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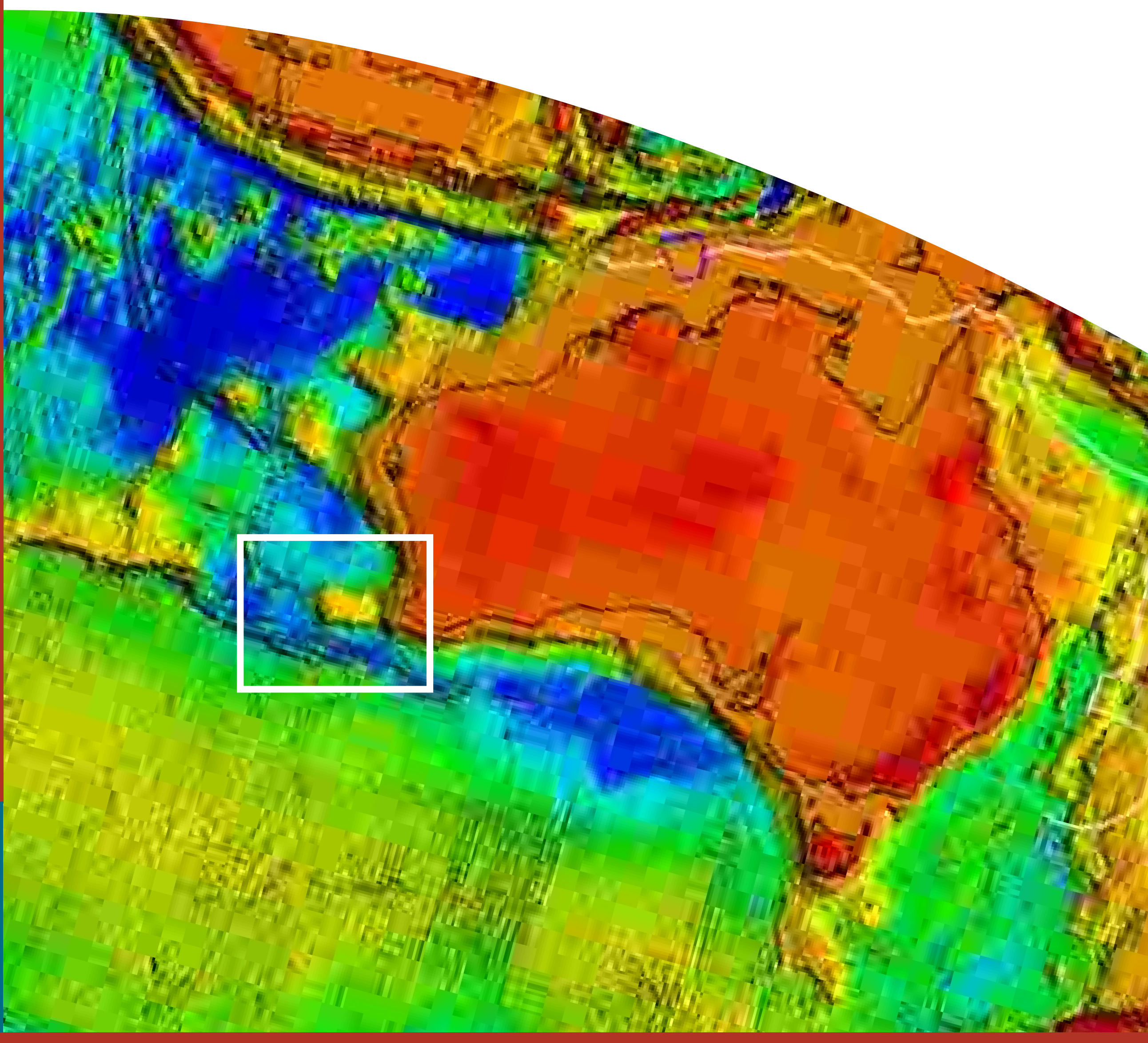

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GEOLOGICAL FRAMEWORK OF THE NATURALISTE PLATEAU

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CONTENTS

The data and the interpretations based on that data, contained in this report are not necessarily indicative or representative of the final information that might be used by Australia to support the location of the outer limit of the continental shelf beyond 200 nautical miles.

