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Re-evaluation of the Mentelle Basin, a polyphase rifted margin basin, offshore south-west Australia: new insights from integrated regional seismic datasets

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Re-evaluation of the Mentelle Basin, a polyphase rifted margin basin

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Abstract

Vintage 2-D (two dimensional) seismic reflection surveys from the sparsely explored Mentelle Basin (western Australian margin) have been re-processed and integrated with recent high quality seismic survey, and stratigraphic borehole data. Interpretation
5 of these data sets allows the internal geometry of the Mentelle Basin fill and depositional history to be reanalysed with a greater degree of confidence. Basin stratigraphy can be subdivided into several seismically defined megasequences, separated by major unconformities related to both the Valanginian breakup between India-Madagascar and Australia-Antarctica, and tectonically-driven switches in deposition through the Al-
10 bian.

Resting on the Valanginian unconformity are several kilometre-scale mounded structures that formed during late Jurassic to early Cretaceous extension. These have previously been interpreted as volcanic edifices, although direct evidence of volcanic feeder systems is lacking. An alternative interpretation is that these features may be carbon-
15 ate build-ups. The latter interpretation carries significant climatic ramifications, since carbonate build-ups would have formed at high palaeolatitude, ~60° S.

Soon after breakup, initial subsidence resulted in a shallow marine environment and Barremian-Aptian silty-sandy mudstones were deposited. As subsidence continued, thick Albian ferruginous black clays were deposited. Internally, black clay megase-
20 quences show previously unresolved unconformities, onlapping and downlapping packages, which reflect a complex depositional, rifting and subsidence history, at odds with their previous interpretation as open marine sediments.

Southwestwards migration of the Kerguelen hotspot led to thermal contraction and subsidence to the present day water depth (~3000 m). This was accompanied by
25 Turonian-Santonian deposition of massive chalk beds, which are unconformably overlain by pelagic Palaeocene-Holocene sediments. This substantial unconformity is related to the diachronous breakup and onset of slow spreading between Australia and Antarctica, which may have led to the reactivation and inversion of basement faults, followed by rapid seafloor spreading from the middle Eocene to the present.

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1 Introduction

The Mentelle Basin is a recently discovered (Borissova, 2002), sparsely explored, deep water (200–4000 m) sedimentary basin that underlies the bathymetric Naturaliste Trough, located between the Naturaliste Plateau and the southern part of the West Australian shelf (Figs. 1 and 2). The basin was originally termed the "Naturaliste Trough" (Jongsma and Petkovic, 1977), but this term is now used solely for the bathymetric feature between the Yallingup Shelf and the Naturaliste Plateau (Borissova, 2002) (Fig. 2). Initial appraisals based on the S18 and "Petrel" seismic surveys map the Mentelle Basin as being slightly elliptical in shape, with minor and major axes ~200 km east-west and ~220 km north-south respectively, with an estimated 3 seconds (s) two-way travel time (TWT) (~3 km) of sedimentary fill in the main depocentre (Borissova, 2002).

A basement ridge in the southern part of the Naturaliste Plateau separates the Mentelle Basin from the Diamantina Fracture Zone to the south (Halpin et al., 2008) (Fig. 2), whereas in the north, the basin merges with the Perth Abyssal Plain. Preliminary interpretation of seismic and gravity data suggested that the Mentelle Basin was probably formed during Late Jurassic-Early Cretaceous rifting (Borissova, 2002).

In this study, we present the results of re-processing and interpretation of the older S18 and "Petrel" data sets combined with a more recent high-quality 2-D multi channel seismic data set. Interpretation of this expanded dataset allows an appraisal of the structural history of the Mentelle Basin with a greater degree of accuracy and certainty in comparison to previous studies, which were undertaken on a regional scale (Borissova, 2002; Bradshaw et al., 2003). In addition, we have provided insights paleoenvironemntal conditions prior to, during, and subsequent to Gondwana fragmentation in the Late Cretaceous.

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2 Geological setting

The western margin of Australia (Fig. 1) is the northern arm of a triple junction that formed during the final stages of Gondwana breakup (e.g. Powell et al., 1988; Royer and Coffin, 1992; Direen et al., 2008). The tectonic history of the Mentelle Basin

5   within this milieu is poorly defined (Borissova, 2002; Bradshaw et al., 2002), with basin history largely extrapolated from better studied areas to the north (e.g. the Perth Basin: Bradshaw et al., 2002), and south (e.g. Diamantina Fracture Zone (DZ), Fig. 1: Halpin et al., 2008; Beslier et al., 2004). After a polycyclic history of continental extension that commenced in the Permo-Carboniferous (Mutter et al., 1989; Metcalfe, 1996; Stagg

10 et al., 2004), Greater India began to break away from Australia–Antarctica in the Argo Abyssal Plain (AP), ~1500 km to the north of the Mentelle Basin, commencing in the latest Middle Jurassic (Callovian) (Markl, 1978; Mihut and Mueller, 1998). This rift propagated southwards through the Gascoyne, Cuvier and Perth margins during the Early Cretaceous producing a free plate boundary (Valanginian–Hauterivian) (Veevers

15 and Li, 1991; Song and Cawood, 2000).

The Argo AP – Wallaby-Zenith Fracture Zone rifted margin to the north, is volcanic in nature (Planke et al., 2000; Direen et al., 2008). South of the Houtman Sub-basin, this margin becomes more complex, stepping westward across the basement-controlled Harvey Transfer Zone (Bradshaw et al., 2003), into the Mentelle Basin, and the south-

20 ern part of the Perth Basin. The Vlaming Sub-basin, is separated from the true margin by the crystalline basement high of the Leeuwin Complex, and the Yallingup Shelf (Fig. 2).

This Valanginian Australian–Antarctic conjugate rifted margin with India then stepped westward again to the western side of the Naturaliste Plateau – Bruce Rise, and

25 originally continued into the Enderby Basin, where the oldest true seafloor spreading anomalies are M9 (133 Ma – Hauterivian: timescale of Gradstein et al., 2004) (Stagg et al., 2004, 2005, 2006; Gaina et al., 2007), and are associated with seaward dipping reflector sequences (indicative of a volcanic margin) from the western flank of Bruce

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Rise to the Princess Elizabeth Trough (Stagg et al., 2006). These latter features pre-date Kerguelen Plateau volcanism, and are associated with anomaly "M4" (= M5 of Ogg and Smith, 2004, ~130 Ma: Barremian).

The character of the Perth margin to the north of the Mentelle Basin is not well constrained (Bradshaw et al., 2003), but is characterized by distribution of on and off-shore volcanic rocks of the Bunbury Basalt (Frey et al., 1996; Coffin et al., 2002; Ingle et al., 2004; Gorter and Deighton, 2002) and also considered to be a volcanic mar-gin (e.g. Menzies et al., 2002). The Bunbury Basalt contains two geochemical age groupings: the older "Casuarina type" is 132.2 ± 0.3 Ma (Hauterivian), and the younger "Gosselin type" is 123 Ma (Aptian) (Frey et al., 1996). The Gosselin type has been cor-related with the Rajmahal Traps of eastern India (Coffin et al., 2002), which are dated at 118.1 ± 0.3 Ma (Kent et al., 1997, 2002), and are thought to be linked to mantle plume activity associated with the formation of the Kerguelen Plateau (Kent et al., 1997, 2002; Coffin et al., 2002).

From the Middle Jurassic, during rifting and breakup of Greater India from Australia–Antarctica, the proto-Southern Rift System (SRS) (Stagg et al., 1990) situated south and east of the Mentelle Basin was undergoing extension. Syn-rift sequences were deposited in the SRS at this time (Totterdell et al., 2000), and on the Naturaliste Plateau (Burkle, 1967; Borissova, 2002).

At around 95 Ma (Cenomanian) (Duncan, 2002; Coffin et al., 2002) there was mafic volcanism and the onset of rifting of the Broken Ridge microcontinent from the Ker-guelen Plateau, west of the Naturaliste Plateau (Royer and Coffin, 1992; Tikku and Cande, 1999, 2000). Final breakup between these features appears to have taken place at C34 time (Coniacian-Santonian: ~85 Ma) (Tikku and Cande, 2000; Tikku and Direen, 2008). This ultimately resulted in the gradual propagation of the Southeast Indian Ridge System (e.g. Royer and Coffin, 1992; Gaina et al., 2003, 2007) to the southeast, forming a new magma poor margin and a continent ocean transition zone in the Diamantina Zone south of the Mentelle Basin (Direen et al., 2008; Beslier et al., 2004), younging to the east (Tikku and Direen, 2008).

In summary, the Mentelle Basin is a rifted continental margin basin, located at the southern end of the Hauterivian-Barremian volcanic margin formed between India and Australia-Antarctica. To the south, the Mentelle Basin is cross-cut by the younger Turonian-Maastrichtian magma poor margin formed between Australia and Antarctica.

