure 6 of this Report. Additional palynological information from well completion reports (WCR) and summary reports (e.g. Mory, 2010) is presented in the tables and summary sections on each log. WCR data for each well or BMR drill hole are available through the Western Australian Petroleum and Geothermal Information Management System (WAPIMS; https://wapims.dmp.wa.gov.au/wapims). The original log notes, as transcribed in Yeates et al. (1975b), are included on each of the BMR stratigraphic hole logs.

Table 2.1. Summary of all BMR stratigraphic holes and petroleum wells that contain palynological information for the Liveringa Group

Type	*Name*	*Map sheet (1:250 000)*	*Latitude*	*Longitude*	*Total depth (m)*
BMR stratigraphic hole	BMR Mt Bannerman 1	Mount Bannerman	19°55'42.00"S	127°13'50.00"E	203
BMR stratigraphic hole	BMR Mt Bannerman 2	Mount Bannerman	19°03'56.00"S	126°10'23.00"E	139
BMR stratigraphic hole	BMR Cornish 1	Cornish	20°09'56.00"S	126°34'05.00"E	164
BMR stratigraphic hole	BMR Crossland 1	Crossland	19°12'57.00"S	125°53'35.00"E	262
BMR stratigraphic hole	BMR Crossland 2	Crossland	19°08'09.00"S	125°28'06.00"E	138.7
BMR stratigraphic hole	BMR Lucas 14	Lucas	20°16'36.00"S	127°46'44.00"E	102.1
Petroleum well	Blackstone 1	Derby	17°35'07.92"E	124°21'10.98"S	3049.5
Petroleum well	Booran 1	Derby	17°20'03.32"E	123°39'53.47"S	2800
Petroleum well	East Yeeda 1	Derby	17°37'54.17"E	124°02'54.59"S	3556
Petroleum well	Jum Jum 1	Derby	17°07'15.70"E	123°05'02.05"S	2600
Petroleum well	Kilang Kilang 1	Cornish	20°12'41.91"E	127°07'41.64"S	2300
Petroleum well	Lake Betty 1	Mount Bannerman	19°34'05.88"E	126°19'57.34"S	3145.8
Petroleum well	Meda 1	Derby	17°23'51.12"E	124°11'36.91"S	2685
Petroleum well	Mimosa 1	Lennard River	17°44'52.58"E	124°35'04.99"S	4117
Petroleum well	Moogana 1	Pender	16°56'11.98"E	122°41'31.69"S	2213
Petroleum well	Petaluma 1	Mount Anderson	18°16'00.59"E	124°19'34.83"S	2086
Petroleum well	Puratte 1	Derby	17°05'11.10"E	123°14'22.05"S	3750
Petroleum well	West Philydrum 1	Lennard River	17°48'15.44"E	124°36'57.83"S	1109

Palynological data are discussed in detail in the Report. Palynological zones interpreted from petroleum wells, stratigraphic holes and outcrops are shown on the correlated sections presented in Appendix 3.

Glossary for Appendix 2 logs

CS	Casing shoe
Cutt.	Cuttings
D-INPEFA	Dynamic Integrated Prediction Error Dilter Analysis
D-INPEFA (GR)	D–INPEFA conducted on the gamma ray log
DT	Sonic log
GR	Gamma ray log
Nkbh	Noonkanbah Formation
LJ	Lightjack Formation
RHOB	Density log
SWC	Side wall core
WCR	Well completion report

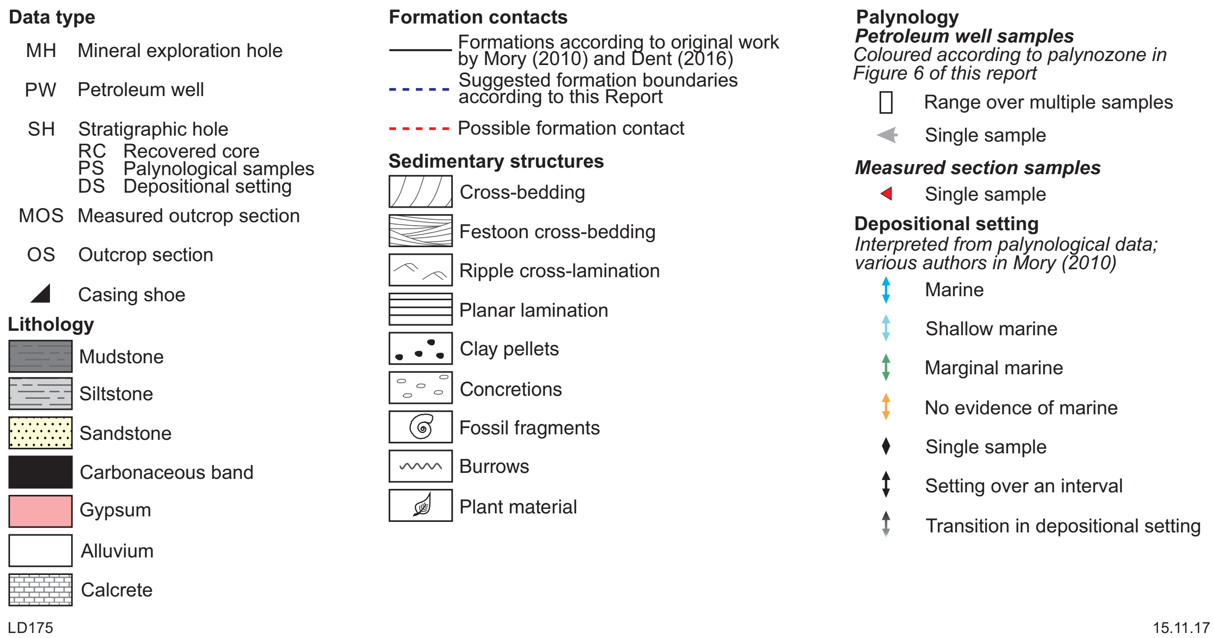
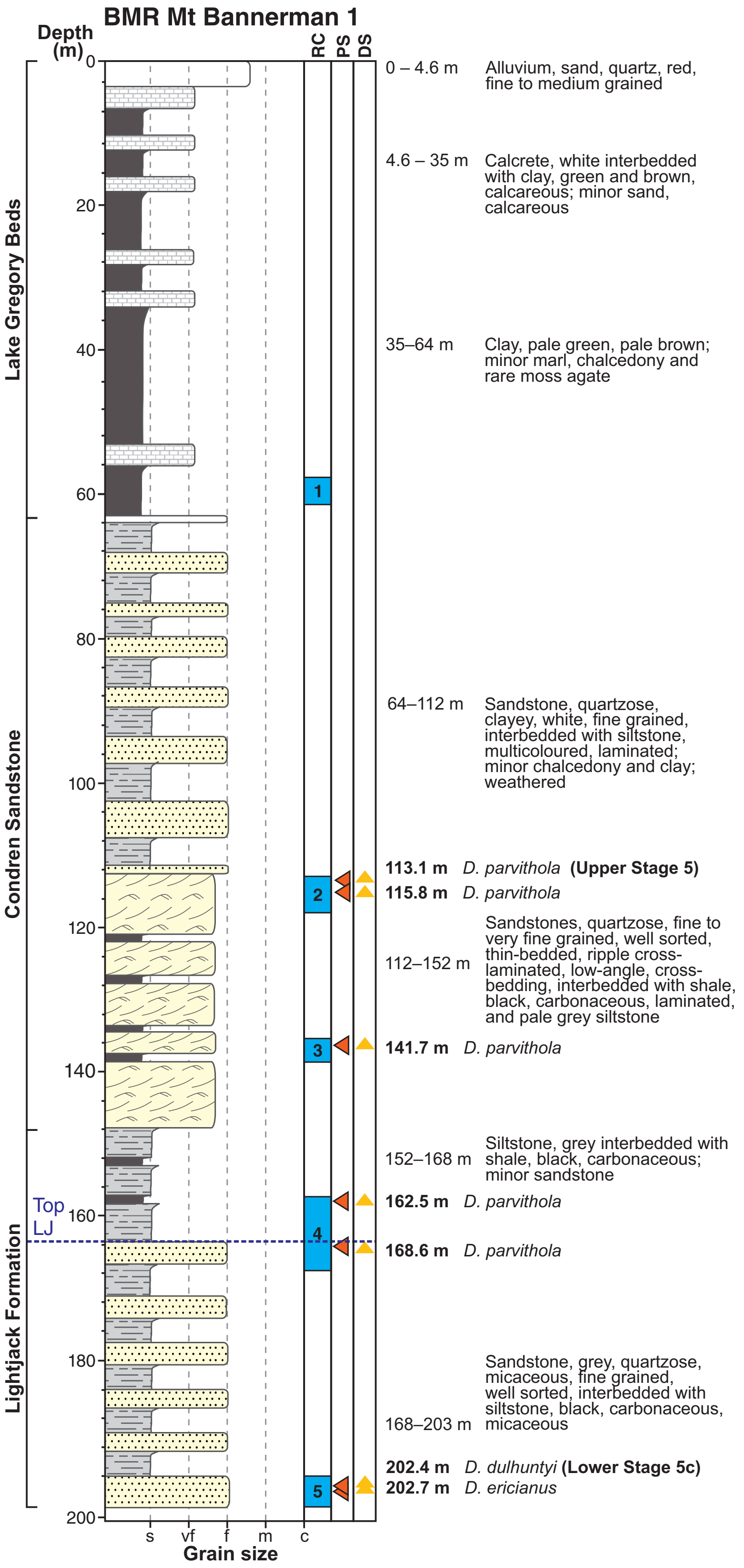


Figure 2.1. Legend for logs of petroleum wells and BMR stratigraphic holes included in this Appendix; refer to the Report for detailed discussion



Log notes

Palynology data

Depth (m)	Sample type	Zone	Notes	Reference
113.1	Core	Lower Stage 5c (*D. parvithola*)	Possibly non-marine (no spinose acritarchs)	Appendix C of Paten and Price *(in* Yeates et al., 1975b)
115.8	Core	*D. parvithola*	as above	Backhouse (2009, *in* Mory, 2010)
141.7	Core	*D. parvithola*	as above	as above
162.5	Core	*D. parvithola*	as above	as above
168.6	Core	*D. parvithola*	as above	as above
202.4	Core	Lower Stage 5c (*D. dulhuntyi*)	as above	Appendix C of Paten and Price *(in* Yeates et al., 1975b)
202.7	Core	*D. ericianus*	as above	Backhouse (2009, *in* Mory, 2010)

Palynology Notes

Paten and Price (*in* Yeates et al., 1975b) classified the two lowermost samples (202.4 and 202.7 m) as upper Stage 5c. which is equivalent to *D. dulhuntyi*. However, later work by Backhouse (2009, *in* Mory, 2010) reclassified the sample at 202.7 m as *D. ericianus*. The sample at 202.4 m was not reclassified and the interpretation should be treated with speculation.

Core discrepancies

Core depths depicted on this log are approximate. No records of the cored intervals are available and cored sections depicted on the original schematic well log are sometimes inconsistent with the recorded palynology samples. For example, the palynological sample at 162.5 m is recorded as sampled from Core 4 although the top of Core 4 is illustrated to begin at ~168 m depth. In such cases, the represented cored section has been extended to include the palynological samples.

Log alterations

Based on the wireline log data from neighbouring wells it is suggested that the top of the Lightjack Formation be aligned with the top of the lowermost coarsening-up cycle. Based on the palynology, this surface is thought to be represented just above 170 m depth giving the Condren Sandstone a thickness of ~100–110 m in this well. This and the palynology are consistent with the 100 m thick coarsening-up cycle in nearby well Kilang Kilang 1.

15.11.17

Figure 2.2. Representative lithological log of BMR stratigraphic hole BMR Mt Bannerman 1 including palynological sampling locations and results; see Figure 2.1 for legend

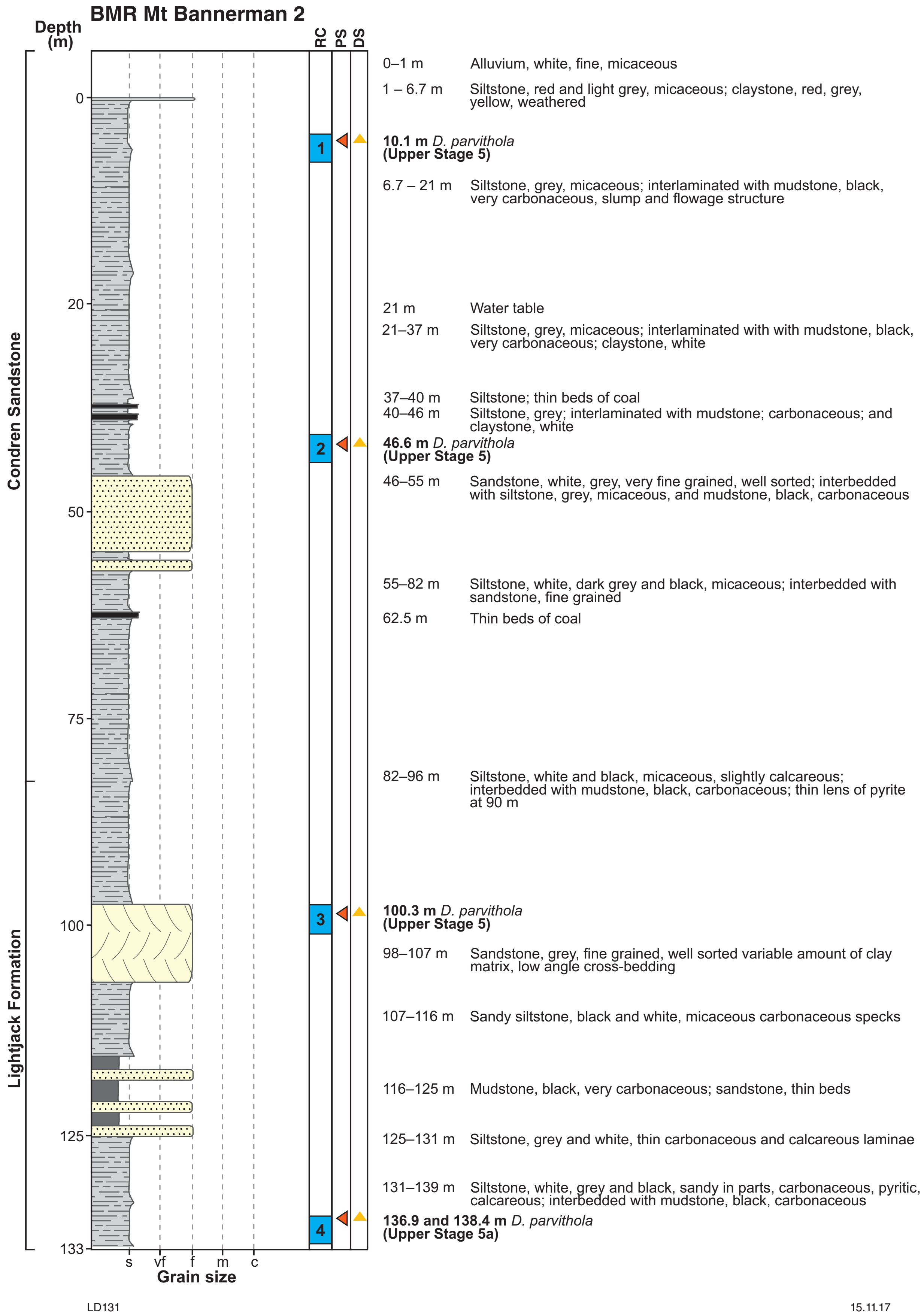
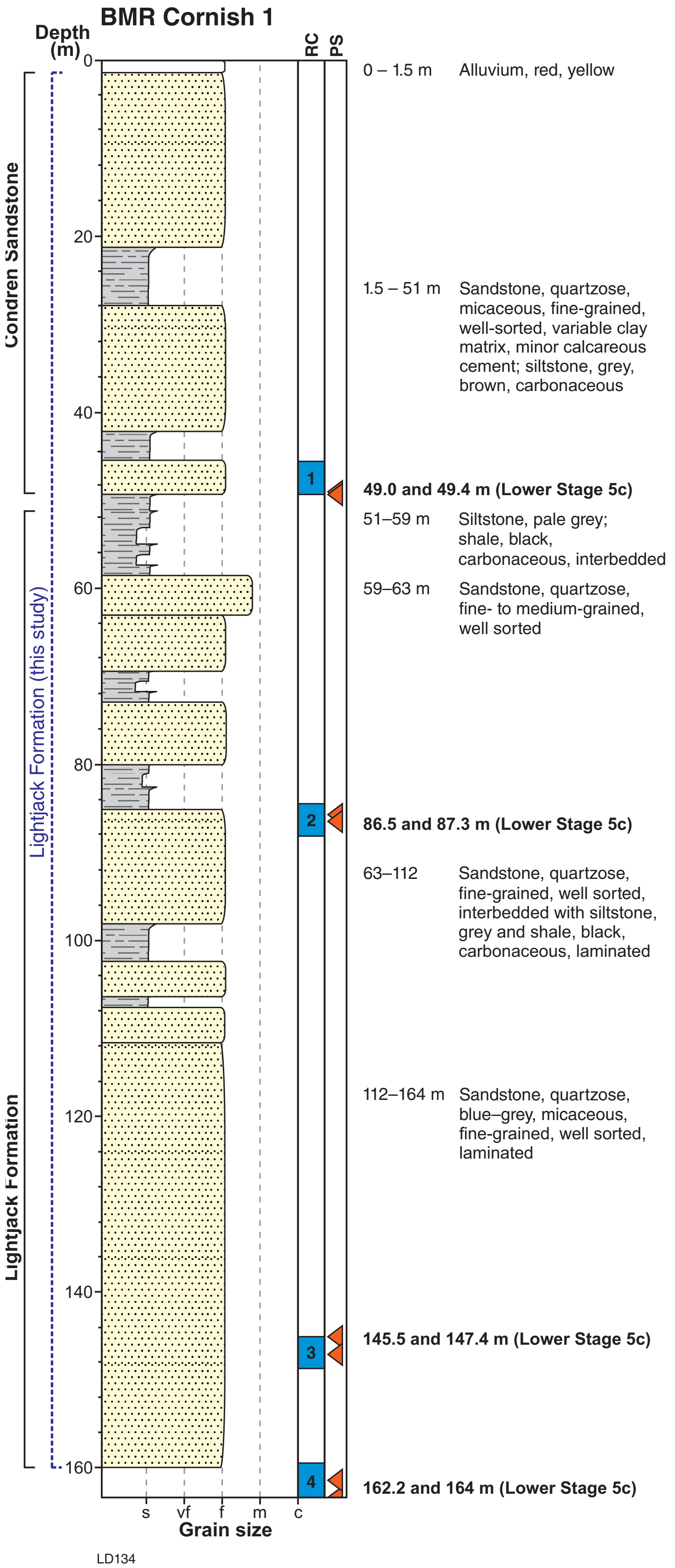