EXECUTIVE SUMMARY

The Naturaliste Plateau is a large submarine plateau lying off the southwestern tip of mainland Australia to the west of Cape Leeuwin and Cape Naturaliste. It lies in water depths of 2000 to 5000 m, has an area of about 90 000 km^2, and extends for about 400 km E-W and 250 km N-S. The eastern half of the plateau lies within Australia's Exclusive Economic Zone (AEEZ) and the western half will form part of Australia's Extended Continental Shelf under the terms of the United Nations Convention on the Law of the Sea.

In previous studies the Naturaliste Plateau has been alternatively interpreted as a continental fragment or as an oceanic plateau. This analysis of seismic reflection data shows that a large number of small rift basins on the Naturaliste Plateau were formed prior to the breakup in the Perth Abyssal Plain, which borders the plateau to the north. Recovery of continental rocks on the southern margin of the plateau, and the presence of sedimentary sequences similar to those in the Perth Basin suggest that the plateau is underlain mostly by continental crust.

Small rift basins mapped on the plateau contain up to 2.5 km of possibly Late Jurassic to Early Cretaceous sediments. Insufficient sediment thickness in these basins indicates poor petroleum prospectivity. However, if the Naturaliste Plateau basement beneath these basins is composed of Late Paleozoic rocks the whole plateau, including the rift basins, may have some petroleum potential. Whereas prospectivity of the main part of the Naturaliste Plateau is highly speculative, petroleum potential of the Naturaliste Trough area (Mentelle Basin) is possibly equivalent to that of the southern Perth Basin. The eastern part of this area contains at least 5 km of Early Cretaceous to Jurassic or older sediments, which are likely to be similar to those in the southern Perth Basin.

The Naturaliste Plateau is surrounded by a wide continent-ocean transition (COT) zone, which is 30 to 90 km wide in the north and up to 250 km wide to the south of the plateau. The northern COT formed as part of a volcanic rifted margin associated with Valanginian breakup in the Perth Abyssal Plain. The southern COT probably formed in the Barremian to Cenomanian during continental extension between the Naturaliste Plateau and its conjugate feature off Antarctica, the Bruce Rise. Continental crust off the southern margin of the Naturaliste Plateau underlies at least the inner part of the COT. The outer part of the COT may be in part underlain by old slow-spreading oceanic crust, but most likely is a mixture of highly extended continental and magmatic crust. The outermost part of this COT is represented by a zone of peridotite ridges.

This report represents an up to date analysis of the stratigraphy, structure, geological evolution and petroleum prospectivity of the Naturaliste Plateau based on revised interpretation of seismic reflection data combined with drilling and geological sampling results and supported by potential field interpretation.

1. INTRODUCTION

The 1982 United Nations Convention on the Law of the Sea (UNCLOS, United Nations, 1983) defines a nation's legal seabed and subsoil jurisdiction as extending throughout its Continental Shelf (Appendix 1). Where the continental margin of a nation extends beyond 200 nautical miles, the outer limit of the "legal" Continental Shelf[1] is defined by a series of rules contained within Article 76 of UNCLOS. The rules require definition of the foot of the continental slope, knowledge of sediment thickness and good bathymetric information defining the 2500 m bathymetric contour. In areas of complex bathymetry, geological considerations, such as structure and crustal origin, may be used to support the definition of the outer limit.