3 Seismic data

3.1 Exploration history

The earliest geophysical data recorded in the vicinity of the Mentelle Basin were magnetic and seismic refraction profiles acquired during a regional survey of the Perth Basin (Hawkins et al., 1965). Knowledge of the sedimentary and basement geometry was vastly improved by USNS Eltanin cruises (e.g. Hayes et al., 1975). These early acoustic profiles across the Naturaliste Plateau showed a thin acoustically transparent sedimentary cover above the acoustic basement defined by a rough, strongly reflecting surface (Petkovic, 1975). The first dense seismic program was the 1972 regional Geoscience Australia Continental Margins Survey 18. This survey consisted of a continuous set of seismic profiles, 8 orientated north-south and a further 9 aligned east-west (Fig. 2), supplemented with continuous gravity, magnetic and bathymetric data. In the following year the Shell Petrel Development Survey acquired four long profiles in approximately north-south orientations across the Naturaliste Plateau and Mentelle Basin. These profiles were intersected by two east-west trending profiles that terminated on the Yallingup Shelf, and are a subset of the Petrel survey that comprised a large series of overlapping profiles around the western and southern Australian margins. No further seismic data was collected until 1997, when a single deep (16 s TWT) profile was undertaken as part of Geoscience Australia Survey 187, shot across the Diamantina Zone up on to the Naturaliste Plateau (Fig. 2).

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4   Methodology

4.1   Seismic data

Geoscience Australia survey S280 was acquired in 2004 using a tuned 4900 in^3 airgun array energy source and a 636 channel 7950 m seismic streamer digital recording sys-
tem. Profiles S280-401 and S280-501 extended on to the Western Australian Shelf, with profile S280-401 crossing the crystalline Yallingup Shelf into the heavily faulted Vlaming Sub-basin. Profiles pass close to borehole DSDP-258 on the eastern edge of the Naturaliste Plateau, providing an important geological correlation tie-point for the final processed seismic stacked sections. In 2009, Geoscience Australia survey S310 was acquired, and was integrated with the older S280, S18 and Petrel surveys to reappraise the stratigraphy and history of the Mentelle Basin (Fig. 2). All the seismic profiles shown are displayed in s TWT.

4.2   Processing

Raw shot records for the S18, "Petrel" and S280 seismic reflection surveys (Fig. 2) were reprocessed. We present the processing sequence applied to the high-quality S280 survey that yielded high resolution images of the sub-surface geology for inter-pretation (Fig. 3). Older vintage S18 and Petrel surveys gave poorer, but still signif-icantly improved final time-migrated stacked sections, and were used for closing the loops of interpreted horizons.

   The S280 survey was acquired with a 4900 in^3 airgun array, and a digital recording streamer yielding a nominal fold of coverage of 80 with a 6.25 m common midpoint spacing image. This acquisition set-up produced a high-quality dataset, however the raw shots had to be conditioned with a 5 Hz @ 48 dB/octave low-cut filter to curtail spurious low-frequency internal instrumentation noise and random swell noise bursts. Using a minimum of processing steps, the objective was to maximise the temporal resolution of the thick Mentelle Basin sedimentary sequence.

Two non-standard zero-phase filters were designed to remove the secondary source bubble pulse and frequency limiting ghost notches from the seismic data. In a stacked section, the secondary source bubble pulse is exhibited as a broad event sub-parallel to the seabed reflection cross-cutting primary geological reflections, and potentially can be misinterpreted as a methane hydrate layer. The source debubble filter was applied to all shot records early in the processing sequence before demultiple, whereas the deghost filter was convolved with un-migrated post-stack data producing a flat amplitude spectrum of up to 4 octaves.

Deep water environment long-path multiples, though not a major artefact, were muted in Radon space (Russell et al., 1990). The long-path multiple suppression was aided by the power of the stack process and an inside trace mute on common midpoint gathers. Radon space demultiple also countered short-path multiples related to the high-amplitude Valanginian breakup unconformity. Where S280 profiles passed across the shallow water West Australian Shelf, closely spaced water bottom generated reverberations were suppressed with a surface related multiple elimination algorithm (Verschuur et al., 1992). Pre-stack reflection point smear was reduced by a Fourier domain implementation of dip moveout (Hale, 1984). The optimum P-wave stacking velocity field was interactively picked at 1 km intervals post-dip moveout.

Post-stack time and spatially varying bandpass filtering suppressed unwanted spurious low and high-frequency noise, whereas spherical divergence and absorption wave energy loss was compensated by applying a smooth inverse amplitude decay curve along the length of each profile. The Kirchhoff time-migration algorithm was well suited to smooth Mentelle Basin P-wave stacking velocity field (Yilmaz, 2001). Prior to the time-migration process FX deconvolution (Canales, 1984) was required to prevent the relocation of out-of-plane diffractions destroying the continuity of the shallow geology.

The Shell Petrel Development Survey was acquired in 1973 with a 1090 in^3 airgun array and a digital recording streamer, yielding a nominal fold of coverage of 24 with a 50 m common midpoint spacing. The processing sequence was the same as that developed for the S280 survey, although the parameters were tailored to suit the lower

data quality and narrower frequency bandwidth. The short 2400 m streamer favoured the use of the Karhunen-Loève transform (Jones and Levy, 1987) to suppress multiple energy, rather than Radon demultiple. To aid the geological interpretation, the Petrel final time migrated sections were amplitude, phase and time matched to the S280 survey (Bishop and Nunns, 1994).

The Geoscience Australia Continental Margins Survey 18 raw 6-channel shot records dataset are of very low quality. Filters were designed to compress the complex 100 ms long 12 kJ sparker energy source wavelet, additional temporal resolution improvement was provided by post-stack zero-phase spiking deconvolution. Sophisticated demultiple or dip moveout processing was not applied to the S18 dataset.

5   Seismic observations

The newly processed seismic data reveal at least 6.6 s TWT, and up to a maximum of 7.8 s TWT of sedimentary column within the Mentelle Basin (Figs. 4 and 5). Major unconformities and seismic packages through the section that can be tied to the DSDP-258 borehole, together with regional variations in seismic character, have allowed us to divide the stratigraphy into major seismically derived tectonostratigraphic megasequences (Figs. 4 and 5). We describe each of these megasequences and major unconformities below with regard to the stratigraphy and geological history of the Mentelle Basin from youngest to oldest respectively.

5.1   Neogene (miocene-quaternary) megasequence

The youngest sequence in the Mentelle Basin comprises low-amplitude, thin, seafloor parallel reflections (Figs. 4 and 5). Seismic data analysis corroborates the borehole data that Neogene beds are regionally unconformable with underlying Cretaceous sediments. Neogene sediments are associated with deepwater carbonate oozes and pelagic sedimentation across the Mentelle Basin region. This youngest megasequence typically forms a thin veneer across the basin reaching a maximum thickness of 0.5 s within the main depocentre.

5.2 Miocene unconformity

The DSDP-258 borehole records a substantial hiatus of Miocene age that separates Neogene from Eocene sediments. The Miocene unconformity appears as an undulating surface on seismic data, at which the underlying sub-horizontal Turonian-Santonian
5 chalk beds subtly terminate. Directly eastward of the DSDP-258 borehole the Miocene unconformity is expressed as a sharp down-cutting reflection, with abrupt reflection terminations of Turonian-Santonian age chalk beds apparent. This unconformity then becomes seismically indistinguishable moving eastward across the Mentelle Basin, appearing conformable to underlying reflections, and hence is difficult to pick, particularly
10 in the low-resolution old vintage S18 and Petrel surveys. The geological time difference across this unconformity varies, reaching a maximum of ∼10 My in the central area of the Mentelle Basin where thin Oligocene reflections terminate against the Miocene unconformity (Fig. 6).

5.3 Palaeogene megasequence

15 Adjacent to the slope of the Yallingup Shelf a ∼350 milliseconds (ms) TWT thick sub-basin, consisting of Oligocene and Eocene sediments is seen to onlap onto the underlying Cretaceous megasequence (Fig. 6). Within this sub-basin, Eocene sediments are represented by a series of dipping reflections, with a decreasing easterly dip, whose upper surfaces abruptly terminate at the Miocene unconformity. This sediment pack-
20 age is bound at its base by the late Cretaceous Megasequence. Close to the base of this megasequence is a major unconformity, marked by downlapping reflection terminations, which is interpreted to be Eocene in age. The Eocene unconformity is difficult to trace, appearing to trend parallel to bedding in the west, and is diffuse towards the east, terminating upon the Western Australian shelf. Palaeocene sediments are re-
25 ported in borehole DSDP-264 (Fig. 3), and form part of a pelagic package up to 4 s TWT thick over the Naturaliste Plateau (Figs. 4 and 5). Internal higher-amplitude reflections within this section may represent chert bands. These beds thin out rapidly at the southern scarp slope and more gradually on the gentle northern slope. In general,

sub-basins aside, the Palaeogene megasequence is characteristically thin across the Western Australian slope and shelf, draped unconformably on the underlying Cretaceous megasequence.