Figure 2.3. Representative lithological log of BMR stratigraphic hole BMR Mt Bannerman 2 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

Depth (m)	Sample type	Zone	Reference
113.1	Core	Lower Stage 5c	Appendix C of Paten and Price *(in* Yeates et al., 1975b)
115.8	Core	as above	as above
141.7	Core	as above	as above
162.5	Core	as above	as above
168.6	Core	as above	as above
202.4	Core	as above	as above
202.7	Core	as above	as above

Palynology notes

Paten and Price *(in* Yeates et al., 1975b) classified all samples as lower Stage 5c, which would make them equivalent to the *D. dulhuntyi* zone. However, a lower Stage 5c zonation was also assigned to palynoflora examined from the BMR Mt Bannerman 1 well in the same report; this was later reclassified to the *D. ericianus* zone. The upper palynofloral zonations from BMR Mt Bannerman 1 were identified the same by two studies. Based on this, accepting a lower Stage 5 age seems reasonable although an exact lower Stage 5c age may not be reliable.

Log alterations

Based on a comparison of the palynology with nearby sections from Kilang Kilang 1 and BMR Mt Bannerman 1, it seems unlikely that the Condren Sandstone begins at the identified ~50 m downhole depth. In the neighbouring well, Lawford Deepening 1, the Lightjack Formation is ~170 m thick. Based on this and the palynological evidence, a thickness of ~160 m for the Lightjack Formation in this hole is considered reasonable and it is suggested that the whole section be reclassified as Lightjack Formation.

15.11.17

Figure 2.4. Representative lithological log of BMR stratigraphic hole BMR Cornish 1 including palynological sampling locations and results; see Figure 2.1 for legend

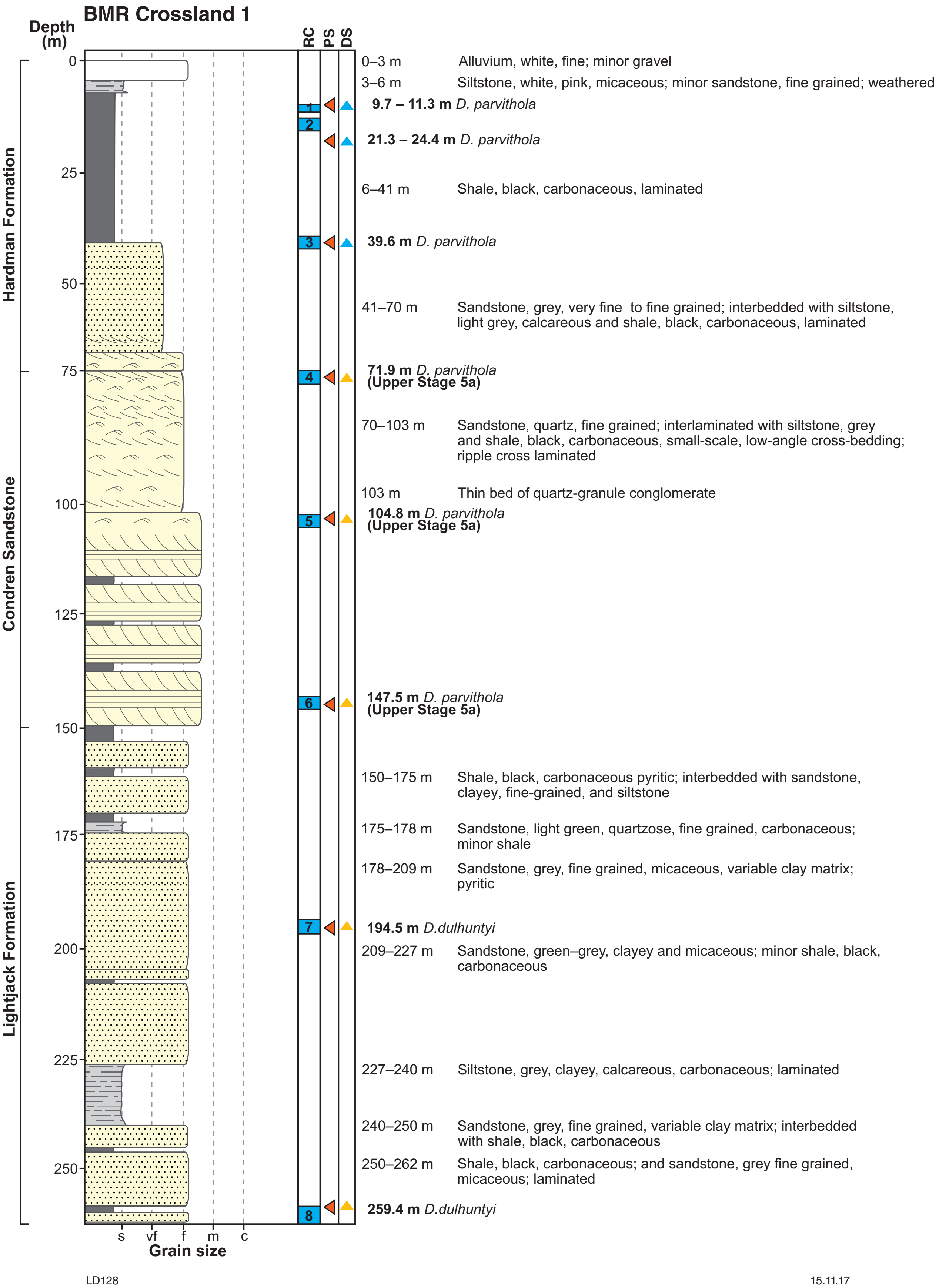


Figure 2.5. **Representative lithological log of BMR stratigraphic hole BMR Crossland 1 including palynological sampling locations and results; see Figure 2.1 for legend**

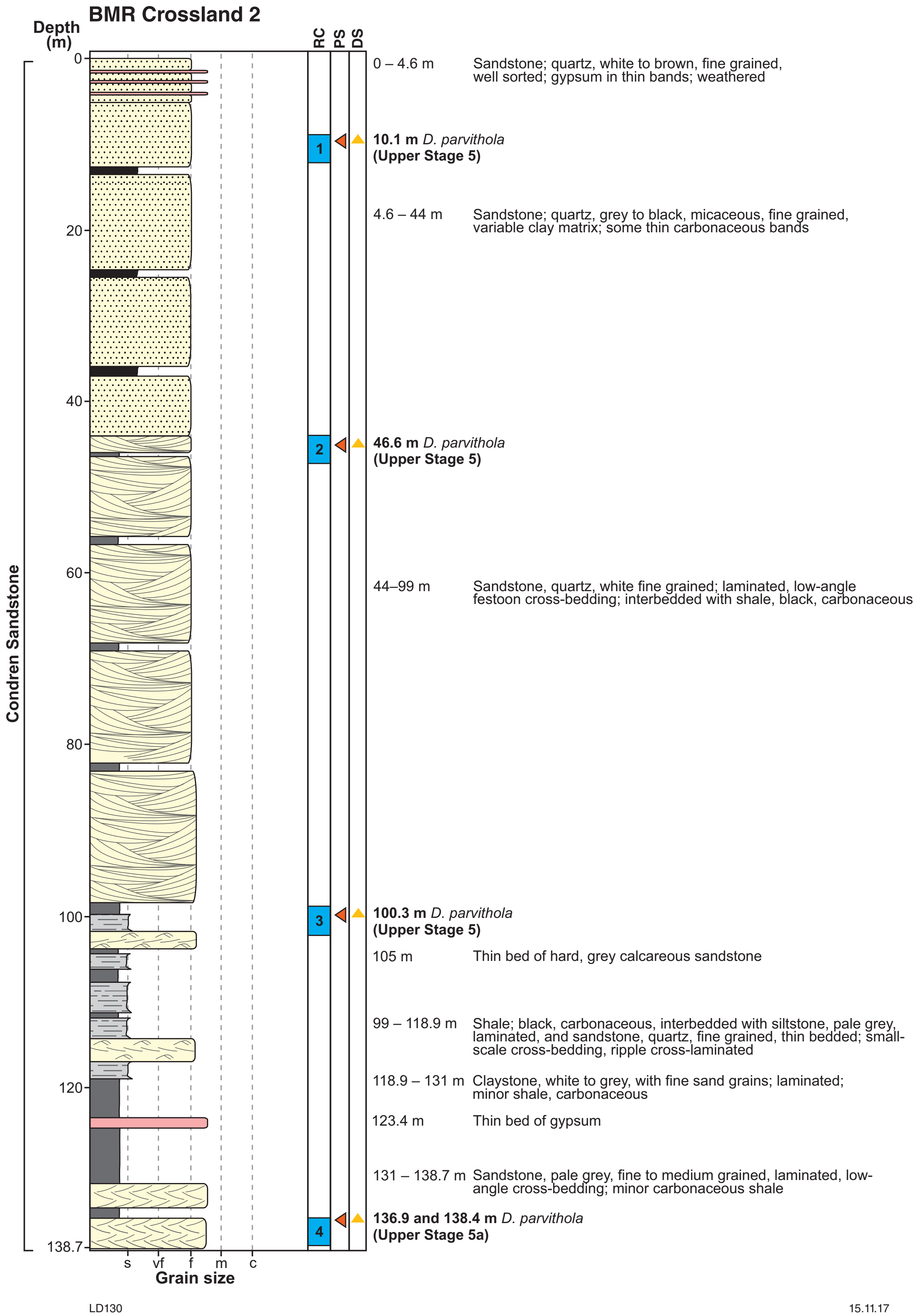


Figure 2.6. Representative lithological log of BMR stratigraphic hole BMR Crossland 2 including palynological sampling locations and results; see Figure 2.1 for legend