The Naturaliste Plateau is one of nine areas around Australia and its land territories, that could be claimed under the terms of UNCLOS as areas of Extended Continental Shelf; several of these areas lie off Australia's western margin (Fig. 1). The total area of Extended Continental Shelf in the vicinity of the Naturaliste Plateau has been estimated at 190,000 km^2 (Symonds & Willcox, 1989; Symonds et al., 1998).

The Naturaliste Plateau is a large submarine plateau forming part of Australia's continental margin (Fig. 1). It lies in approximately 2000 to 5000m of water. The plateau is separated from the Western Australian Shelf by the Naturaliste Trough, and is abutted to the north by the Perth Abyssal Plain, to the west by the Naturaliste Fracture Zone, and to the south by the Diamantina Zone (Plate 1).

1 The "legal" Continental Shelf (LCS), defined by a complex series of rules or formulae, is quite distinct from the geomorphic continental shelf as understood by a marine scientist. The LCS includes the geomorphic continental shelf, the continental slope, marginal plateaus and sometimes the continental rise and the inboard edge of deep ocean basins.

2. DATASETS USED IN THE STUDY

2.1 Bathymetry

Bathymetric datasets used in the study included GEBCO digital contours (IOC, IHO, & BODC, 1994) and the Geoscience Australia gridded dataset based on the integration of conventional shipboard records, swath bathymetry and the predicted bathymetry of Smith et al. (1997) (Petkovic & Buchanan, 2002). Swath mapping provides high-resolution bathymetry, which often allows correlation of the seafloor morphology to tectonic elements. A swath mapping survey by R/V "*Marion Dufresne*" (Cruise 110) in 1998 acquired data to the south of the Naturaliste Plateau in the Diamantina Zone (Royer and Beslier, 1998).

2.2 Potential Field Data

Gravity and magnetic data have been used to constrain the geological interpretation provided in this report. Sources of potential field data included free-air gravity anomaly and magnetic anomaly data calculated from the shipboard recordings. Spatial correlations between the structural elements have been facilitated by interpretation of satellite gravity and magnetic anomaly images produced by Geoscience Australia from multiple datasets. These images have been particularly valuable for understanding the relationships between different geological structures.

2.3 Seismic Reflection Data

Most of seismic surveys and drilling on the Naturaliste Plateau took place in the 1960s to early 1970s. The R/V *"Robert Conrad"* completed several seismic reflection traverses in 1965 (Burkle et al., 1967). In 1971-72, the Naturaliste Plateau was surveyed by R/V "*Eltanin*" (cruises 54 and 55A; USNS *Eltanin*, 1978).

Two seismic programs were designed to survey the Naturaliste Plateau in some detail: GA Continental Margins Surveys 18 and 19 (1972); and the Shell Development "Petrel" Survey (1973). In this study, we used digital data from the Shell "Petrel" Survey (7 lines), and transcribed analog records from GA's Survey 18 (8 lines). We also interpreted two lines from Geoscience Australia's Survey 81 (1988) in the Perth Basin which tie to the easternmost "Petrel" line. One line from GA Law of the Sea Survey 187 was interpreted extending from the Diamantina Zone to the western part of the plateau (Fig. 2).

2.3.1 Geoscience Australia Continental Margins Survey 18

The aim of this survey was to develop a general regional understanding of the Naturaliste Plateau as part of a series of margin-wide surveys conducted by GA (then BMR) in the early to mid 1970s. The survey was acquired with a 12-kj sparker energy source and six-channel seismic streamer. There are eight N-S lines and one E-W tie line in the northern part of the plateau (Fig. 2).

2.3.2 Shell "Petrel" Survey

As part of its 1973 "Petrel" Survey Shell Development shot 4 zigzag lines across the plateau in a generally in N-S direction, and two E-W lines (Fig.2). The survey was undertaken using a 1090 cubic inch airgun array and a 24-channel streamer. The seismic record on the lines is approximately 8 s TWT.