5.4 Late Cretaceous-Eocene megasequences

In the vicinity of the DSDP-258 borehole situated at ~3.5 s TWT are a couplet of high amplitude reflection combinations which are identified as Turonian-Santonian chalk beds from the DSPD-258 borehole (Figs. 3 and 4). Regionally, these beds are relatively thin, ranging from close to zero in thickness to a maximum thickness of ~1.5 s TWT. Within these chalk beds high amplitude reflection combinations are evident. The high-amplitude reflection doublet at just over 4 s TWT (Figs. 3 and 4) coincides with an increase in P-wave velocity, which is interpreted to represent chert beds logged at 220 m in borehole DSDP-258 (Luyendyk and Davies, 1974). Strong high amplitude reflection events at 3.9 s and 3.8 s TWT may also represent chert bands. Within the central Mentelle Basin the upper boundary of the Albian black clays is, in places, unconformable with overlying Palaeogene-Neogene sediments. The contact is marked by reflections downlapping onto a sharp high-amplitude event whose acoustic impedance contrast is caused by Albian black clays and Turonian-Santonian chalk beds.

Immediately underlying the high amplitude chert and chalk bands are a series of low amplitude parallel reflections. The contact between the Turonian-Santonian chalk and underlying black clays, dated Albian in age, is seismically diffuse. Close to borehole DSDP-258 the contact is represented by a 30 m gradational interface resulting in this boundary being seismically indistinct (Fig. 4). In the immediate vicinity of the DSDP-258 borehole the Albian black clays themselves posses very little lithologic variation (Luyandyk and Davies, 1974). In contrast to the upper contact, a large P-wave velocity disparity between the Albian black clays and underlying 5 m thick bed of glauconitic sand ensures that the base Albian black clay is represented by a pronounced high amplitude reflection situated at ~4.3 s TWT, which can be traced across the entire Mentelle Basin (Figs. 4, 5 and 7).

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The basal sedimentary sequence intersected by borehole DSDP-258 is dated as Barremian-Aptian in age. On seismic data this basal sequence is represented by washed-out sub-parallel seismic events of variable amplitudes (Figs. 3 and 4). DSDP-258 borehole data indicate that this sequence is composed of interbedded silty sandy mudstones (Fig. 3). This package thickens eastward to ~1 s TWT at the base of the main Mentelle Basin depocentre (Fig. 6). This megasequence can be correlated to adjacent contemporaneous sediments: a Cretaceous shale logged in the Vlaming Sub-Basin (Fig. 5, Sugarloaf-1 borehole). The Barremian-Aptian sequence pinches out on the eastern slopes of the Naturaliste Plateau, although equivalent age deposits are interpreted to be in small discrete rift basins present on the Naturaliste Plateau (Borissova, 2002). These deposits probably have a different lithology, since they are expressed seismically by a stronger, more defined reflection character when compared to Barremian-Aptian sediments imaged around DSDP-258 borehole (cf. Figs. 4 and 6).

The internal architecture of the Cretaceous megasequences is not as homogeneous as it appears in the stratigraphy intersected by the DSDP-258 borehole, or on seismic profiles adjacent to it. The Cretaceous megasequences all wedge and thicken eastwards within the central Mentelle Basin depocentre, and display considerable heterogeneity in their internal architecture as numerous unconformities, downlapping and onlapping reflection terminations are imaged. Where the combined thicknesses of the Cretaceous megasequences reach a maximum thickness of 900 m s TWT, within the central depocentre (Fig. 8), a thick sequence of organic rich black clays has been deposited, which correlates with Albian black marine mudstones within the DSDP-258 borehole.

Overlying the base Albian black clay reflection in the central Mentelle Basin is a high amplitude reflection combination, which dramatically cuts up-section over the Western Australian shelf, and typically separates underlying high amplitude reflections from overlying eastward dipping, poorly resolved seismic reflections (Figs. 6 and 9). These eastward dipping reflections can be subdivided into three packages that onlap, downlap and terminate against the high amplitude reflection combination. This marks the

high amplitude reflection combination as a major unconformity within the Albian clay, which does not coincide with the correlated base Albian clay interval. From herein this unconformity will be referred to as the "intra black clay unconformity" based upon its location within the stratigraphy. This unconformity pinches-out upon the Western Australian shelf (Fig. 9).

The late Cretaceous megasequence in the central Mentelle Basin onlaps and terminates against a distinct, high amplitude reflection that continues up and over the Yallingup Shelf (Fig. 6). This megasequence is bound by both the top reflection defining the underlying downlapping megasequence and the intra black clay unconformity. It reaches a maximum thickness of 0.5 s TWT in the central depocentre and thins and pinches out over the Western Australian shelf. Reflections situated internally within this megasequence terminate against the top reflection of the underlying downlapping megasequence, which locally, also marks this top defining reflection as an unconformity within the central Mentelle Basin.

The three downlapping Cretaceous megasequences thin westward, with reflections clearly terminating upon the intra black clay unconformity. Cumulatively these three downlapping megasequences reach a maximum thickness of 0.8 s TWT in the main depocentre (Fig. 8). Here, the internal seismic character of the Albian black clays has a staccato appearance, reflection events are discontinuous and offset vertically on the millisecond scale at frequent intervals laterally (Fig. 6). These small scale features are the 2-D seismic representation of three dimensional (3-D) polygonal faults that are common in thick deposits of fine grained materials (e.g. Cartwright and Dewhurst, 1998).

Eastwards, the contact between the Albian black clays are conformable with underlying Barremian-Aptian sediments before pinching out upon the Western Australian shelf (Figs. 4 and 5). However, small wedges of Albian age sediments are interpreted to infill remnants of the small rift basins on the Naturaliste Plateau (Fig. 5).

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5.5 Valanginian breakup unconformity

A high-amplitude reflection situated at ∼4.5 s TWT (Figs. 4 and 5) is observable laterally across the Mentelle Basin (Fig. 10). This reflection displays numerous breaks in lateral continuity and is vertically offset indicating the presence of normal faults. This exten-

5   sive horizon is interpreted as a Valanginian unconformity associated with the breakup between India-Madagascar and Australia-Antarctica (Borissova, 2002; Direen et al., 2008). This unconformity is thought to constitute a layer of volcanics, an interpretation that is reinforced from P-wave velocity analysis. P-waves travel typically through the Neogene-Paleogene pelagic deposits, Turonian-Santonian chalk beds and Albian

10   black clays at ∼2000 m s^{-1}, and through the Barremian-Aptian silty sandy mudstones at ∼2500 m s^{-1} (Fig. 11). The base of the Barremian-Aptian silty sandy mudstones is marked by a dramatic increase in P-wave interval to ∼4000 m s^{-1}, which is interpreted to reflect a hard crystalline lithology. Isolated high amplitude reflections that curl up at the edges often overlie the Valanginian unconformity.

15   Across the central Mentelle Basin the Valanginian unconformity surface is overlain by several kilometre scale moundal structures (Fig. 12). These mounds have various shapes, ranging from triangular/conical, to more laterally extensive square or convex topped platforms, with the larger structures generating seismic shadows. All of these structures display a high-amplitude leading edge, implying a hard compact lithology

20   compared to the overlying drape of Cretaceous sediments, and a "zig-zag christmas tree" structure (Fig. 12), which is interpreted to reflect the interdigitation of material forming between the mounds with adjacent Barremian-Aptian clastics. Further evidence that these mounds are composed of a hard lithology is given recorded by the excessive differential compaction systems evident within overlying sediments, which

25   in places has led to the development of fine-scale fault systems propagating upwards through the Albian black clays.

5.6 Jurassic megasequence

A series of sub-parallel reflections are imaged below the high-amplitude Valanginian break-up unconformity (Figs. 4 and 5). Seismic resolution below the Valanginian unconformity drops rapidly as a consequence of the overlying volcanic deposits. This seismic megasequence has a thickness of ~0.8 s TWT and displays numerous breaks in lateral reflection continuity. Reflections are vertically offset along high angle discontinuities that indicate the presence of normal fault traces. The upper tip lines of faults appear to terminate at the Valanginian breakup unconformity. These vertical reflection discontinuities resemble the geometry of rotated fault blocks. Jurassic sediment packages wedge and thicken into the hanging walls of fault blocks and are interpreted to be deposited during fault growth, coeval with Jurassic syn-rift extensional structures. Overlying contacts appear erosional where they terminate against the Valanginian unconformity. This megasequence is laterally discontinuous throughout the Mentelle Basin, highly rotated and primarily situated within major depocentres. We interpret this Jurassic section to be contemporaneous with the Perth Basin fluvial sediments, the Eneabba Formation through to the cyclical muddy sandstone beds of the Yaragadee Formation (Iasky, 1993; Song and Cawood, 2000).