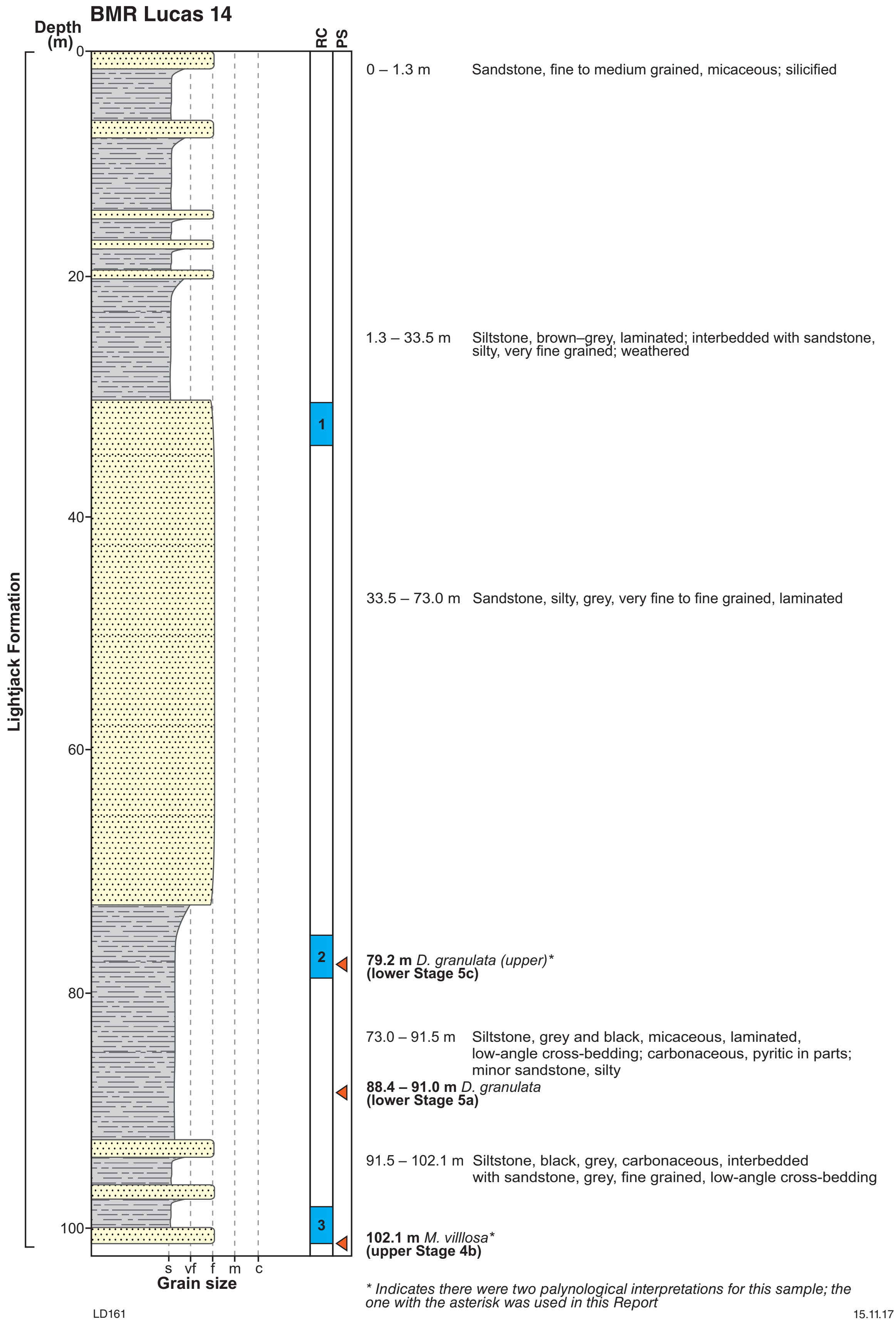
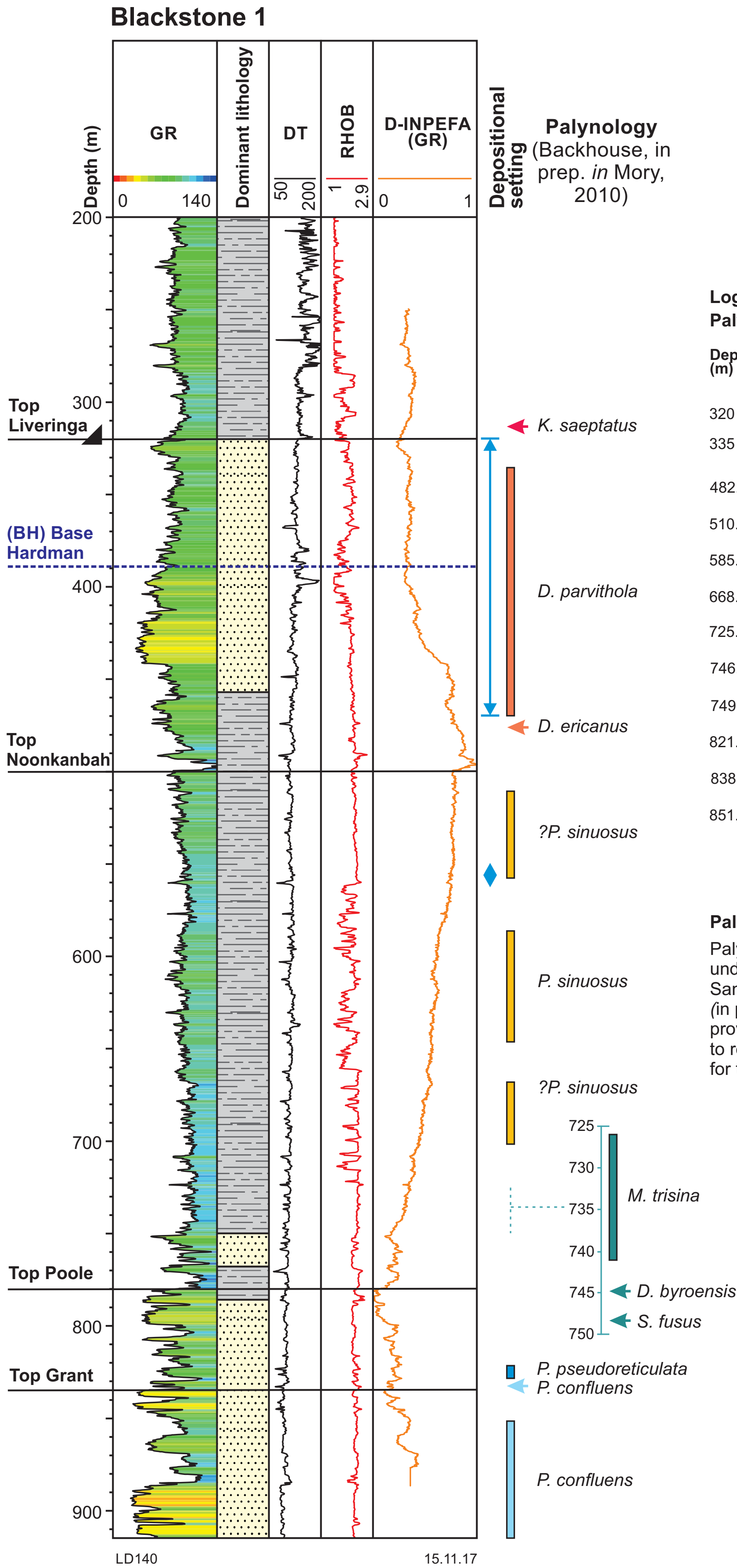


Figure 2.7. Representative lithological log of BMR stratigraphic hole BMR Lucas 14 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

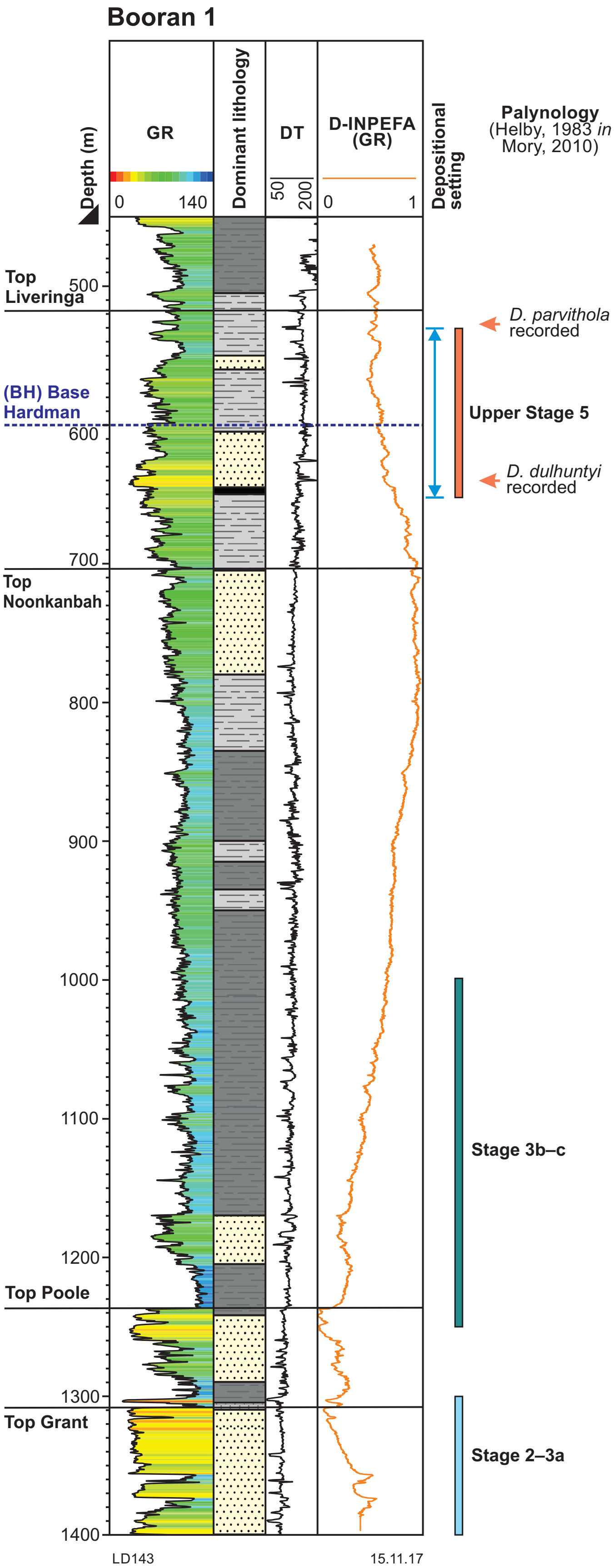
Palynology data

Depth (m)	Sample type	Zone	Notes
320	SWC	*K. saeptatus*	
335 – 472.4	SWC	*D. parvithola*	Marine
482.2	SWC	*D. ericanus*	
510.8 – 577.5	SWC	*?P. sinuosus*	
585.5 – 648	SWC	*?P. sinuosus*	
668.7 – 705.6	SWC	*?P. sinuosus*	
725.4 – 524.5	SWC	*M. trisina*	
746.8	SWC	*D. byroensis*	
749.2	SWC	*S. fusus*	
821.1 – 827.5	SWC	*P. pseudoreticulata*	
838.8	SWC	*?P. confluens*	
851.3 – 1400.6	SWC	*?P. confluens*	

Palynology notes

Palynological analysis of this well was originally undertaken by Balme (WCR, *in* Mory, 2010). Samples were later re-examined by Backhouse, (in prep., *in* Mory, 2010). Analysis by Backhouse provided a more detailed analysis and conforms to recent palynological schemes and was used for this well in this report.

Figure 2.8. Well log, schematic lithology and D-INPEFA of petroleum well Blackstone 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

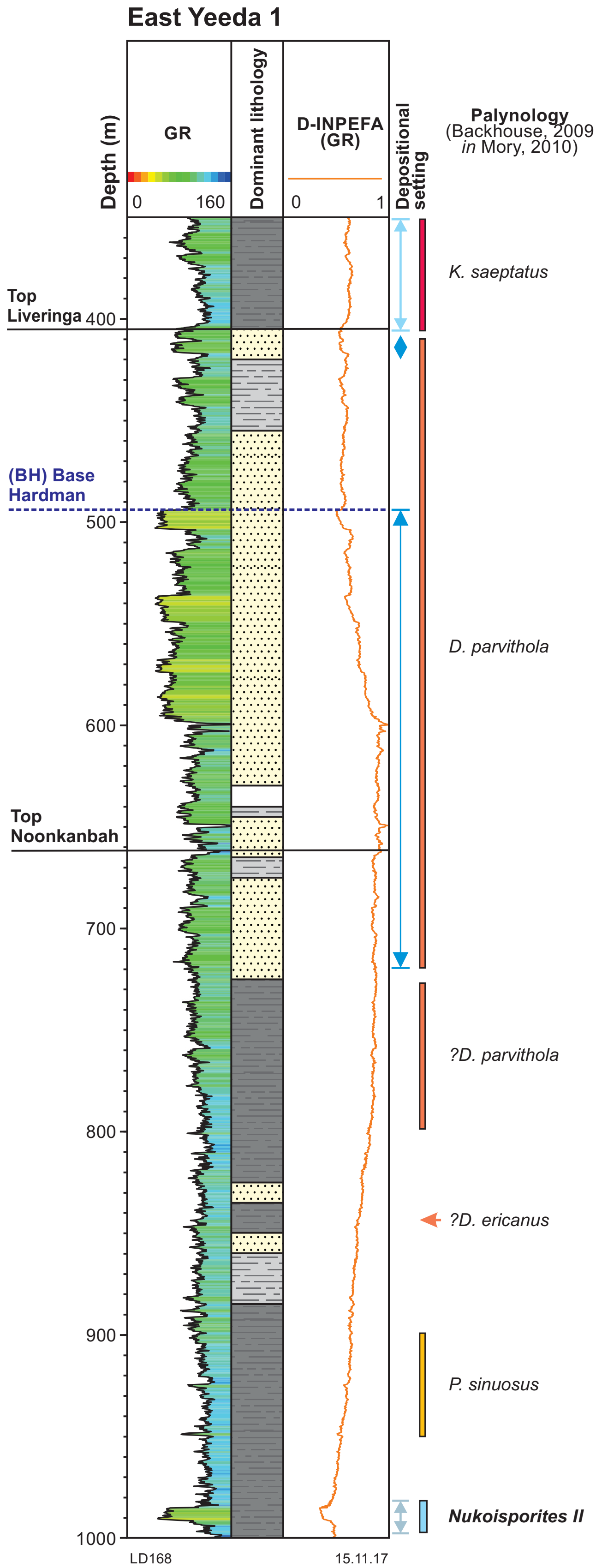
Depth (m)	Sample type	Zone	Notes
530–650	cuttings	upper Stage 5	Marine
1000–1294	SWC	Stage 3a – lower Stage 4	
1300–1690	SWC	Stage 2 – Stage 3a	

Palynology notes

Palynology presented here is from the original well completion report. Helby (1983, *in* Mory, 2010) identified an upper Stage 5 zone at 630.0 and 650.0 m.

Palynomorphs *D. dulhuntyi* were identified between 645–650 m and *D. parvithola* were identified between 530–535 m. The first appearance of each of these palynomorphs marks the base of their eponymous zones. It is reasonable to suggest that the base of the interpreted upper Stage 5 zone is equal to, or younger than, zone *D. dulhuntyi* and that the top of this zone is within the *D. parvithola* zone. Both samples were taken from cuttings; however, the general zones described, and more specific zones implied, are consistent with palynology from neighbouring wells which increases the confidence in this interpretation.

Figure 2.9. Well log, schematic lithology and D-INPEFA of petroleum well Booran 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

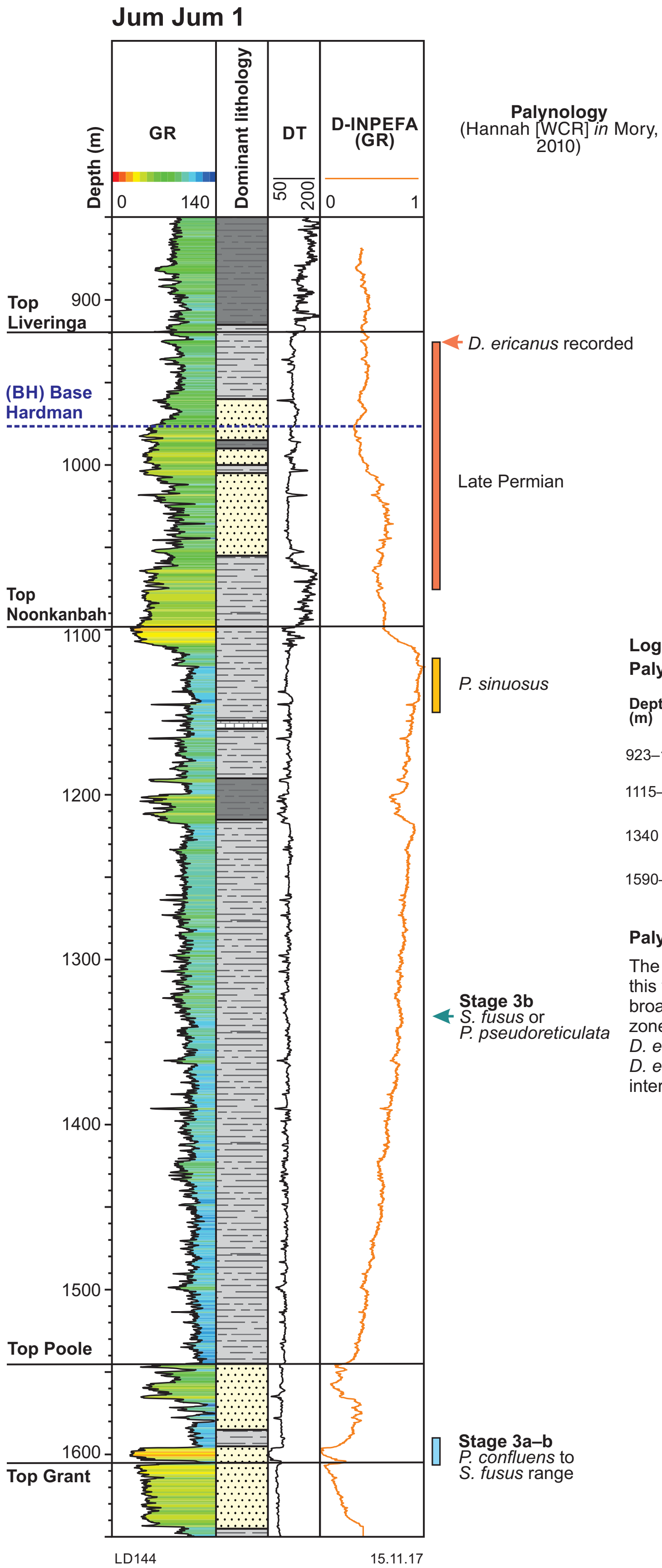
Depth (m)	Sample type	Zone	Notes
200–405	Cuttings	*K. saeptatus*	Moderately marine
410–720	Cuttings	*D. parvithola*	Marine
725–800	Cuttings	*?D. parvithola*	
850	Cuttings	*D. ericanus*	
900–950	Cuttings	*Probably P. sinuosus*	

Palynology notes

Palynological analysis of this well was originally undertaken by RR Purcell and Milne. Samples were later re-examined by Backhouse (2009, *in* Mory, 2010). Analysis by Backhouse (2009, *in* Mory, 2010) provided a more detailed analysis and conforms to recent palynological schemes and is thus used for this well in this report. Comment on depositional environment are from the analysis by Purcell and Milne *(in* Mory, 2010).