2.3.3 Geoscience Australia Survey 81 (1988)

GA Survey 81 lines are located in the Southern Perth Basin (Fig.2). Only Lines 35 and 40 in the Vlaming Sub-Basin were interpreted in this study. Several petroleum wells located on or close to these lines provided age control for seismic sequences. The lines tie onto other seismic lines on the Naturaliste Plateau. The seismic data were shot with a 26.3 litre airgun array and 72-channel receiver. Seismic penetration of 5 to 7.5 s TWT was commonly achieved.

2.3.4 Geoscience Australia Survey 187 (1997)

GA Survey 187 seismic line NP-1 extends from the central part of the Naturaliste Plateau, south across the whole Diamantina Zone (Fig. 2). The line was shot on the return voyage from surveying the Kerguelen Plateau and was designed to complement existing lines with deep (16 s TWT) seismic data in the continent-ocean transitional zone. The survey used 3 bolt 1500C air guns and a 54-channel streamer.

2.4 Geological Samples.

Two Deep Sea Drilling Project (DSDP) wells (258 and 264, Fig 3) were drilled on the Naturaliste Plateau during the two separate drilling programs: Leg 26 (1972) and Leg 28 (1972). None of the wells reached basement, however, volcaniclastic conglomerates recovered at Site 264 are thought to overlie acoustic basement. Both DSDP sites are located close to Shell "Petrel" Line 321 (Fig. 2).

There are no petroleum exploration wells on the Naturaliste Plateau, however some of the wells in the southern Vlaming Sub-Basin of the Perth Basin to the northeast provide indirect information about the possible age and composition of sediments on parts of the Naturaliste Plateau and adjacent Naturaliste Trough. In this study, three Vlaming Sub-basin wells, Parmelia 1, Challenger 1 and Felix 1, were tied to GA Line 81-35 and Sugarloaf 1 was tied to GA Line 81-40 (Fig. 3).

Only three geological samples were taken on the Naturaliste Plateau. In 1966 the "*Robert Conrad*" took a 2.2 m core (RC8-56) in a location close to DSDP Site 258 (Fig. 3, Appendix 2). The first sample of Naturaliste Plateau basement rocks was dredged by the *"Eltanin"* on the steep NW margin of the plateau (Elt55-12) in 1972 (Fig. 3). Another sample of the plateau basement was dredged on its southern scarp during the recent (1998) "*Marion Dufresne*" *110* campaign (MD110-DR11, Fig. 3).

A number of geological sampling programs have been conducted in the Diamantina Zone to the south of the Naturaliste Plateau, including dredge sampling during "Marion Dufresne" cruises 80 and 110 (Appendix 2).

3. BACKGROUND

3.1 Physiography

The Naturaliste Plateau lies about 260 km to the west of the southwestern tip of the Australian mainland (Cape Leeuwin and Cape Naturaliste). In the north it borders the Perth Abyssal Plain, in the east it is separated from the Western Australian margin (Yallingup Shelf) by the Naturaliste Trough (Plate 1). Its western boundary is defined by the Naturaliste Fracture Zone and the Diamantina Zone lies to the south. The NW-SE oriented Naturaliste Fracture Zone separates the plateau from an area known as Gonneville Triangle (Plate 1). The latter is characterised by relatively flat seafloor enclosed between two prominent basement ridges and the Diamantina Zone.

The Naturaliste Plateau lies in water depths of approximately 2000 to 5000m with about 47% of its total area lying in 2000 to 3000m of water, 15% lying in 3000 to 4000m, and 38% in greater than 4000m (Plate 1). The relatively flat surface of the plateau is mainly enclosed by the 2500m isobath. The northwestern part of the plateau is separated from the rest of the plateau by a large sea valley at about 34° South (Fig 2). The generally rectilinear outline of the plateau is a product of different episodes and directions of rifting and seafloor spreading effecting its northern, western and southern margins.