5.7 Permian megasequence

The Jurassic syn-rift is underlain by a much thicker megasequence that exhibits the same planar laminated seismic character, but is composed of dipping events that are discernable in the seismic section locally to ~8 s TWT. The boundary between these two megasequences is primarily identified by a significant increase in P-wave interval velocity from ~4000 m s^{-1} to ~6000 m s^{-1} (Fig. 11), whereas on seismic data the contact between interpreted Jurassic and Permian sediment is broadly undistinguishable, and hence the contact is approximated by a dashed line on the seismic sections shown (Figs. 4 and 5). The significant increase in P-wave interval velocity (Fig. 11) implies a hard, compacted lithology. This basal megasequence is also laterally discontinuous

throughout the Mentelle Basin with Permian reflections only imaged within the major depocentre and fault bound grabens (Figs. 4 and 5). Further to the east, on the western flank of the crystalline Yallingup Shelf, steeply-dipping reflections are interpreted as Permian sedimentary rocks deposited in fault-rotated, and now peneplaned

5 small internal basins. Other areas of the Mentelle Basin may also be underlain by older Permo-Triassic deposits; however these are mostly beyond the depth of seismic resolution with the data available to this study. Rotated reflections are imaged adjacent to hangingwalls of basement fault blocks where the megasequence thickens. This thickening is interpreted to represent growth strata, identifying that deposition was

10 synchronous with rifting, indicative of the increase in accommodation created in the hanging walls of normal faults. As intervals at this depth are generally dominated by seismic noise, where Permian age reflections are interpreted the contact with underlying Permo-Triassic deposits and/or the crystalline basement is approximated where coherent reflections are absent.

15 6 Interpretation

6.1 Structural reappraisal of the Mentelle Basin

Improved seismic resolution and accurate interpretation of reflection megasequences has enabled us to reconstruct with increased accuracy the structural history of the Mentelle Basin. Deep seated Jurassic and Permian megasequences are coinci-

20 dent with an early period of rifting and basin extension, wedging growth geometries show that Jurassic and Permian deposition was syn-kinematic with respect to fault growth. Erosional contacts between Permian and Jurassic megasequences, and the Valanginian unconformity suggests subareal exposure of the India-Australian margin before break-up began.

25 The increase in P-wave velocity across the Valanginian unconformity is consistent with the occurrence of an igneous lithology, likely to be basaltic in composition. The

Valanginian unconformity is related to major rifting and volcanism involving the separation of India-Madagascar and Australia-Antarctica. The isolated high amplitude reflections that lie above the Valanginian unconformity displaying "smiles" are interpreted to be sills associated with breakup volcanism (Direen et al., 2008). The thickness of the basalt is assumed to be relatively thin, based on the fact that underling Permian and Jurassic megasequences are imaged, and thick basaltic flows are known to degenerate seismic signal dramatically. Experience from the north-west Atlantic shows that hard compact basaltic horizons are difficult to seismically penetrate without special seismic acquisition parameters (Maresh and White, 2005) and/or special processing (Gallagher and Dromgoole, 2008).

It is conceivable that the high-amplitude kilometre scale structures imaged upon the Valanginian breakup unconformity surface (Fig. 12) are of volcanic origin, contemporaneous with the Casuarina-type Bunbury Basalts, which have been dated at 132 Ma (Hauterivian) (Frey et al., 1996), 4 to 8 m.y. younger than the Valanginian breakup age. Similar structures are observed in seismic data from the northern Perth Basin and have been interpreted as volcanic cinder cones (Gorter and Deighton, 2002). Degradation of the seismic signal occurs in places beneath the kilometre scale structures, however no volcanic feeder systems (dykes, climbing sills) (e.g. Direen et al., 2008) have been imaged. Coherent layer parallel reflections are imaged beneath some of these mounds, suggesting that such igneous intrusive features may be absent, although we caution that at the scale of observation, and in the limitations of the signal to noise ratio that such features may be essentially undetectable, especially if they are sub-vertical.

Carbonate build-ups have similar seismological characteristics as basalts, and so offer an alternative interpretation for the kilometre scale pinnacle and flat topped structures (Fig. 12). 3-D seismic data from the Finnmark Platform has imaged sinuous, kilometre-wide Permo-Carboniferous reefs (Rafaelsen et al., 2008) and infilled atoll-like structures very similar in shape to the flat top structures imaged in the Mentelle Basin. Additionally the characteristic "christmas tree" interdigitation between carbonate build-up and clastic apron may also support a carbonate origin for these features,

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although is not unequivocal. Ongoing Valanginian rift related subsidence may have led to a marine transgression, in which large reefal structures could have flourished in a shallow, sediment-starved enclosed gulf.

Any reef building organisms existing in these waters would have been extinguished by the increasing turbidity as sediment flowed in westwards from the land. Proximal to the sediment supply source, the deposits are probably coarse grained relative to the distal silty sandy mudstones logged at the base of borehole DSDP-258, and form a complex unconformity surface produced by overlapping prograding fans and channel-cut fills (Fig. 10). These clastic deposits reach a maximum thickness of $\sim$1000 m in the $\sim$50 km diameter proto-Mentelle Basin, which indicates more rapid subsidence during the Barremian and Aptian than in the surrounding area (Fig. 8). Beyond borehole DSDP-258, this sediment package pinches out on the eastern flanks of the Naturaliste Plateau, suggesting the latter feature may have been sub-aerial throughout the Barremian and Aptian.

The post break-up phase is represented by the thick succession of Cretaceous black clays. A critical observation is the presence of the downlapping and onlapping sequences, and major unconformities, which define the internal architecture of Albian black clay megasequences in the central Mentelle Basin. Previously, the Albian clays were interpreted to have been deposited in a thermally subsiding, open marine environment (Borissova, 2002), but the seismic megasequences imaged clearly show that basin history was more complex.

The Aptian-Barremian megasequence saw a change in deposition to open marine with the deposition of silty mudstones. Through the Albian, the Mentelle Basin was undergoing extension and subsidence as a consequence of the underlying the Kerguelen hotspot. The Kerguelen hotspot was particularly active throughout the Albian with an estimated magma flux of $0.9\,km^3\,yr^{-1}$ (Coffin et al., 2002) which rapidly built-up a massive basaltic platform. Heat flux from the Kerguelen hotspot is a possible cause for the thin continental crust in the vicinity of the Mentelle Basin as predicted by Direen et al. (2008). By the time of maximum magma output, plate motion resulted in

the Kerguelen hotspot moving westwards relative to the Mentelle Basin leading to thermal relaxation induced subsidence creating the central depocentre. Sediment input initially began from the east, with ferruginous source material eroded from the Bunbury Basalts, as determined by geochemical analysis (Luyendyk and Davies, 1974).

5 The Aptian-Barremian megasequence is relatively thin and its upper surface is characterised by the intra black clay unconformity. This unconformity reflects a distinct change from open marine conditions and represents either: (1) a brief lowstand event which led to an influx of coarse grained turbiditic material into the basin; or (2) margin flexure, as a consequence of thermal subsidence and/or sediment loading, which could have

10 generated turbidity flows in shelfal regions if accommodation was low.

Megasequences overlying the intra shale unconformity both downlap and onlap upon the intra black clay unconformity and stratigraphically pinch-out over the Western Australian Shelf (Figs. 4, 5 and 6). This implies that a period of rapid subsidence followed and a return to open marine depositional conditions occurred. Onlap against the in-

15 tra shale unconformity displayed by the Late Cretaceous megasequences is likely to represent basin flexure, and/or a rapid episode of subsidence, which was synchronous with deposition.

The lack of any Albian black clays on the Naturaliste Plateau suggests that the plateau remained a structural high relative to the rapidly infilling Mentelle Basin dur-

20 ing the Albian, as was the Western Australian Shelf.

Throughout the Cenomanian, the region rapidly subsided to the present water depth of ~3000 m. This event is recorded in the stratigraphy in borehole DSDP-258 as a 30 m transition zone from black clays to chalk beds (Fig. 3). It is hypothesised that rapid subsidence was caused by a loss of thermal buoyancy as the Kerguelen hotspot

25 continued to move southwestwards (Weis et al., 2002).