The zones as described by Backhouse (2009, *in* Mory, 2010) are contradictory to the formation boundaries as recorded by Mory (2010) and Dent (2016) with the *D. parvithola* zone extending into the top of the Noonkanbah Formation. However, the correlation of this Top Noonkanbah Formation to neighbouring wells is robust. Given the palynological samples are taken from cuttings, it is suggested that there has been some contamination of samples.

Figure 2.10. Well log, schematic lithology and D-INPEFA of petroleum well East Yeeda 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

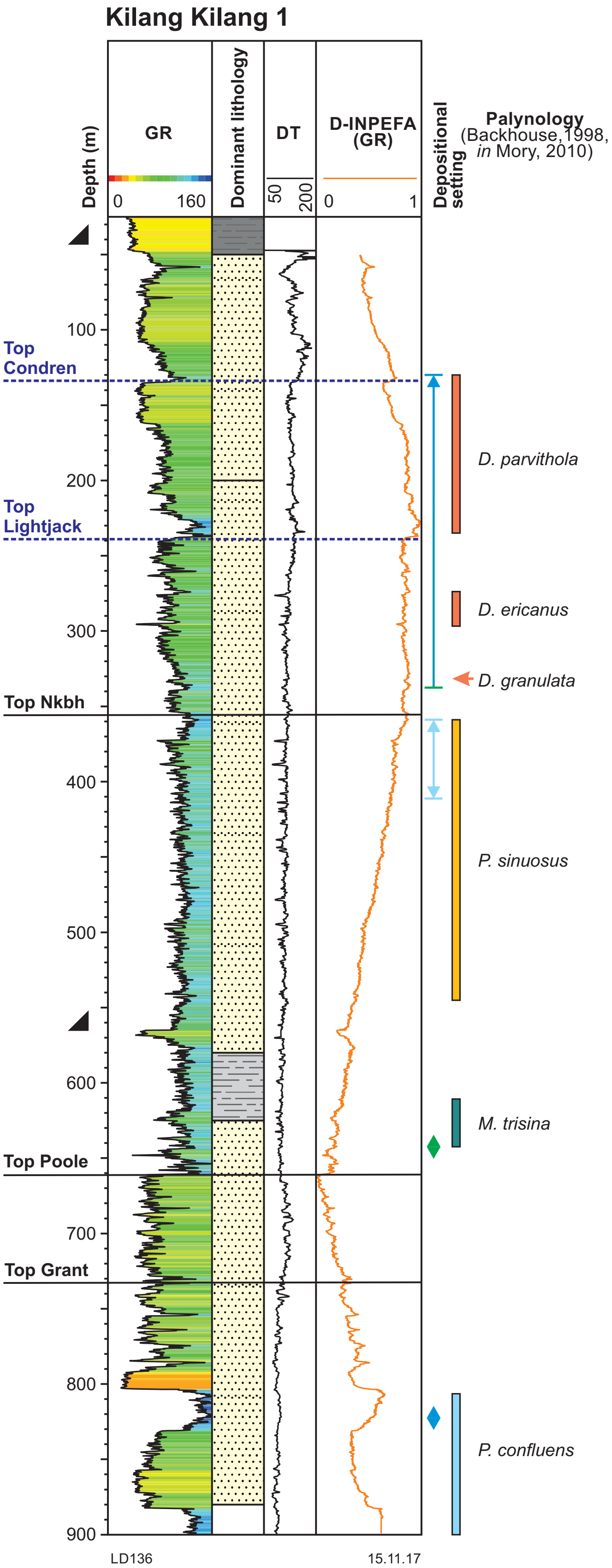
Palynology data

Depth (m)	Sample type	Zone
923–1075	SWC	Late Permian
1115–1150	SWC	*P. sinuosus*
1340	SWC	Stage 3b (*P. pseudoreticulata* to *S. fusus*)
1590–1605	SWC	Stage 3a–3b (*P. pseudoreticulata* to *S. fusus*)

Palynology notes

The original palynological work from the Liveringa Group in this well by Hannah (WCR, *in* Mory, 2010) assigns only a broad late Permian age. This would suggest equivalence to zone *D. parvithola* or younger. The presence of palynomorph *D. ericianus* in side wall core from 923 m indicates zone *D. ericianus* or younger and is consistent with this late Permian interpretation.

Figure 2.11. Well log, schematic lithology and D-INPEFA of petroleum well Jum Jum 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

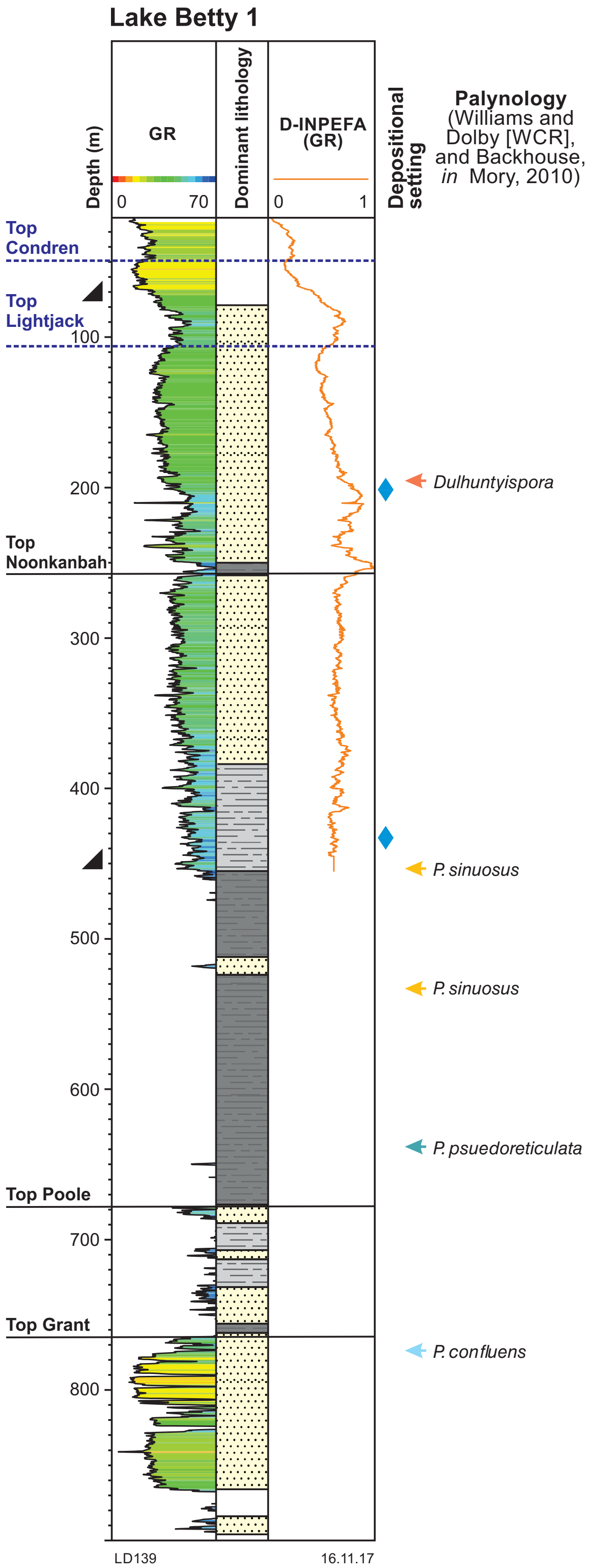
Palynology data

Depth (m)	Sample type	Zone	Notes
131.8 – 236.8	SWC	*D. parvithola*	Marginal marine to marine (131.8 – 338.7 m)
274 – 294	SWC	*D. ericanus*	
338.7	SWC	*D. granulata*	
359 – 545	SWC	*P. sinuosus*	Shallow marine (359 – 406.7 m)
610 – 642.5	SWC	*M. trisina*	Marginal marine (637 – 642.5 m)
807 – 1135	SWC	*P. confluens*	Marine (807–822 m)

Palynology notes

Palynological analysis in this well was originally undertaken by Purcell (*in* Mory, 2010), and assigned to the zones of Evans (1969). Samples were re-examined by Backhouse (1998, *in* Mory, 2010) and assigned to the zones presented here. The depositional setting information is sourced from the original interpretations by Purcell (WCR, *in* Mory, 2010).

Figure 2.12. Well log, schematic lithology and D-INPEFA of petroleum well Kilang Kilang 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

Depth (m)	Sample type	Zone	Notes
210.3	SWC	*Dulhuntyspora*	Marine
431.9	SWC	*Vittatina* (Unit II)	Weakly marine
338.7	SWC	*P. sinuosus*	
	SWC	*P. sinuosus*	
	SWC	*P. pseudoreticulata*	No evidence of marine (635.5 m)
	SWC	*P. confluens*	Marginal marine (637 – 642.5 m)

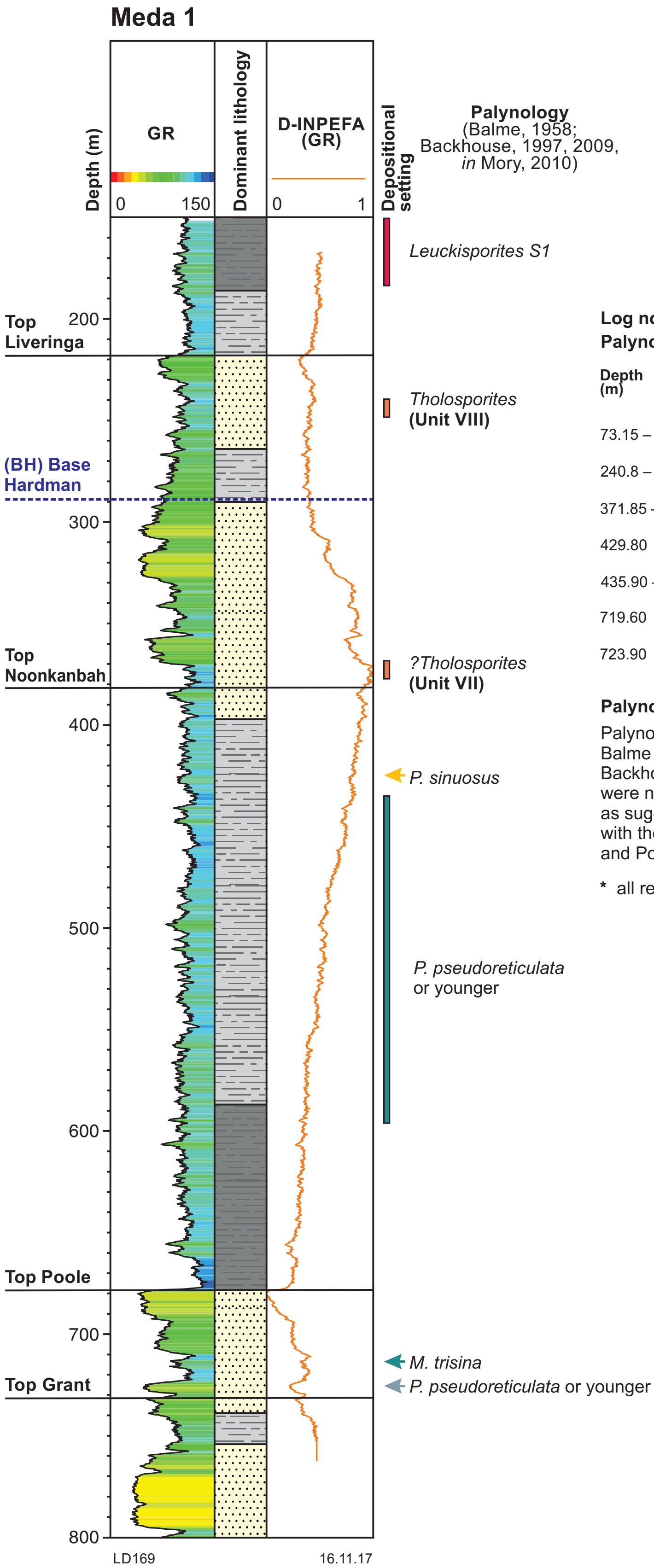
Palynology notes

The original palynological work on this well was undertaken by Williams and Dolby (WCR, *in* Mory, 2010), and was later re-examined and revised by Backhouse (in prep., *in* Mory, 2010). The data represented here are the Backhouse interpretations, which are assigned to the current classification scheme. A single sample at 210.3 m classified according to Williams and Dolby (*in* Mory, 2010), which was not re-examined, is also presented as it is of the most importance in this report. Information on depositional setting has been sourced from the original Williams and Dolby (*in* Mory, 2010) work.

Williams and Dolby (WCR, *in* Mory, 2010) assigned a general *Dulhuntyispora* zone to the samples at 210.3 m, placing it anywhere from the Roadian to the Wuchiapingian. They identified the species *M. villosa*, *D. ericianus*, and *D. dulhuntyi*. The first appearance of *D. dulhuntyi* occurs at the base of its' eponymous zone. This would suggest that the sample resides in the *D. dulhuntyi* zone, or younger.

The overlying *D. parvithola* zone is marked by the first appearance of the *D. parvithola* palynomorph, which is often prolific where present. Given this, and the suite of palynomorphs observed, it could be reasonably expected that *D. parvithola* would have been identified. Its notable absence may suggest that this sample belongs to the *D. dulhuntyi* zone; however, re-examiniation of the samples is necessary to be sure.