The plateau has steep southern and western flanks (typically 7-11°) whereas its northern flank is gentler (generally 2 to 4°). The physiography of its western flank is complicated by the presence of a large seamount on its lower slope at about 33.5° South and the Naturaliste Fracture ridge system controlling morphology of the lower slope from 34.5 to 36° South. Along the southern margin of the plateau, the steep upper and middle slopes flatten out to a terrace feature between 4500 and 5000m prior to descending to abyssal depths of the Diamantina Zone.

North of the Naturaliste Plateau, the Perth Abyssal Plain is typically flat whereas to the west and south the surrounding seafloor is complicated by a series of ridges and troughs (Plate 1). In particular, to the south, the seafloor consists of a series of alternating, broadly E-W-trending basement ridges and troughs of the Diamantina Zone. This zone is up to 200km wide and extends from the easternmost part of the Broken Ridge to about 120° East (Fig 1). Most of its ridges consist of exposed basement, and even in the troughs, sedimentary cover is patchy and thin (typically not exceeding a few hundred metres). The boundary between the Diamantina Zone and the Australia-Antarctica Basin further to the south is marked by a rapid shallowing of bathymetry (6000-6500 to 4500-5000m) and a change to a much smoother topography (Plate 1).

The Naturaliste Trough (Fig. 3, Plate 1) is a northerly-trending bathymetric feature, which separates the plateau from the middle and upper continental slope and Yallingup Shelf of mainland Australia to the east. The Naturaliste Trough is underlain by a significant sedimentary depocentre termed the "Mentelle Sub-basin" by Hocking (1994). This depocentre was considered by Hocking et al (1994) to be part of the Perth Basin, but in this study it is regarded as a separate basin, the Mentelle Basin

(Fig. 3), isolated from the southern Perth Basin by shallow basement of the Precambrian Leeuwin Complex. The western part of this basin contains at least 5km of Early Cretaceous to Jurassic or older sediments, which may be similar to those in the southern Perth Basin, or basins of the Great Australian Bight. The boundary between the Naturaliste Plateau and the Mentelle Basin is mapped at the pinch out of Cretaceous and older sequences of the Mentelle Basin onto the Naturaliste Plateau basement to the west.

3.2 Plate tectonic setting

During the Gondwana breakup the Naturaliste Plateau was located at the junction of the three major plates: Australia, Antarctica and India. Magnetic anomalies to the north of the Naturaliste Plateau (Fig. 4) in the Perth Abyssal Plain contain evidence of the Early Cretaceous breakup between India and Australia/Antarctica. The breakup started first in the Argo Abyssal Plain in the Latest Jurassic and gradually propagated to the south. The oldest mapped anomaly in the Perth Abyssal Plain is chron M10 – Early Hauterivian (Cande et al., 1989), however, seismic data from the Naturaliste Plateau surroundings indicate that most of anomalies currently mapped as M10 and M9 are located on Australia's continental margin or on the Naturaliste Plateau and cannot be regarded as seafloor spreading anomalies; M8-M7 are the oldest reliably mapped anomalies in the Perth Abyssal Plain.

The Gonneville Triangle, separated from the Naturaliste Plateau by the Naturaliste Fracture Zone (Plate 1), does not have any identified magnetic anomalies (Fig. 4). Based on variety of geophysical data, Munschy (1998) suggested that it is floored by oceanic crust 120-90 Ma in age, which corresponds to the Magnetic Quiet Period.

The oldest magnetic anomaly to the south of the Naturaliste Plateau is Chron 17 – Middle Eocene (Fig. 4), corresponding to the breakup between the Diamantina Zone and the southern Labuan Basin and the start of fast spreading in the Australian-Antarctic Basin. This anomaly occurs about 200 km to the south of the plateau on the seaward boundary of the Diamantina Zone. No magnetic anomalies have been identified in the Diamantina Zone itself and its origin is highly debatable, with proposals ranging from trapped Early Cretaceous oceanic crust (Munschy, 1998) to extended continental crust (Chatin et al., 1998). Tikku and Cande (2000) re-examined existing magnetic data and suggested that southern part of the Diamantina Zone (about 58 km) was formed during an ultra-slow spreading between Australia and Antarctica between Chron 34 and Chron 20, which is responsible for its rough basement.