The regional Eocene unconformity represents the breakup between Australia and Antarctica, an event that was highly diachronous (Tikku and Direen, 2008). South of the Mentelle Basin, breakup appears to have started prior to ~95 Ma (Beslier et al., 2004), and on the southern flank of the Naturaliste Plateau is recorded as a hiatus

between Palaeocene-Eocene deposits and underlying Turonian-Santonian chalk beds (Fig. 6) as detailed near borehole DSDP-264 (Fig. 3).

A later tectonic event disturbed the Mentelle Basin and surrounding region more dramatically. Mid Eocene magnetic anomalies present in the oceanic crust south of the east-west orientated 250 km wide Diamantina Zone (Tikku and Cande, 1999) correspond to the separation of the Diamantina Zone and the Labuan Basin, coinciding with the onset of fast spreading between Australia and Antarctica (Cande and Mutter, 1982), and the start of rapid northward motion of Greater India (Royer and Coffin, 1992). The Mid Eocene fast spreading event is interpreted to have tilted the Mentelle Basin region to the north. Tilting also appears to have reactivated some basement faults, including those controlling the main depocentre within the Mentelle Basin. Figure 5 shows apparent inversion of a basement fault block where Jurassic sediments are in contact with Albian age sediments.

Subsequent to the establishment of the Eocene fast spreading, Australia's southern margin became a stable trailing margin (Totterdell et al., 2000). Miocene to Holocene deposits form a thin (200 m s TWT) veneer across the Mentelle Basin and Naturaliste Plateau, and are interpreted to have been deposited on the stable trailing margin.

7 Discussion

7.1 Climatic implications

Geological records show that the Jurassic through to the Cretaceous was an exotic world compared to the present day. Tropical sea surface temperatures in the late Albian to Turonian may have reached 35 °C (Wilson et al., 2002), high-latitude sea surface temperatures were possibly in excess of 20 °C (Huber et al., 1995). Atmospheric CO_2 concentrations are thought to have been greater than 4000 ppm (Bice and Norris, 2002) approximately 10 times the present day CO_2 level. However, the existence of substantial carbonate production at high palaeo latitude ~60° S would provide key

insights into local oceanographic conditions during rifting. Climate modelling predicts temperatures of ~30 °C in the interior of the Australian-Antarctic land mass during the Early Cretaceous winter months (Fluteau et al., 2007). The high latitude Albian section within the Mentelle Basin may record such cycles, but this remains to be tested more
5   fully.

8   Conclusions

Integration of new and vintage seismic datasets from the Mentelle Basin provides new insights into the structural evolution of this poorly known and underexplored basin, and has revealed hitherto unknown tectonostratigraphic features. Coherent seismically re-
10 solvable reflections forming the basal megasequences are nested Jurassic–Lower Cretaceous and Permian rift basins. Truncating these meagasequences is a major regional angular unconformity, the Valanginian break-up unconformity, which is overlain by constructional mounds that may be carbonate reefs, as opposed to a more conventional interpretation as volcanic features.
15   Above the Valanginian unconformity lie a younger series of tectonostratigraphic sequences separated by major unconformities. A thick sequence of black clays shows evidence of a significant, but short lived lowstand event before a return to open marine conditions. Black clay deposition reflects the thermal contraction of the rifted margin basin, punctuated by thermal thinning events due to the presence of the Kerguelen
20 plume; breakup in the Southern Rift System to the south; and the onset of mid Eocene fast spreading in the Australian-Antarctic Basin. The geological architecture of the Mentelle Basin was determined by this complex rifting sequence and proximity to the migrating Kerguelen hotspot.
        The presence of substantial Cretaceous carbonate buildups at high palaeolatitude,
25 if proven, would also provide valuable data on local oceanographic conditions during and subsequent to continental breakup.

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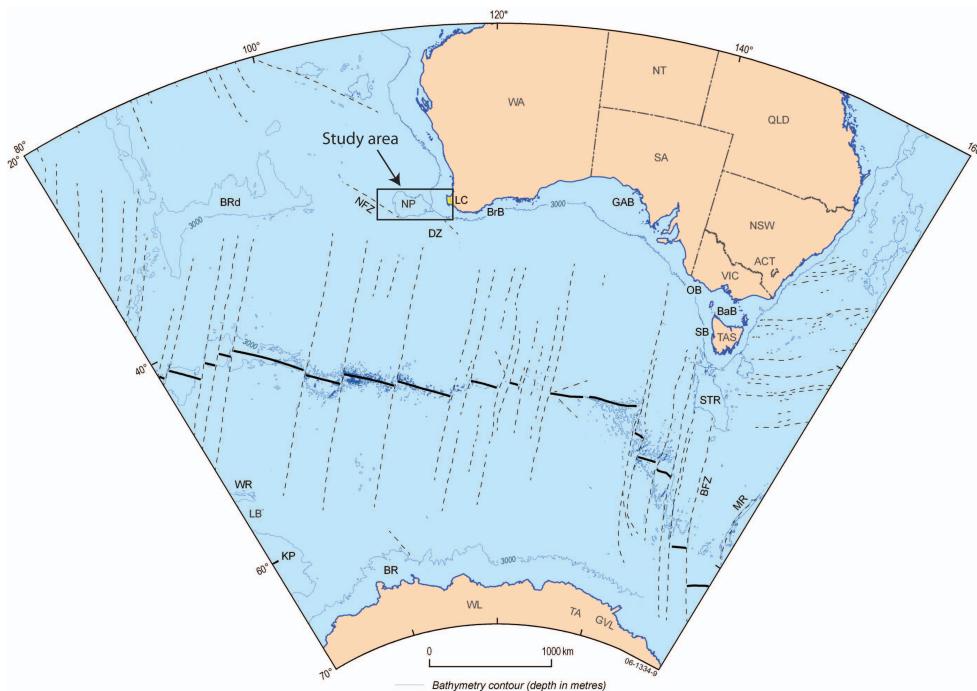
Fig. 1. Regional structural elements map of the Western Australian margin displaying the location of structural features that have led to the development of the Mentelle Basin. BRd = Broken Ridge; BR = Bruce Rise; DZ = Diamantina Zone; NP = Naturaliste Plateau; NFZ = Naturaliste Fracture Zone; LC = Leeuwin Complex; BrB = Bremer Basin; GAB = Great Australian Bight; GC = Gawler Craton; OB = Otway Basin; BaB = Bass Basin; SB = Sorell Basin; STR = South Tasman Rise; BFZ = Balleny Fracture Zone; MR = Macquarie Ridge; WR = Williams Ridge; LB = Labuan Basin; KP = (southern) Kerguelen Plateau; WL = Wilkes Land; TA = Terre Adélie; GVL = George V Land. WA = Western Australia; NT = Northern Territory; SA = South Australia; QLD = Queensland; NSW = New South Wales; ACT = Australian Capital Territory; VIC = Victoria; TAS = Tasmania (after Direen et al., 2010).