Figure 2.13. Well log, schematic lithology and D-INPEFA of petroleum well Lake Betty 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

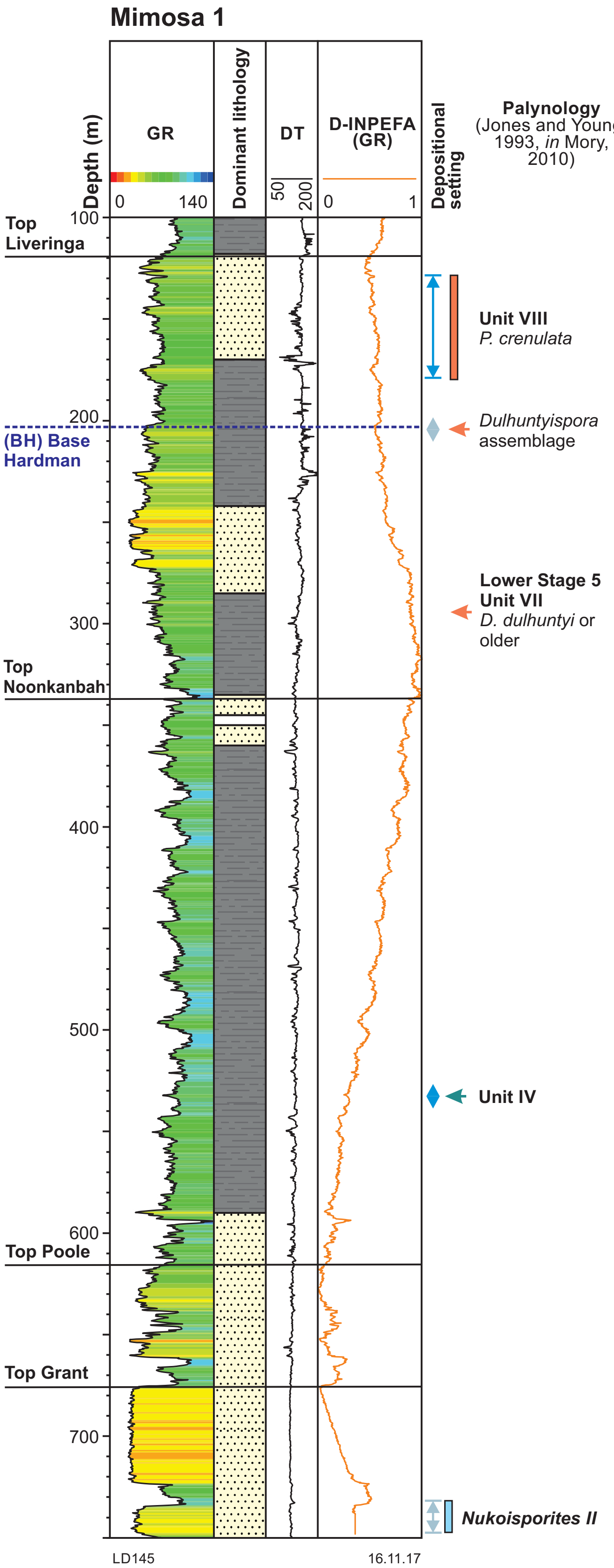
Depth (m)	Sample type	Zone	Reference*
73.15 – 185.93	Cuttings	*Leuckisporites S1*	Balme (1958)
240.8 – 249.95	Cuttings	*Tholosporites* (Unit VIII)	Balme (1958)
371.85 – 381.00	Cuttings	*?Tholosporites* (Unit VII)	Balme (1958)
429.80	Core	*P. sinuosus*	Backhouse (1997)
435.90 – 598.30	Core	*P. pseudoreticulata* or younger	Backhouse (2009)
719.60	Core	*M. trisina*	Backhouse (1997)
723.90	Core	*P. pseudoreticulata*	Backhouse (2009)

Palynology notes*

Palynological analysis of this well was originally undertaken by Balme (1958). Some samples were later re-examined by Backhouse (1997, 2009). Samples from the Liveringa Group were not re-examined. However, the ages of these samples as suggested by Balme (1958) are stratigraphically consistent with the ages suggested for the underlying Noonkanbah Formation and Poole Sandstone by Backhouse (1997, 2009).

* all references from Mory (2010, appendix 6)

Figure 2.14. Well log, schematic lithology and D-INPEFA of petroleum well Meda 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

Palynology data

Depth (m)	Sample type	Zone
120 – 180	cuttings	*P. crenulata*
201	SWC	*Dulhuntyispora* assemblage
300	SWC	Lower Stage 5
406	SWC	Unit VI
541	SWC	Unit IV
573.2 – 982	SWC	Nuskoiporites II

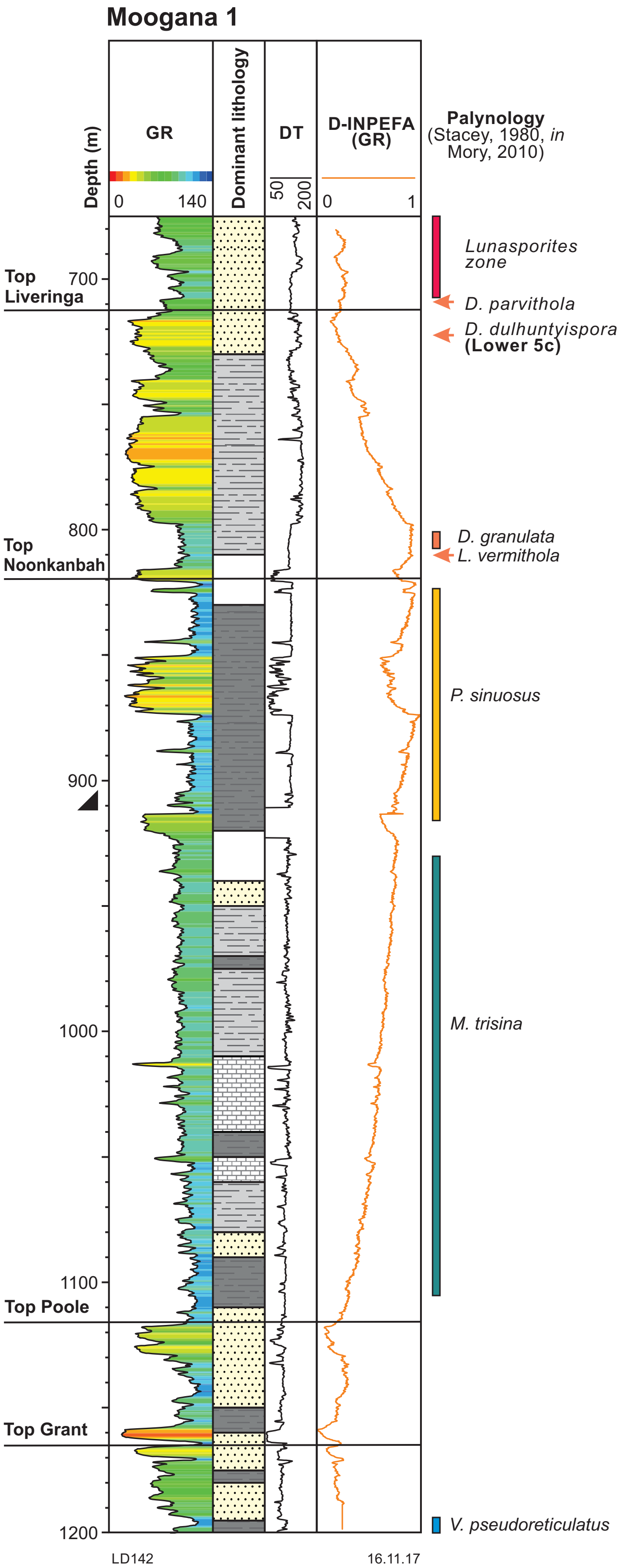
Palynology notes

The original palynological analysis of this well was undertaken by Dolby et al. (*in* Mory, 2010) and described only broad, late Permian, ages for the Liveringa Group. This early work was later re-assessed by Jones and Young (1993, *in* Mory, 2010) and some samples were reclassified.

According to Jones and Young (1993, *in* Mory, 2010) the side wall core sample at 201 m yielded a *Dulhuntyispora* assemblage. They re-examined the list of species from the original analysis and determined that the assemblage contained palynofloras of late early Permian to late Permian age.

Jones and Young (1993, *in* Mory, 2010) also analysed cuttings from 300 m depth not included in the original report. This sample yielded a lower Stage 5 palynoflora. This classification would make it equivalent to zones *D. dulhuntyi* or older.

Figure 2.15. Well log, schematic lithology and D-INPEFA of petroleum well Mimosa 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

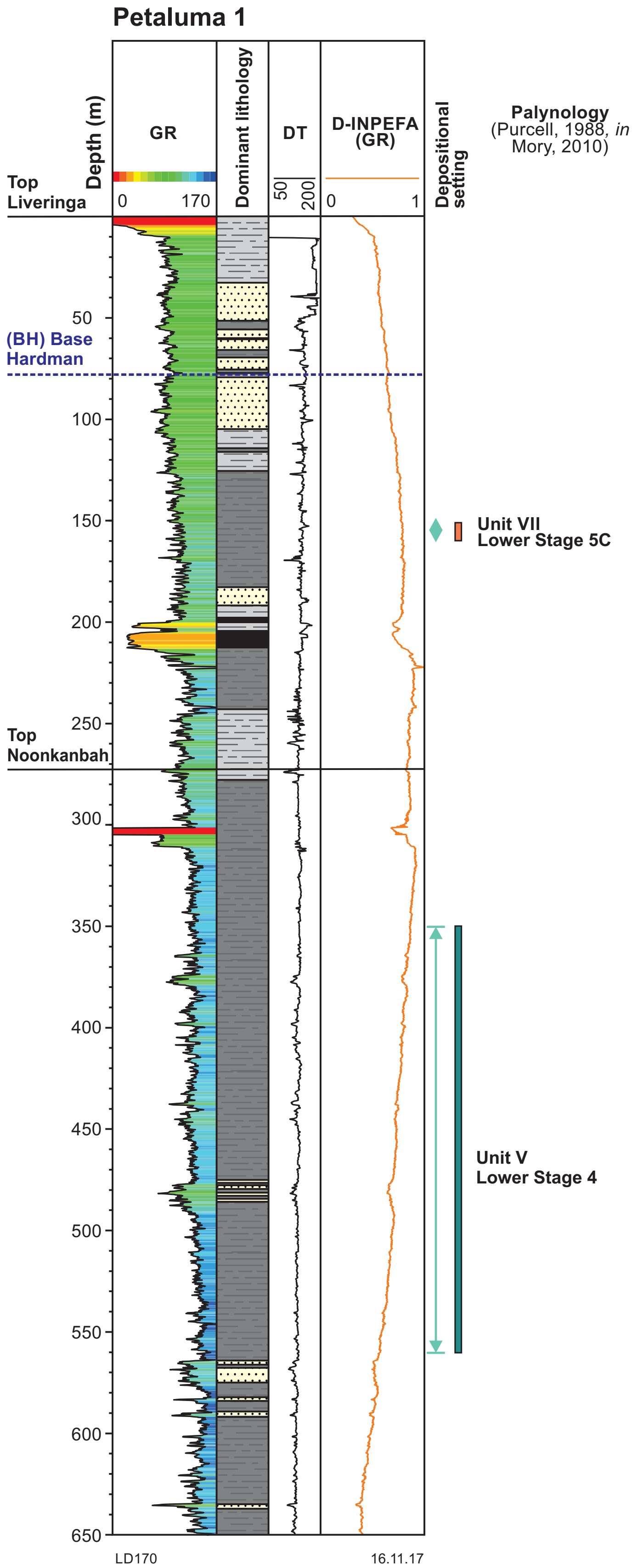
Palynology data

Depth (m)	Sample type	Zone
652 – 709.5	SWC	*Lunasporites*
713	SWC	*D. parvithola*
730.2	SWC	*D. dalhuntyspora* (lower Stage 5 c)
802 – 806.4	SWC	*D. granulata*
814.7	SWC	*L. vermithola* (upper Stage 4b)
822 – 916	SWC	*P. sinuosus*
932 – 1109	SWC	*M. trisina*
1197 – 1513.5	SWC	*V. pseudoreticulatus*

Palynology notes

Sample taken from 730.2 m is classified as *D. dulhuntyispora,* equivalent to the lower Stage 5c; this is also equivalent to the *D. dulhuntyi* zone.

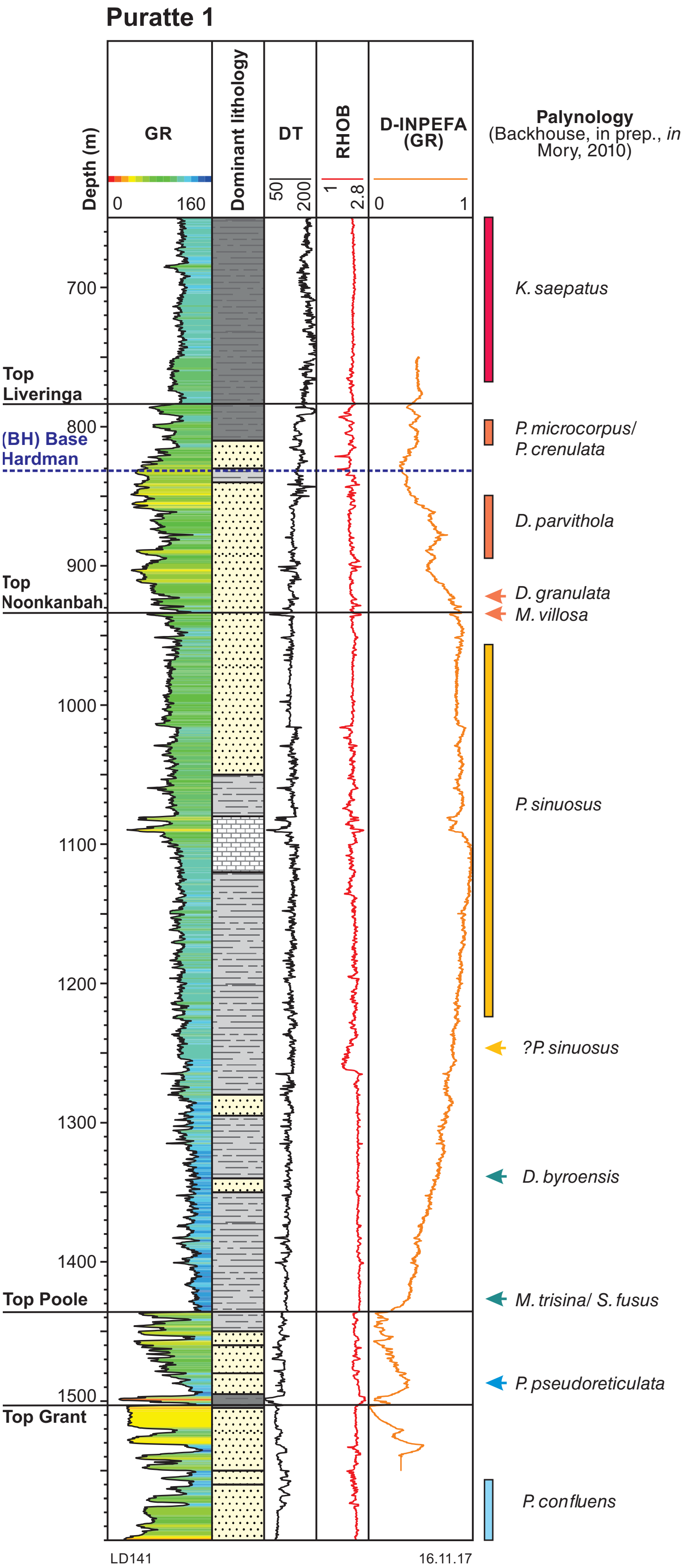
Figure 2.16. Well log, schematic lithology and D-INPEFA of petroleum well Moogana 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes
Palynology data

Depth (m)	Sample type	Zone	Notes
150–160	Cuttings	Unit VII Lower Stage 5C	Shallow marine
350–560	Cuttings	Unit V Lower Stage 4	Shallow marine

Figure 2.17. Well log, schematic lithology and D-INPEFA of petroleum well Petaluma 1 including palynological sampling locations and results; see Figure 2.1 for legend



Log notes

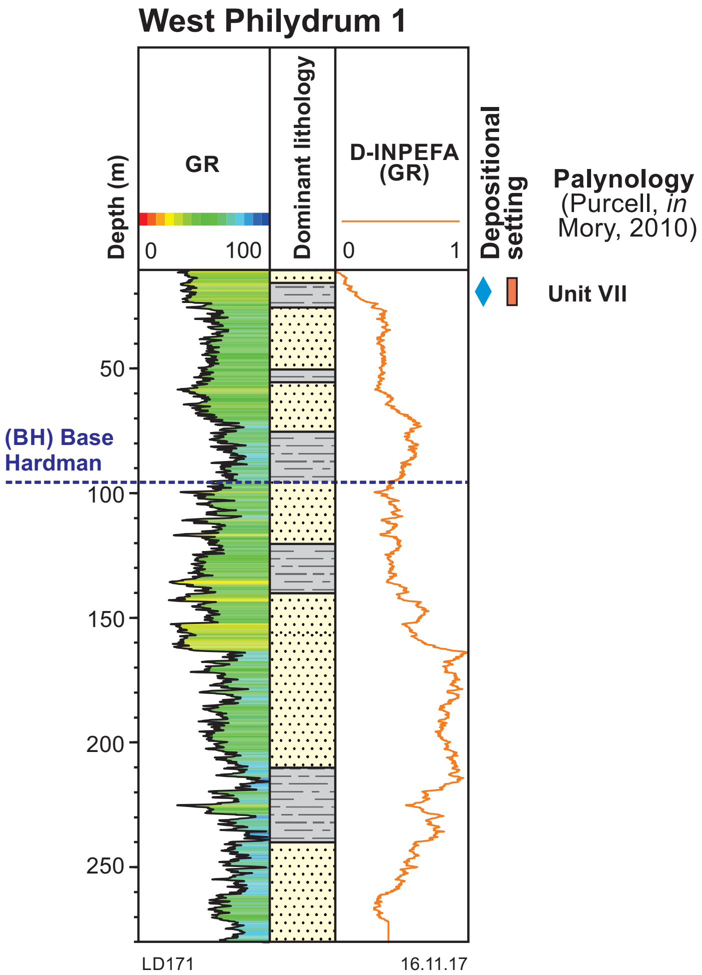
Palynology data

Depth (m)	Sample type	Zone
578–765	SWC	*K. saeptatus*
795–812	SWC	*P. microcorpus/ P. crenulata*
850–894	SWC	*D. parvithola*
926	SWC	*D. granulata*
940	SWC	*M. villosa*
956–1222	SWC	*P. sinuosus*
1251.5	SWC	*?P. sinuosus*
1345	SWC	*D. byroensis*
1432	SWC	*M. trisina/S. fusus*
1494	SWC	*P. pseudoreticulata*
1560–1681	SWC	*P. confluens*

Palynology notes

Palynological analysis of this well was originally undertaken by Stacey (1980, *in* Mory, 2010). Samples were later re-examined by Backhouse (in prep., *in* Mory, 2010). Analyses by Backhouse were used for this well in this report because they provided a more detailed analysis and the results conform to recent palynological schemes.