The Naturaliste Plateau itself has been alternatively interpreted as either a continental or oceanic feature. In the oceanic origin scenario, the Naturaliste Plateau is a Large Igneous Province (LIP) with a thick magmatic crust formed due to excessive magmatism during rifting of Eastern Gondwana around 120-130 Ma (Coleman et al., 1982; Storey et al., 1992). It was suggested that a major mantle plume, the remnant of which is located at present beneath the Kerguelen and Heard Islands, was responsible for this magmatism. It was also proposed (Colwell et al., 1994) that the Naturaliste Plateau may have formed when the ridge tip associated with seafloor spreading between India and Antarctica/Australia passed along major transforms, which served as conduits for excessive magmatism.

In the continental origin scenario (e.g. Beslier et al., 2001), the Naturaliste Plateau is a conjugate to the Bruce Rise on the Antarctic coast (Fig. 4). Borissova et al. (2002) suggested that the Diamantina Zone is floored by remnants of an extensional terrane that formed in the Early Cretaceous between the Naturaliste Plateau and the Bruce Rise during continental rifting preceding the breakup on the southern margin. The continental origin of the plateau is supported by recent geological evidence (see below).

3.3 Regional geology

Seismic surveying and drilling on the Naturaliste Plateau took place mostly in the early 1970s. Deep Sea Drilling Project (DSDP) holes 258 and 264 (Fig. 3) recovered a succession of Cretaceous to Miocene sedimentary rocks. Neither of the wells reached basement, however, volcaniclastic conglomerates of Cenomanian or older age recovered at Site 264 lie close to acoustic basement. Ford (1975) described cobbles from this conglomerate as having an andesitic composition, however a high degree of alteration made interpretation of original composition uncertain.

The first sample of the plateau "basement" was dredged by the *"Eltanin"* (Elt55-12) on the steep NW margin of the plateau (Heezen and Tharp, 1973; Fig. 3). Plagioclase-rich rocks from this dredge were originally interpreted as continental, however, a more detailed petrographic analysis (Coleman et al., 1982; Storey et al.,1992) showed that these rock clasts are in fact altered tholeiitic basalts similar to the Bunbury Tholeiitic Suite (132-122 Ma) on the Australian mainland. Four plagioclase-rich *"Eltanin"* dredge rocks (Elt55-12) and a cobble from volcaniclastic conglomerate at Site 264 were later analysed by Mahoney et al. (1995), who confirmed their mostly basaltic composition. However, it has been also noted (Mahoney et al., 1995) that Naturaliste Plateau samples are chemically and isotopically different from typical hotspot basalts and their composition suggests possible contamination of magmas by continental crust. Overall sampling results were consistent with the viewpoint of an oceanic hotspot origin of the Naturaliste Plateau.

An oceanic origin of the Naturaliste Plateau has been recently questioned in view of a dredge sample taken by "*Marion Dufresne*" in 1998 on the steep southern flank of the plateau (MD110-DR11; Appendix 2; Fig. 3). Analysis of this dredge material shows the presence of high-grade gneisses similar in composition to that of the Australian craton (Beslier et al., 2001). It is now apparent that Naturaliste Plateau, like other Indian Ocean plateaus such as the Kerguelen Plateau, is at least partly composed of continental rocks.