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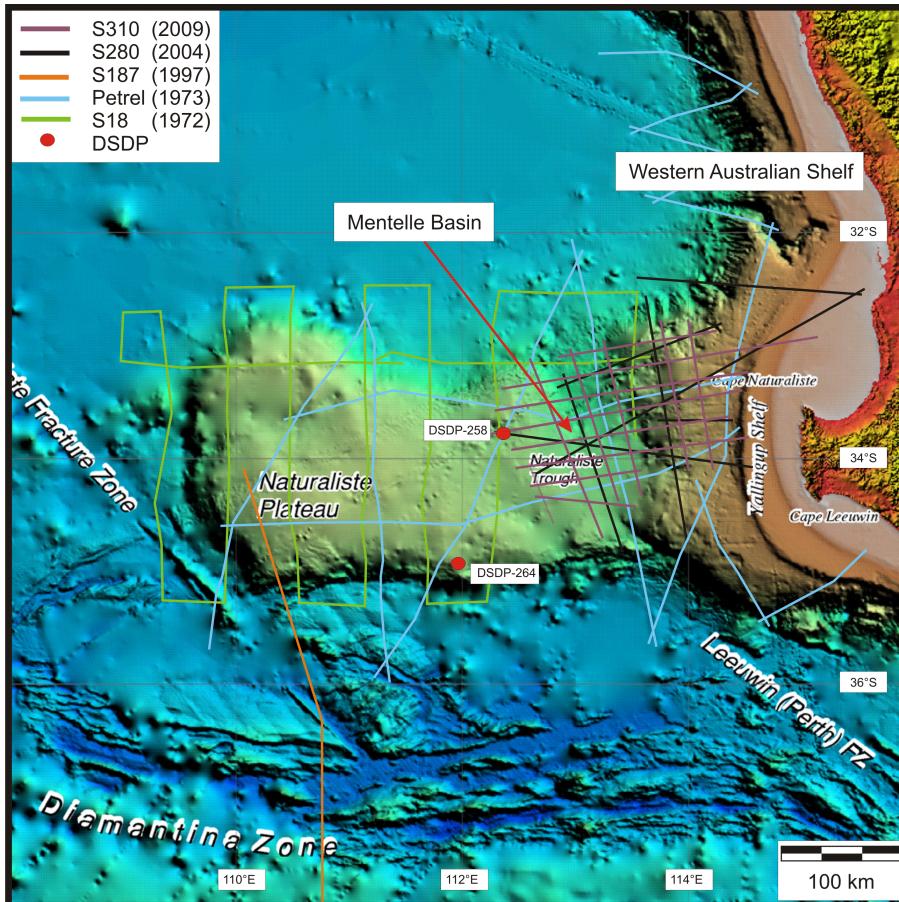
Fig. 2. Bathymetric map of the Mentelle Basin region situated offshore Cape Leeuwin. The positions of the 2-D seismic surveys and seismic lines used together with borehole locations are shown (Modified from Borissova, 2002).
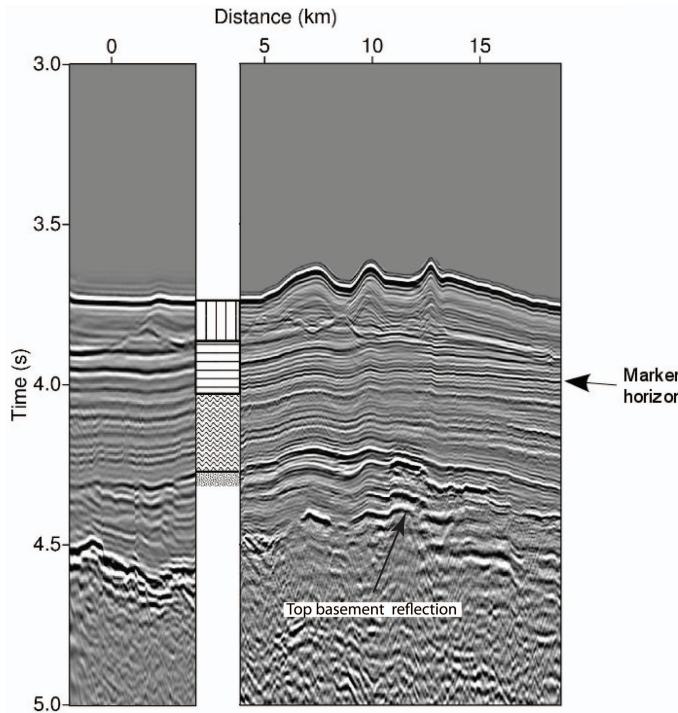
Fig. 3. DSDP-258 borehole data tied to the S280-501 seismic data. The seismic profile to the left of the borehole represents the original data quality before reprocessing. The seismic profile to the right of the borehole represents the improved data quality after reprocessing. The reflection doublet situated at 4 s TWT is not resolved in the original data, after reprocessing this doublet is now a prominent basin wide marker. Within the lithological interpretation vertical hatching represents 114 m of Miocene deepwater carbonates and oozes; horizontal hatching 171 m of limestones and chalks interdispersed with chert bands; wavy hatching Cretaceous black shale and; the basal stippled region represents some 11 m of Lower Cretaceous glauconitic sands penetrated (after Sargent et al., 2011).
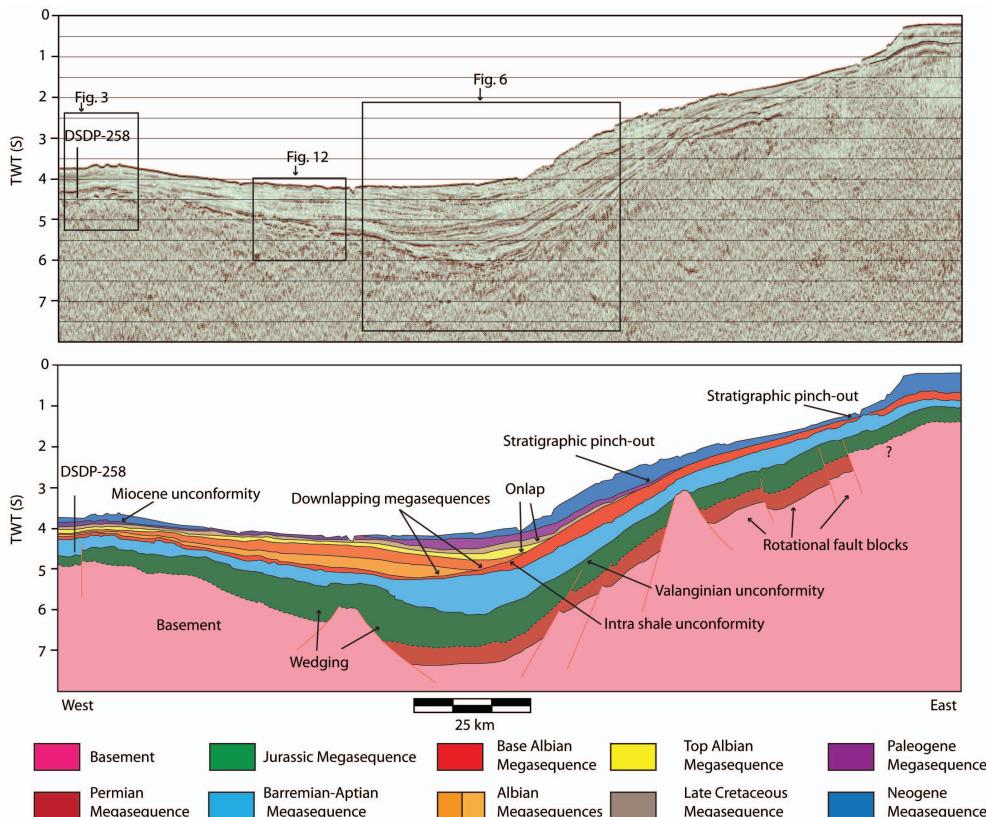
Fig. 4. (A) Uninterpreted cross section through the Mentelle Basin, and **(B)** interpreted section of **(A)** depicting the architecture and characteristic of seismic megasequences, which constitute the Mentelle Basin fill. Basement structure is also displayed. A series of major unconformities are located within the centre of the Mentelle Basin upon which numerous megasequences onlap and pinchout.
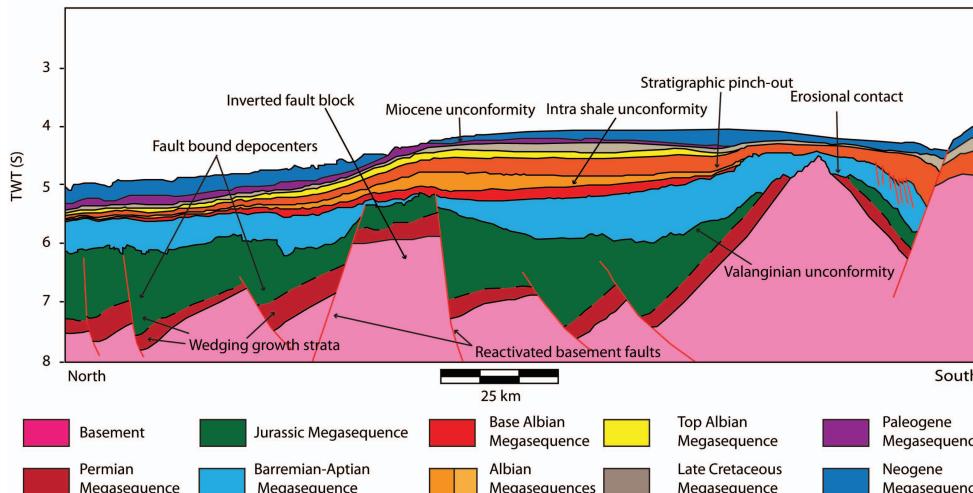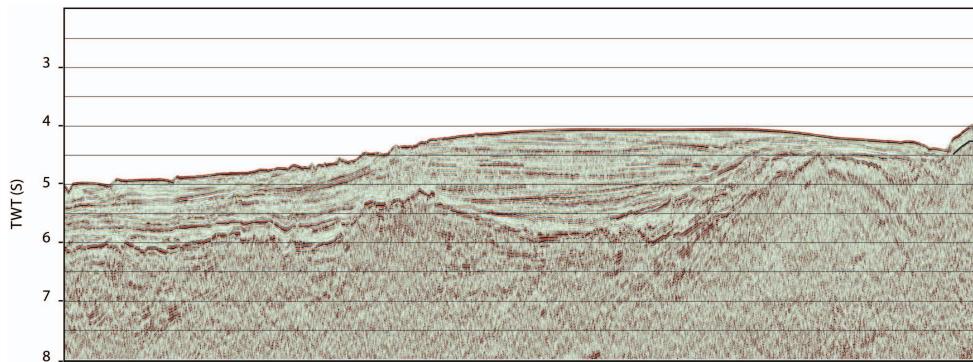
Fig. 5. (A) Uninterpreted and **(B)** interpreted strike line through the Mentelle Basin depicting the architecture of both the basement structure and seismically defined megasequences. Notice the presence of a large inverted basement fault block situated close to the centre of the strike line.