Figure 2.18. Well log, schematic lithology and D-INPEFA of petroleum well Puratte 1 including palynological sampling locations and results; see Fig. 2.1 for legend



Log notes

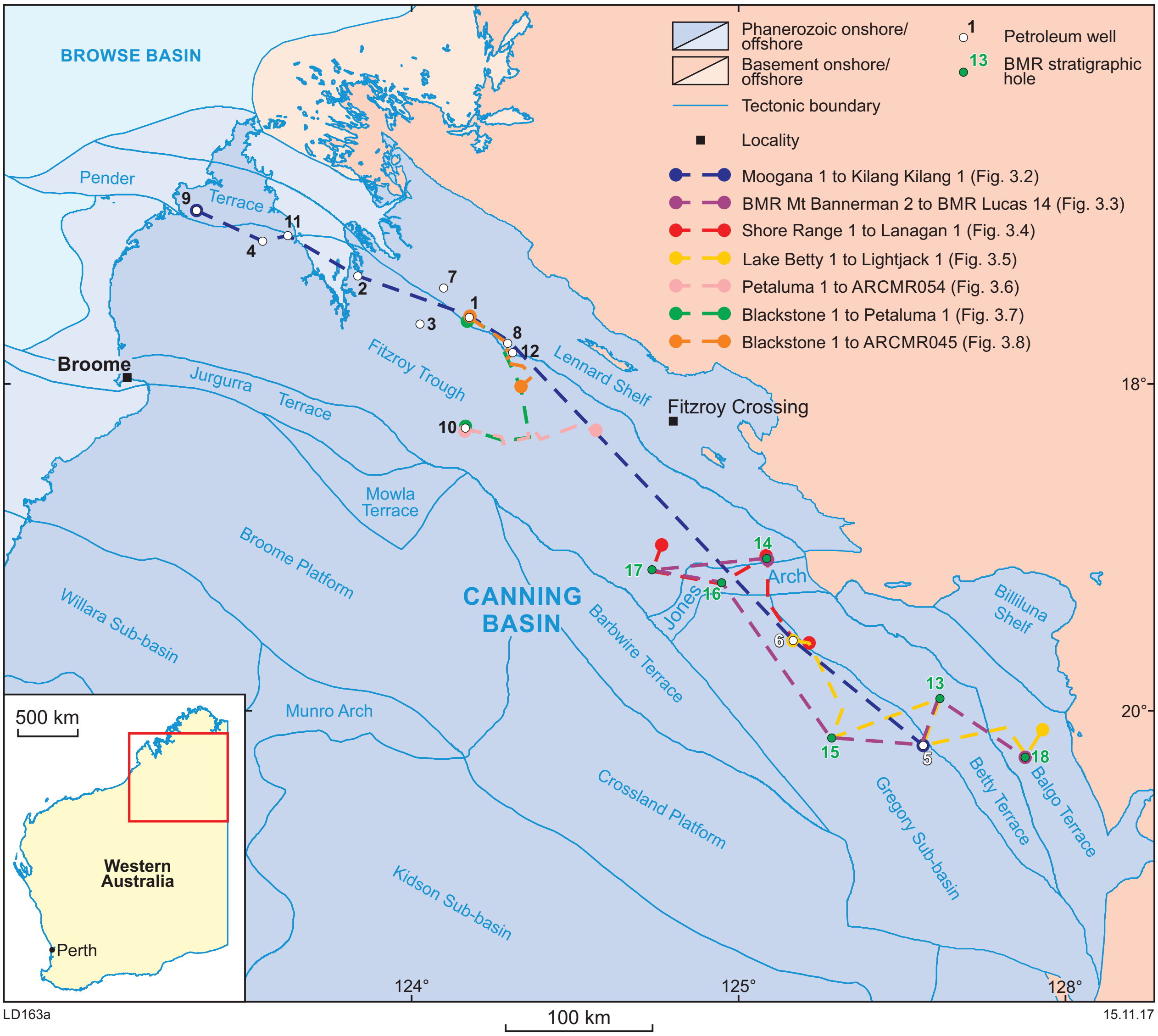
Palynology data

Depth (m)	Sample type	Zone	Notes
13–25	Cuttings	Unit VII	Marine

Figure 2.19. Well log, schematic lithology and D-INPEFA of petroleum well West Philydrum 1 including palynological sampling locations and results; see Figure 2.1 for legend

Appendix 3

Stratigraphic and palynologic correlation sections



1 Blackstone 1
2 Booran 1
3 East Yeeda1
4 Jum Jum 1
5 Kilang Kilang 1
6 Lake Betty 1
7 May River 1
8 Mimosa 1
9 Moogana 1
10 Petaluma 1
11 Puratte 1
12 West Philydrum 1
13 BMR Mt Bannerman 1
14 BMR Mt Bannerman 2
15 BMR Cornish 1
16 BMR Crossland 1
17 BMR Crossland 2
18 BMR Lucas 14

Figure 3.1. Location of the seven correlation sections (Figs 3.2 – 3.8) used to illustrate key interpretations in this Report; note that the numbers assigned to wells, holes and outcrops on all subsequent location maps apply only to the individual correlation section

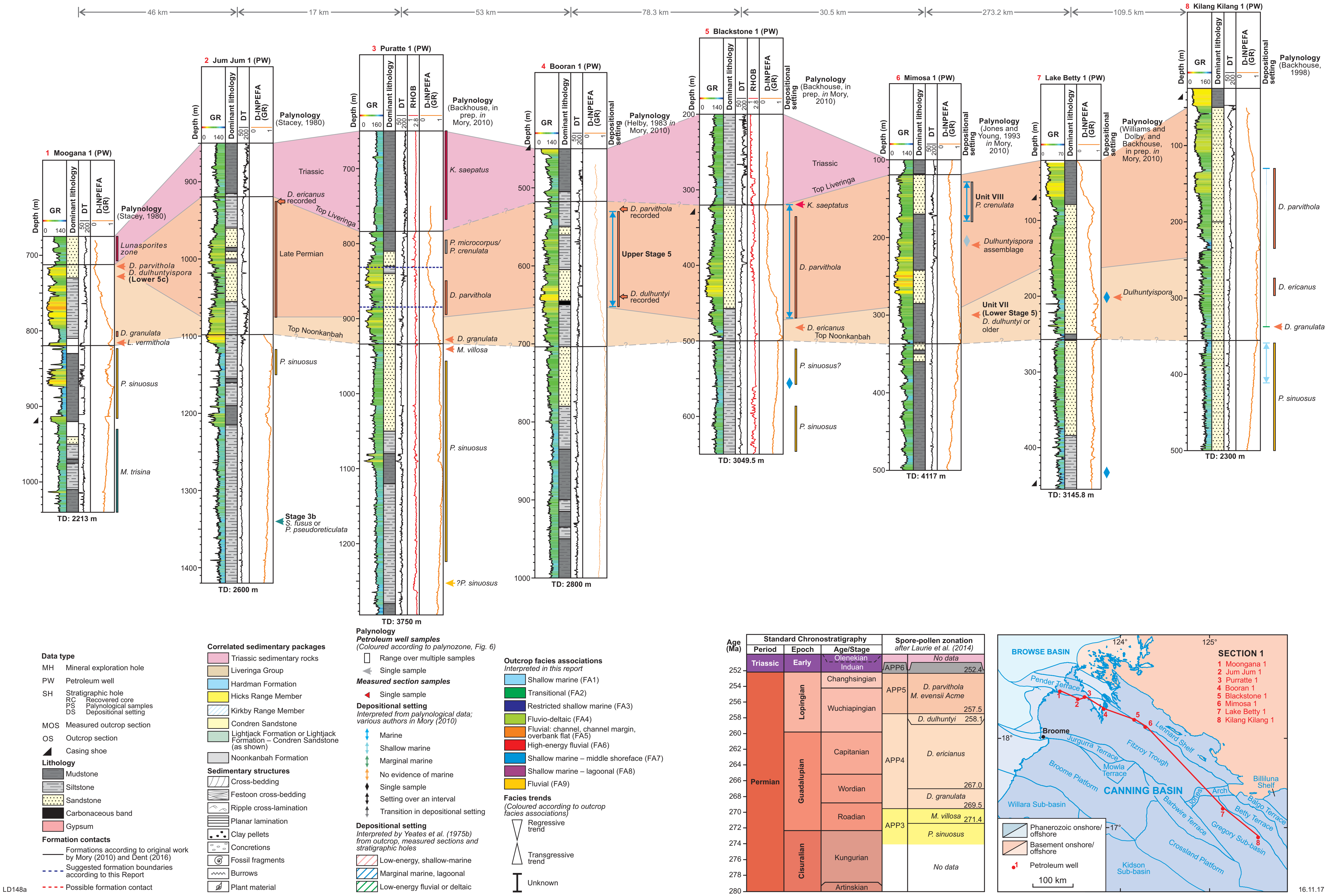


Figure 3.2. Correlation of three palynozones identified in petroleum wells through the Hardman Formation, from northwest to southeast across the study area (Section 1): the lower pale-orange zone correlates sections which record *D. granulata*, *D. ericianus* and *D.dulhuntyi* palynozones; the middle orange zone correlates all records of the *D. parvithola* palynozone and includes the rarely recorded *P. microcorpus* and *P. crenulata* zones; the pink zone correlates all recorded Triassic palynozones

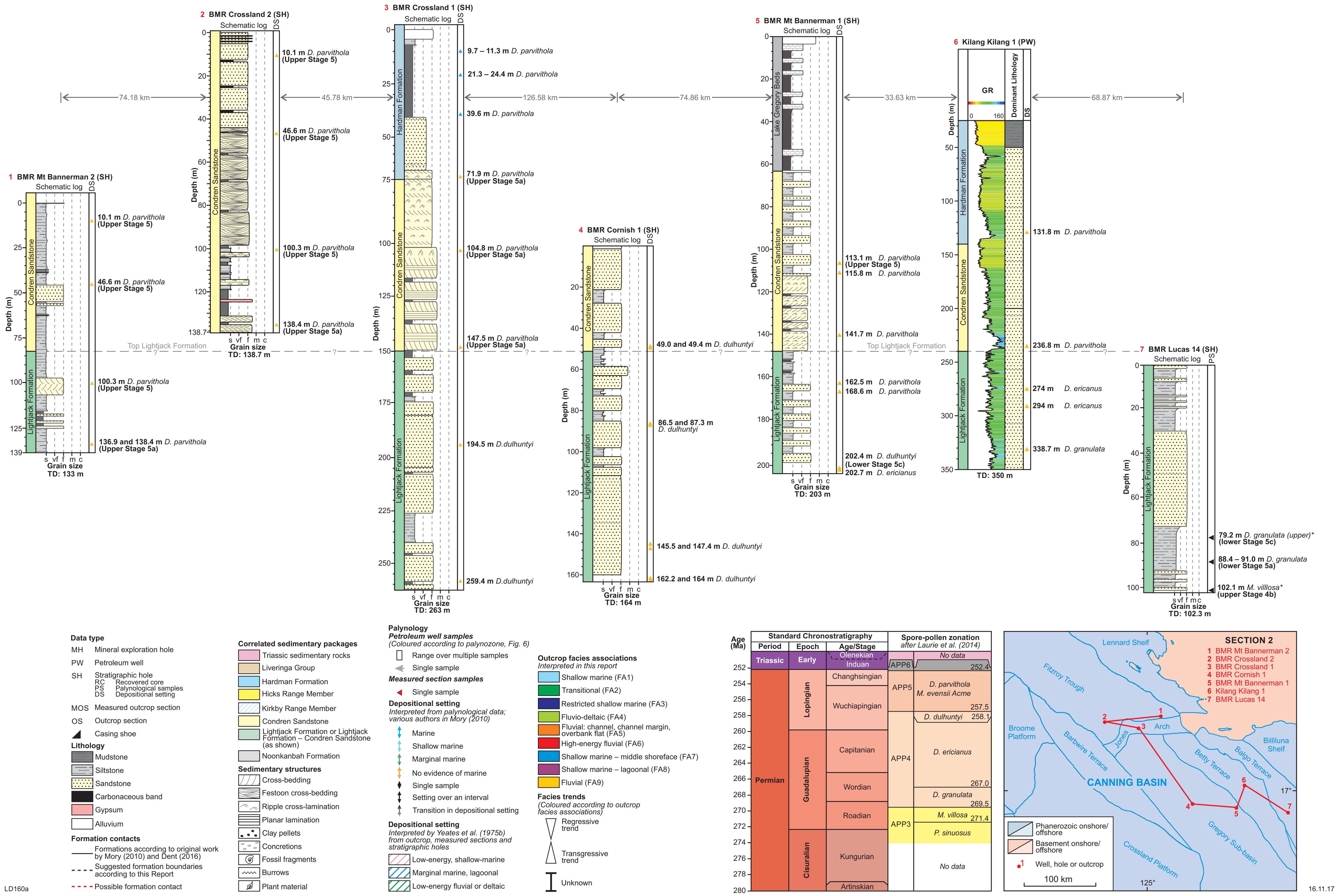


Figure 3.3. Correlation between BMR stratigraphic holes containing palynological data for the Hardman Formation highlights the discontinuity between palynozone and lithostratigraphic interpretations (Section 2). Logs were adapted from the originals presented by Yeates et al. (1975b), and redrawn to display additional information provided in the authors' descriptions. Formation boundaries, palynological samples and corresponding palynozone, and interpreted depositional setting are presented as interpreted by Yeates et al. (1975b); refer to Appendix 2 for details on the palynology of individual sections

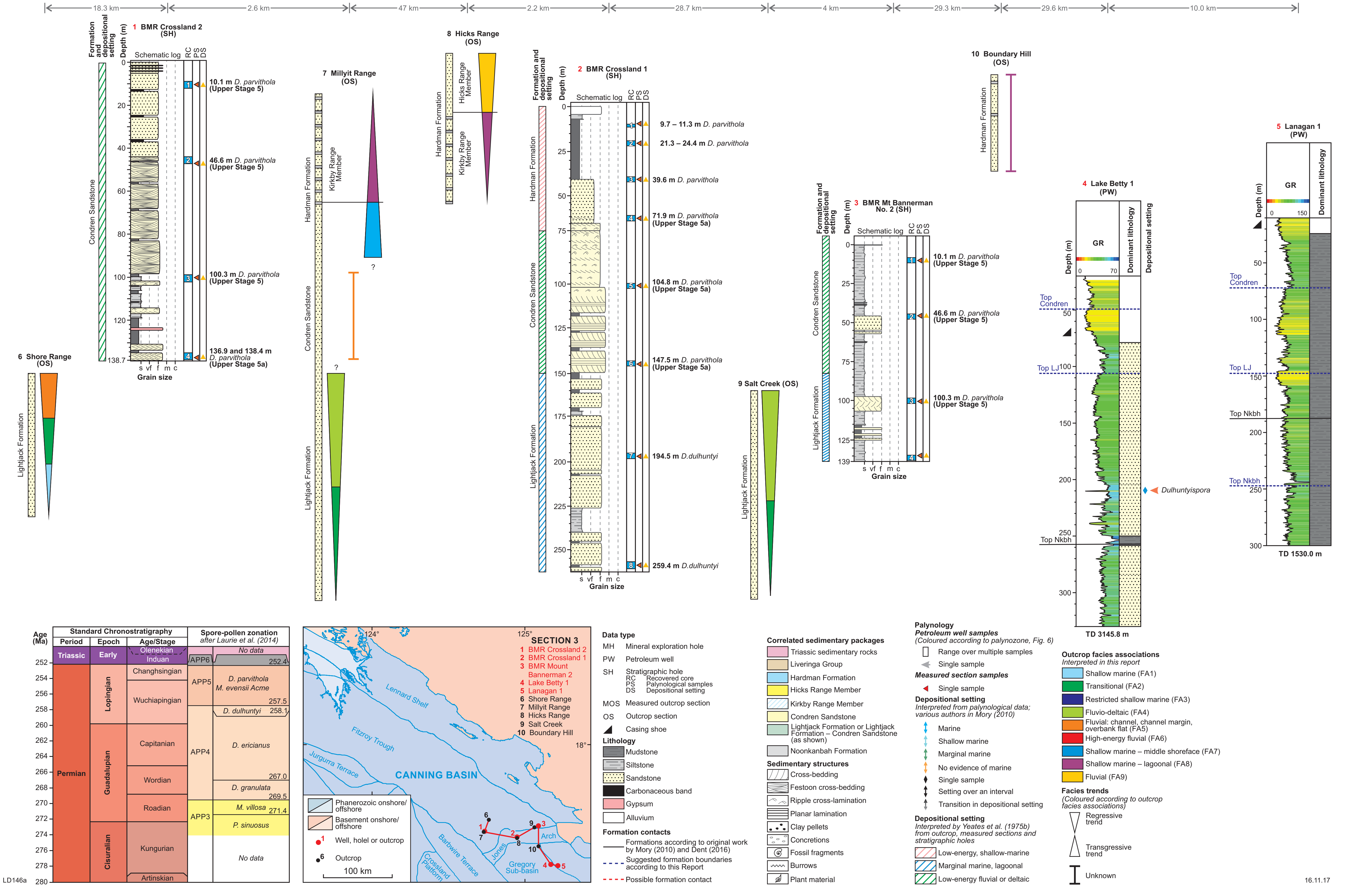


Figure 3.4. Distribution and stacking pattern of outcrop facies compared to the lithology and interpreted depositional setting in nearby stratigraphic holes and petroleum wells (Section 3); schematic outcrop sections illustrate the progression of facies from the base to top of the outcrops with their interpreted trend. The depositional setting in stratigraphic well sections was interpreted by Yeates et al. (1975b); core sections recovered from these wells are shown as blue boxes with the core numbers in white

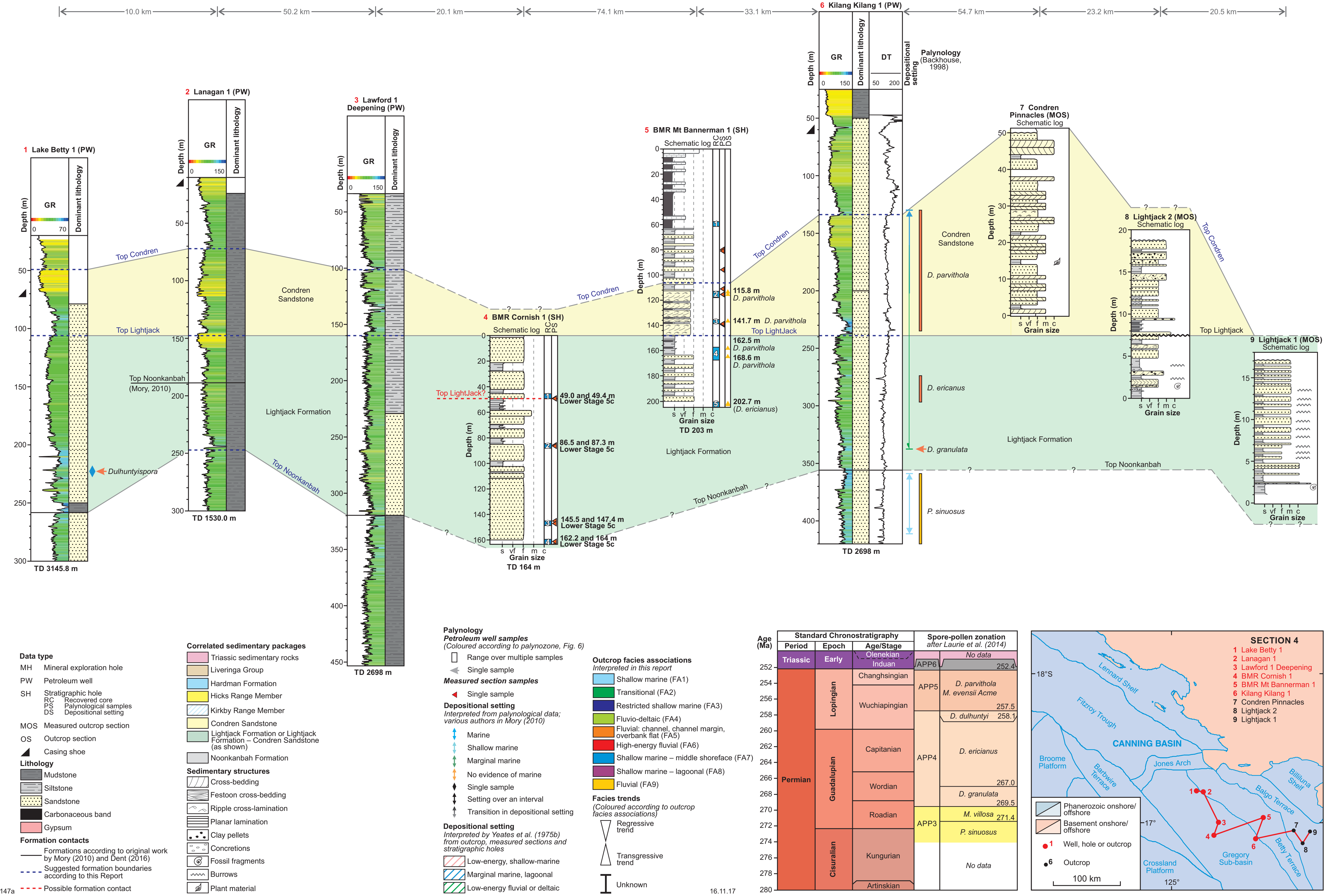


Figure 3.5. Correlation of petroleum wells, stratigraphic holes and measured outcrop sections in the southeast of the study area, using the Top Lightjack Formation as the datum (Section 4); the proposed tops of the Lightjack Formation and the Condren Sandstone are shown and correlated between wells and outcrop sections based on lithology and palynology; a revised pick for the Top Lightjack Formation is suggested for BMR Cornish 1

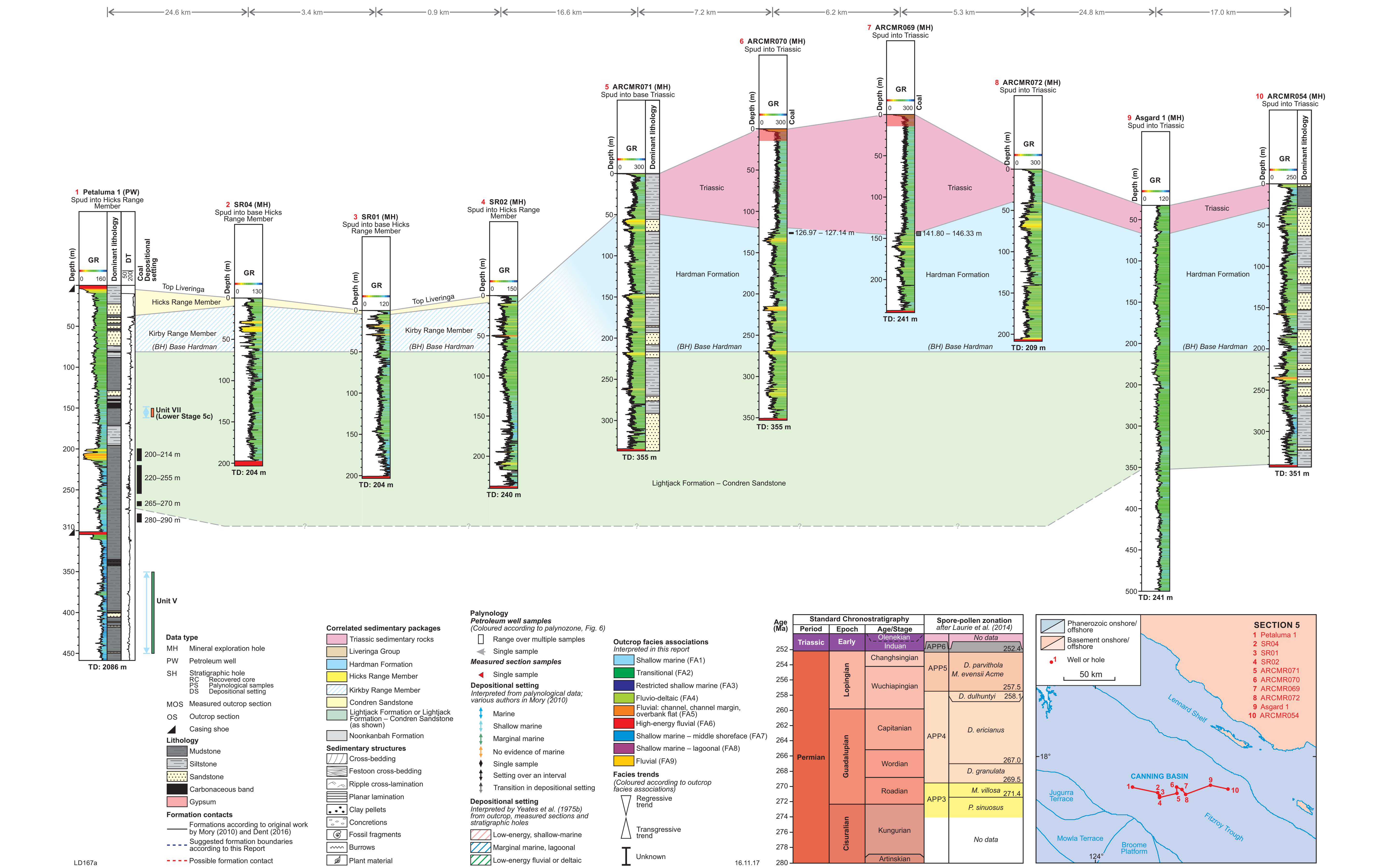


Figure 3.6. Identification and correlation of the Hardman Formation and Lightjack Formation – Condren Sandstone in mineral exploration holes and petroleum wells (Section 5); the Lightjack Formation and Condren Sandstone are grouped together as they were not able to be reliably distinguished. The Hicks Range and Kirkby Range Members of the Hardman Formation were identified in Petaluma 1, SR01, SR02 and SR04 based on mapped outcrop relationships and well log signatures; where these members were unable to be separated, they were classified as Hardman Formation

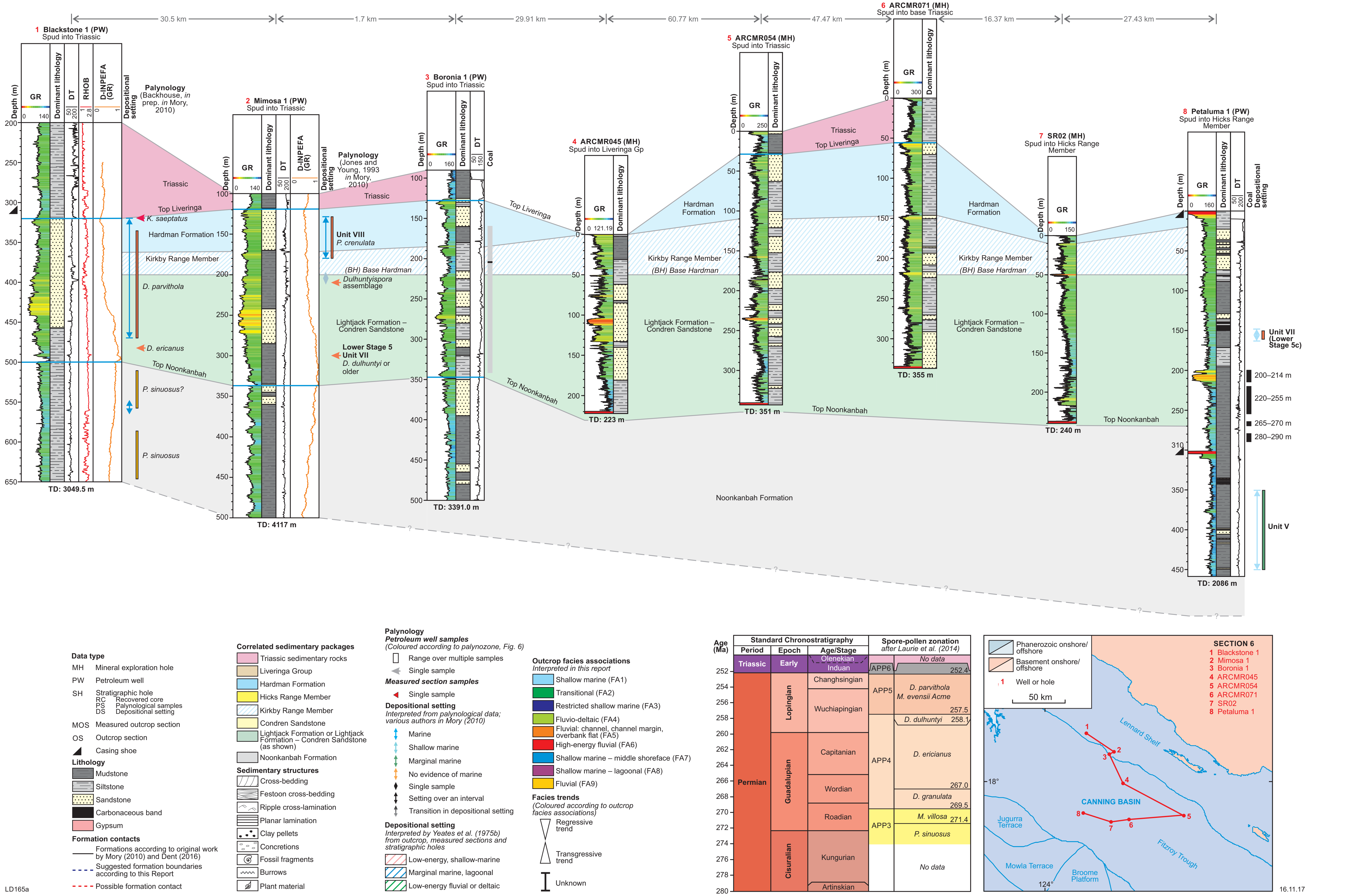


Figure 3.7. Identification and correlation of the Hardman Formation and Lightjack Formation – Condren Sandstone in mineral exploration holes and petroleum wells, using the Base Hardman Formation (BH) as the datum (Section 6); although the Kirkby Range Member was identified, the Hicks Range and the Cherrabun Members were grouped and labelled as the Hardman Formation due to the inability to reliably define them in these wells