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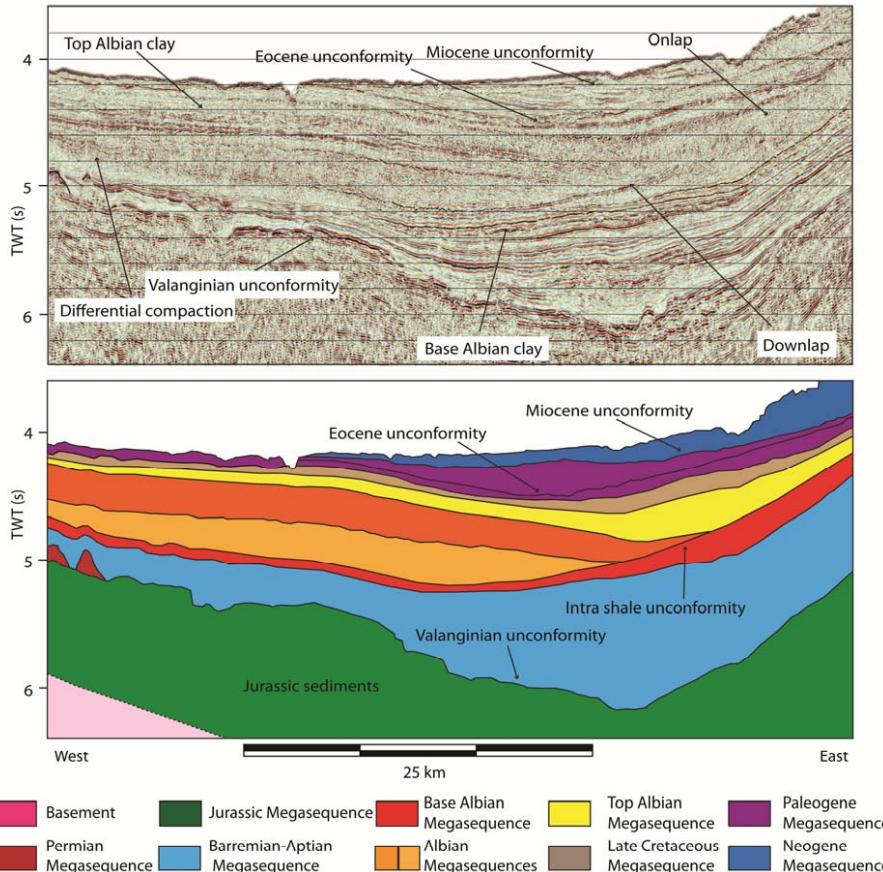
Fig. 6. (A) Uninterpreted and **(B)** interpreted seismic lines showing the seismic characteristics and architecture of megasequences within the centre of the Mentelle Basin.

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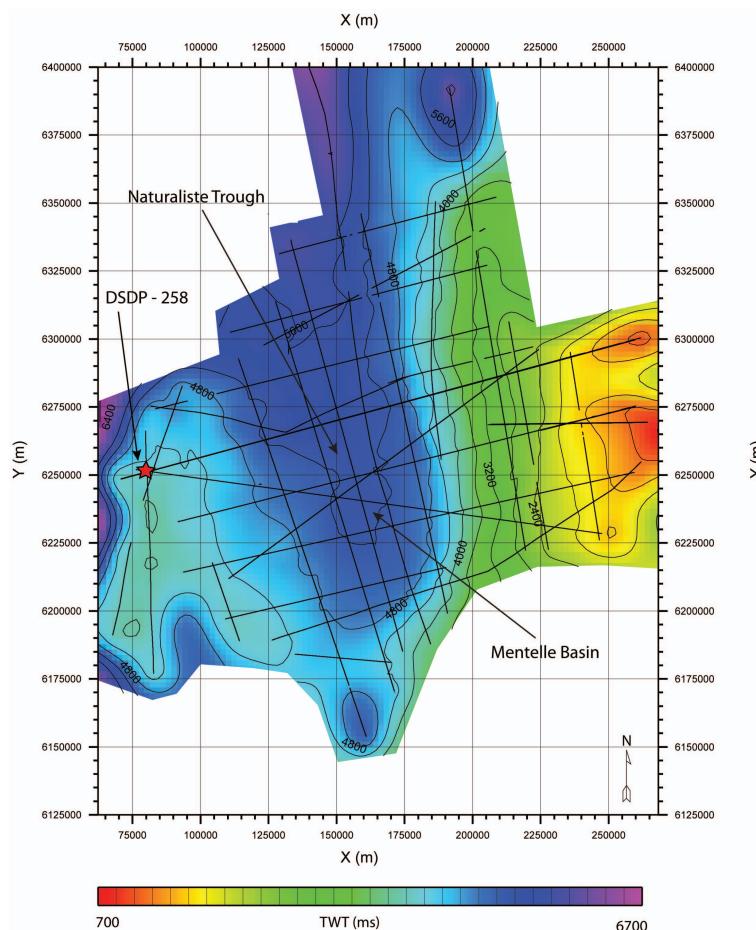
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Fig. 7. TWT map of the base reflection from the Base Albian megasequence.