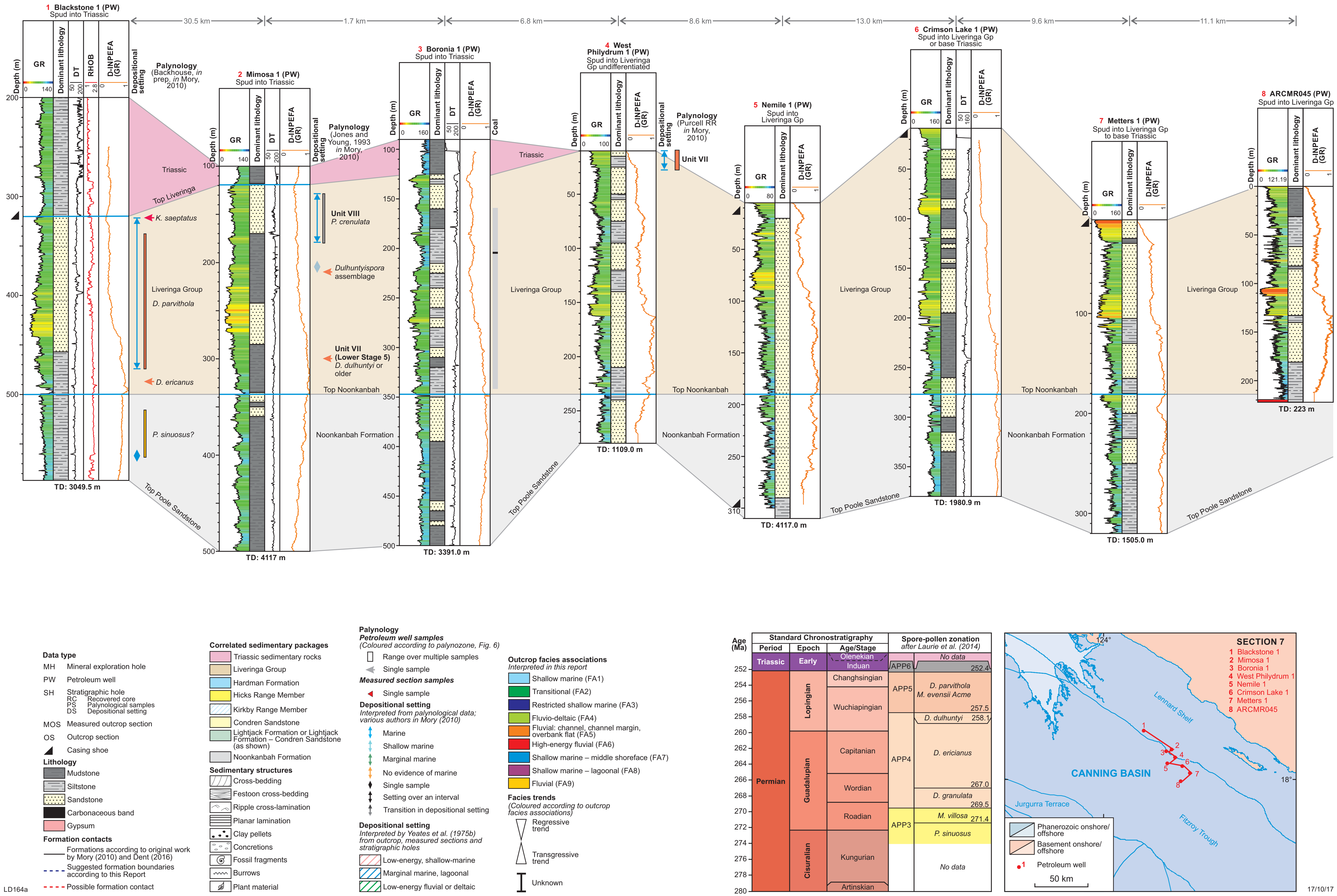


Figure 3.8. Detailed correlation of petroleum wells and mineral exploration holes in the central section of the study region (Section 7); D-INPEFA curves illustrate the change from an overall positive trend in the uppermost Noonkanbah Formation to a negative trend in the Lightjack Formation (lower Liveringa Group); the continuation of the negative trend throughout deposition of the Liveringa Group was interpreted as a return to transgressive conditions

Appendix 4

Table 4.1. Key facies identified in outcrops of the Lightjack Formation, Condren Sandstone and Hardman Formation based on lithology, major bedding styles and sedimentary features

Facies	*Code*	*Lithology*	*Bedding and sedimentary structures*	*Interpretation*
Pebble conglomerate	*Gm*	Rounded fine sandstone and siltstone clasts in a fine-grained sandstone matrix	Thinly bedded 5–10 cm; matrix supported; deposits are lenticular and discontinuous overlying scoured basal surface	Moderate- to high-energy deposition indicated by clast size
Pebbly-granular conglomerate	*Gmc*	Angular quartz pebbles and granules in a coarse-grained sandstone matrix	Thinly bedded; commonly present at the base of amalgamated trough-cross bedded sandstone sections.	High-energy deposition; likely proximal given the angularity of clasts
Swaley to hummocky sandstone	*Ss*	Fine- to medium-grained sandstone	Medium to thickly bedded; swaley to hummocky cross-stratification occurring as single sets ~15–20 cm thick; sets are commonly amalgamated	Moderate-energy conditions above storm wave base but below fair weather wave base
Convolute-laminated sandstone	*Sc*	Fine-grained sandstone with abundant siltstone	Medium bed thickness; occasional soft-sediment deformation in the form of convolute lamination	Rapid deposition of overlying sediments indicated by deformation of sandstone beds
Coarse trough cross-stratified sandstone	*Stc*	Medium- to coarse-grained quartz sandstone, with common angular quartz granules	Thinly to thickly bedded 0.1 to >3 m thick; individual trough sets vary in thickness from 0.1 – 0.8 m thick and commonly amalgamate into thick tabular cosets; well-rounded ?quartzite cobble lags locally present at the bed bases	High-energy current energy deposition; 3D migration of both large and small bedforms; accretionary environment
Trough cross-stratified sandstone	*St*	Fine- to medium-grained sandstone	Thinly to thickly bedded, 0.1 to >1 m thick; individual sets are thin (10–15 cm), although they are commonly amalgamated into sections exceeding 1 m in thickness	Lower flow regime; 3D bedform migration
Horizontally laminated sandstone	*Sh*	Fine- to medium-grained sandstone	Thinly planar bedded, 1-3 cm thick; commonly amalgamated into thicker sections that can be >1 m thick	Upper flow regime conditions
Current ripple cross-laminated sandstone	*Sr*	Fine- to medium-grained sandstone; sometimes argillaceous	Thinly bedded ~1 cm or thick amalgamated sections; unidirectional ripple cross-lamination, erosional and aggradational; climbing and linguoid ripple forms are present	Lower flow regime; shallow-water settings; high suspended sediment where climbing ripples are preserved
Bimodal ripple cross-lamintation	*So*	Fine-grained sandstone with minor siltstone	Thinly bedded, ~1–3 cm thick; commonly amalgamated into thicker sections, up to 30 cm thick; erosional and aggradational forms present; bidirectional cross-lamination with significantly thicker deposits preserved in one direction	Lower flow regime; shallow-water settings; tidal settings suggested from the bidirectional ripples and the dominance of one flow direction
Root-bioturbated sandstone	*Rt*	Fine-grained sandstone; argillaceous	Medium to thickly bedded; primary structure is likely cross-stratification but is obscured by highly abundant root traces; layers of concentrated plant material and indistinct bioturbation are locally present	Low- to very low-energy deposition; aqueous with possible episodes of subaerial exposure

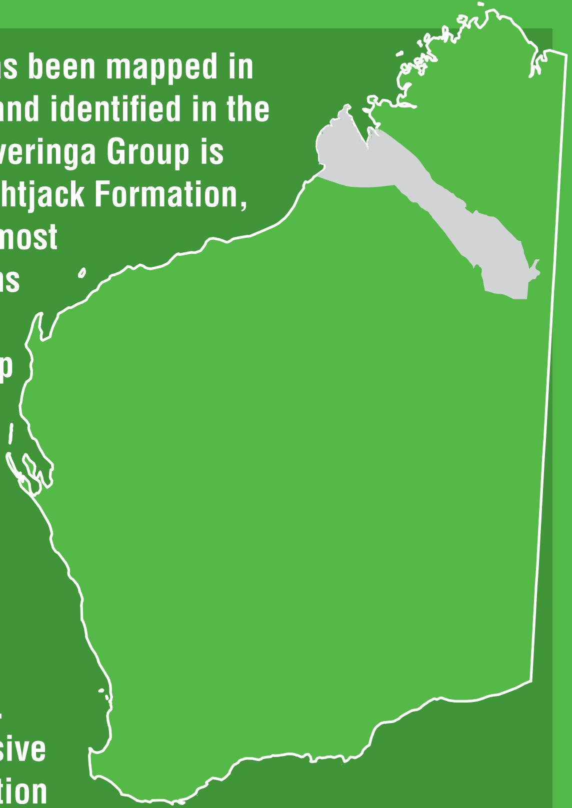
Table 4.1. continued

Facies	*Code*	*Lithology*	*Bedding and sedimentary structures*	*Interpretation*
Heterolithic sandstone–siltstone	*Hp*	Fine- to very fine-grained sandstone and siltstone	Thinly interbedded 0.5–1 cm thick sandstone and siltstone beds; planar and ripple cross-lamination common, amalgamation of beds into thicker sections; occasional small scours infilled with siltstone; dislocate oscillatory ripple trains are present, ripples are commonly sandstone with siltstone drapes	Lower flow regime; fluctuating low-energy and slack shallow-water settings; oscillatory water motion due to either wave- or wind-generated wave processes
Heterolithic-bioturbated siltstone	*Hb*	Heterolithic fine- to very fine-grained sandstone and siltstone	Thinly to thickly bedded; some layers are preferentially oxidised; beds have distinct mottled appearance and are dark purple and white; original sedimentary structure is not evident due to extensive bioturbation. Bioturbation is predominantly horizontal; trace fossil assemblage has high abundance and high diversity	Marine; low-energy setting; biologically favourable
Biofacies 1	*Ba*	Heterolithic fine- to very fine-grained sandstone and siltstone	Thickly bedded; primary structure is obliterated by extensive bioturbation; trace fossil assemblage has high abundance and moderate diversity; *Thalassinoides* traces are sand filled and preferentially oxidized to deep purple colour; *Thalassinoides* dominate the trace fossil assemblage and form laterally extensive boxworks; *Diplocraterion* traces are common in this facies	Marine; low-energy setting; biologically favourable
Biofacies 2	*Bb*	Heterolithic fine- to very fine-grained sandstone and siltstone	Thickly bedded; trace fossil assemblage has high abundance and high diversity; traces are predominantly horizontal, small and include *Chondrites* and *Phycosiphon*; large *Rhizocorralium* are also abundant and *Paleophycus* are present	Marine; low-energy settings

Table 4.2. Facies associations in outcrops of the Lightjack Formation, Condren Sandstone and Hardman Formation

Formation	*Code*	*Facies association*[(1)]	*Major facies*[(2)]	*Minor facies*[(3)]	*Key features*	*Depositional setting*	*Outcrop locality where facies identified*
LIGHTJACK FORMATION	FA1	Shallow marine	Sh, Sr, St		Ferruginous and fossiliferous concretionary layers; *Skolithos* trace fossil assemblage including *Skolithos* and *Rosselia* traces	Marine: shallow, well oxygenated, moderate energy; alternation between upper and lower flow regimes shifting sandy substrates	Shore Range 1 Shore Range 2 Beefwood Park 1
	FA2	Transitional	Sh, Sr, St, Rt	Sp	High clay content; abundant root-bioturbated beds	Shallow water with consistent alternation between upper and lower flow regimes; generally lower energy setting; tidal flat – lagoonal	Shore Range 1 Shore Range 2 Millyit Range Christmas Creek
	FA3	Restricted shallow marine	Sr, St, Ss, Hp	Gm, Sc	Small-scale, channel-fill sequences; swaley–hummocky cross stratification; dislocated wave-ripple chains	Shallow marine: influenced by both waves and currents; fluctuation between high- and low-energy setting; exposed to episodic high-energy events, possibly storms; small- scale channel features also observed	Shore Range 1 Namalook 1
	FA4	Fluvio-deltaic	St, So, Sh,		Broad low-angle trough cross-stratification; opposing ripple cross-lamination; climbing ripples	Tidal: bidirectional current activity; rapid high-energy, shallow-water conditions alternating with shallow, lower flow regime conditions; no distinct marine indicators	Christmas Creek Millyit Range
CONDREN SANDSTONE	FA5	Fluvial: channel, channel margin and overbank flat	Sp, Sr, St	Gmm	Linguoid and wave ripples; channel-fill sequences; siltstone rip-up clasts	Alternating upper and lower flow regime conditions; 3D dune migration and local high-energy events	Millyit Range Condren Pinnacles
	FA6	High-energy fluvial	Stc	Gmc, Sh, Sr	Channel scours; rounded cobble lags and coarse sandstone; +1 m thick amalgamated trough cross-sets in coarse sandstone	Fluvial: relatively high energy; numerous major erosional and scouring events; no marine indicators	Durbai Creek
HARDMAN FORMATION	FA7	Shallow marine – middle shoreface	Ss, Hb		Hummocky–swaley cross bedding with unique monospecific *Skolithos*/*Rosselia* trace fossil assemblage	Marine, above storm wave base, alternating with lower energy, possibly below storm wave base or lagoonal	Millyit Range
	FA8	Shallow marine – lagoonal	Ba, Bb		Abundant highly diverse trace fossil assemblages dominated by horizontal traces	Marine: low energy, alternating between shallow, biologically favourable conditions and deeper conditions	Hicks Range Boundary Hill Condren Pinnacles
	FA9	Fluvial	St	Sh, Sr	Amalgamated trough cross-bedded sections; clay rip-up clasts; root traces	Fluvial: transitions gradationally from shallow marine	Hicks Range

NOTES: (1) Facies associations are shown in Figures 3.2 – 3.8 and discussed in the Report
(2) (3) Major and minor facies are defined in Table 4.1



The middle to late Permian Liveringa Group has been mapped in outcrop in the southeast of the Canning Basin and identified in the subsurface in the northwest. In outcrop, the Liveringa Group is subdivided into three formations: the basal Lightjack Formation, the middle Condren Sandstone, and the uppermost Hardman Formation. However, these formations are frequently not defined in the subsurface. This study develops a facies analysis of outcrop sections and applies it to the logs of nearby wells to define the Liveringa Group formations in the subsurface. Using this method, all three formations are defined in well logs in the southeast of the study area. Two units are defined in the subsurface in the northwest: the Hardman Formation and an amalgamated Lightjack Formation – Condren Sandstone unit. Facies associations indicate an overall regressive trend during deposition of the Lightjack Formation with the Condren Sandstone representing the point of maximum regression within the Liveringa Group. This was followed by a gradual return to shallow-marine conditions during deposition of the Hardman Formation.

Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

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