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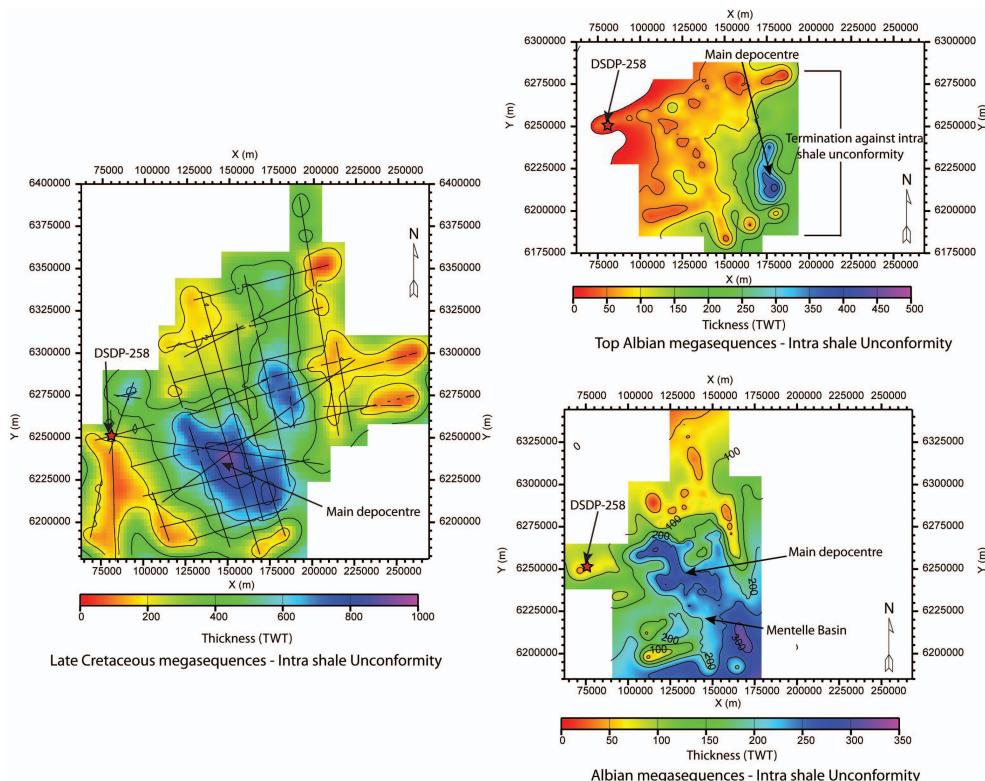
Fig. 8. Isochron maps for the cretaceous black shale megasequences. Representative thickness changes highlighted within each isochron are interpreted to reflect changes in thermal contraction (flexure) and subsidence and accommodation space.
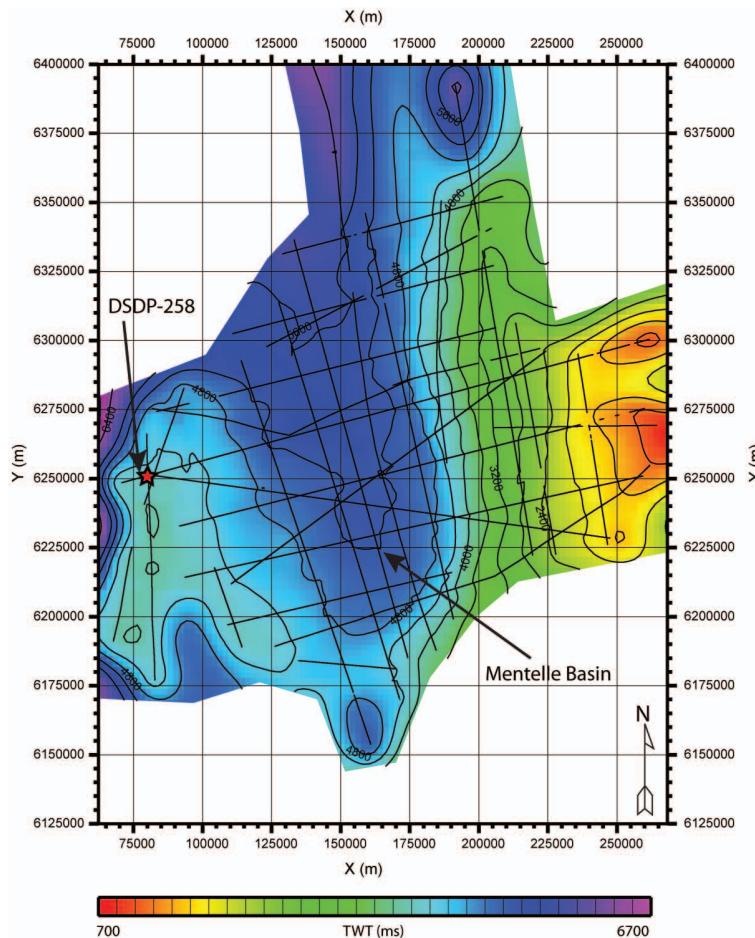
Fig. 9. TWT map of the intra shale unconformity (within the Base Albain megasequence) upon which younger Cretaceous megasequence onlap.
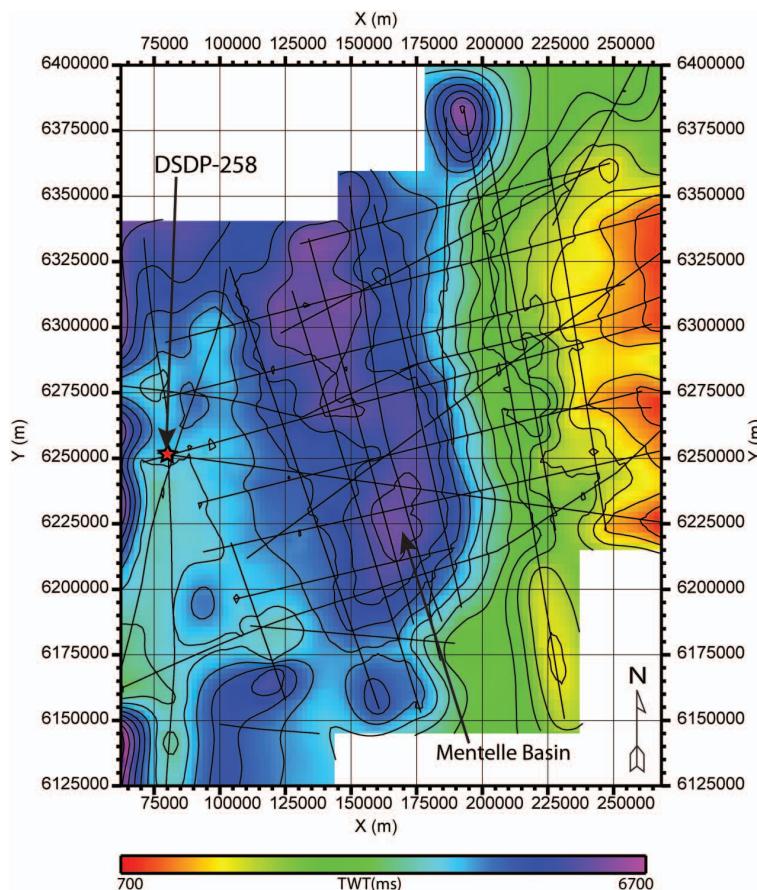
Fig. 10. TWT map of the Valanginian unconformity. This extensive unconformity can be mapped across the entire basin and marks a change from volcanic associated rifting to thermal subsidence and eventual deposition of black shales.

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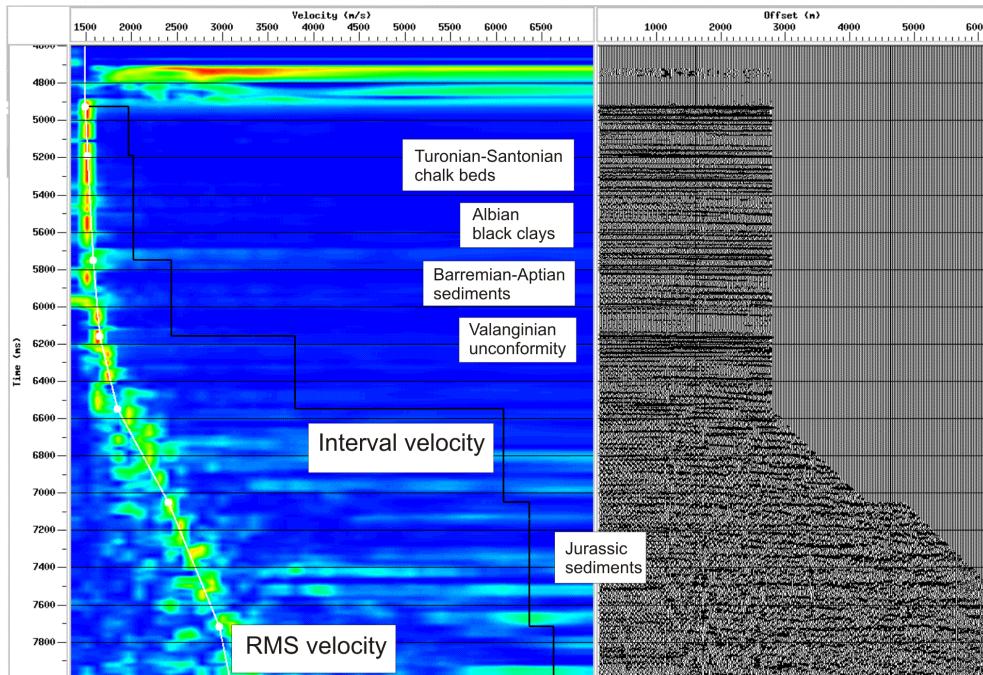
Fig. 11. Stacking and interval velocity trends for a typical depth profile through the Mentelle Basin. Notice the velocity increases associated with the Valanginian unconformity (volcanic lithology) and deeper more compacted lithologies.

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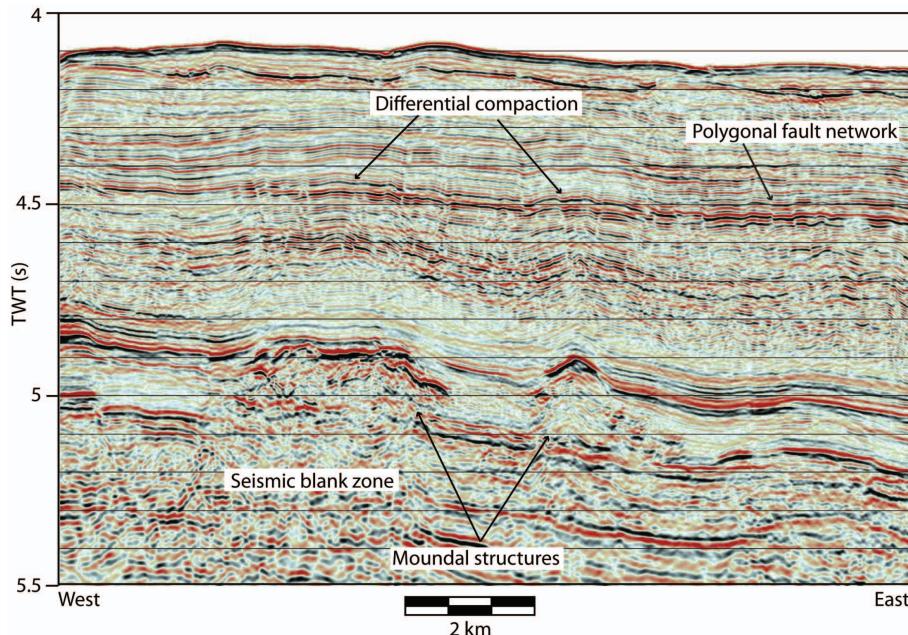
Fig. 12. Seismic line depicting moundal structures lying above the Valanginian unconformity. Notice the extensive differential compaction system indicative of a hard compact lithology.