The Diamantina Zone was first dredged in 1977 by *R/V "Diamantina"* (Appendix 2*)*. The station sampled basement close to the Naturaliste Fracture Zone (Nicholls et al., 1981). Upper mantle rocks (lherzolites and olivine clinopyroxenites) recovered at this location were interpreted to come from an ultramafic body emplaced into shallow crust at the end of the Cretaceous (Nicholls et al., 1981). A more recent program of dredging in the Diamantina Zone recovered alkaline basalts in its inner part and highly-altered peridotites in its outer part (Chatin et al., 1998). Alkaline basalts recovered from the top of a large tilted block are similar in composition to some basalts drilled on the Kerguelen Plateau and, particularly, to the basalts from

Kerguelen Islands. Because alkaline basalts never occur at mid-ocean ridges, Chatin et al. (1998) concluded that Diamantina Zone is not underlain by typical oceanic crust.

Peridotites were recovered at four sites (Chatin et al., 1998; Royer and Beslier, 1998, Appendix 2) on basement ridges. To the west of the Naturaliste Fracture Zone (110^{o} E) their geochemical signature reflects very small degrees of partial melting, indicating rapid mantle exhumation typical of continental rifts (Chatin et al., 1998). Further to the east, peridotites exhibit even more similarity with peridotites from continental margins. The new sampling results indicate extreme crustal thinning in the Diamantina Zone. Beslier et al. (2001) estimated that emplacement of the peridotites in the Diamantina Zone took place between 90 and 84 Ma.

Based on the presence of pre-Neocomian grabens on the Naturaliste Plateau and a magnetic signature interpreted as indicative of metamorphic and intruded igneous basement, Petkovic (1975) and Jongsma and Petkovic (1977) concluded that the Naturaliste Plateau is underlain by continental crust. They suggested that its basement could be similar in lithology to the Leeuwin Block (Fig.5) and to the Precambrian gneisses of the Knox Coast of Antarctica.

4. STRATIGRAPHY

Our knowledge of the stratigraphy of the Naturaliste Plateau and surrounding areas is based on the two DSDP holes (Sites 258 and 264) and the dredged and cored seabed samples (Appendix 2). As part of Australian continental margin, the Naturaliste Plateau lies at the intersection of the western and southern Australian margins (Figs 4 and 5). In this study, the stratigraphy of the southern Perth Basin and the Great Australian Bight Basin were used to help correlate regional events and infer the possible ages of sequences beneath the reach of sampling in the study area.

4.1 DSDP drilling results

DSDP Site 258 is located in the eastern part of the plateau adjacent to the western flank of the Naturaliste Trough (Fig. 2). It recovered 411 m of Cretaceous sediments overlain by 114 m of Miocene to Recent nannofossil ooze. The lowest part of the Cretaceous succession consists of 11 m of glauconitic detrital sandstone and silty clay overlain by 251 m of mid-Albian to Cenomanian ferruginous detrital clays (Fig. 6). Most of the detrital material could have come from uplifted parts of the plateau through erosion of basaltic volcanic rocks (Davies et al., 1974). Planktonic foraminifera recovered from the upper part of these detrital clays suggest a Middle to Upper Albian age (Thirstein, 1974). The lower 100m of the succession does not contain any micropaleontological evidence and could be older. The clays are overlain by 149 m of Turonian to Santonian nannofossil chalk and siliceous limestone. A major hiatus separates the Santonian from the overlying 114 m of Miocene to Recent section. Correlation between interpreted seismic horizons of Jongsma and Petkovic (1977) and the lithostratigraphic units at Site 258 are shown in Figure. 6.

DSDP Site 264 is located near the southern edge of the Naturaliste Plateau, about 125 km southwest of Site 258 (Fig. 3). The hole bottomed in altered fossiliferous volcaniclastic conglomerates (Fig. 7) estimated by Hayes et al. (1975) to be Cenomanian or older in age. This conglomerate could be a lateral correlative of the basaltic detrital sandstone of Site 258 (Coleman et al., 1982). The conglomerates are overlain by a succession of marine carbonate sediments (171 m), including 79 m of Early Cretaceous to Middle Paleocene nanno chalk and 92 m of Early Eocene to Recent nannofossil ooze (Fig. 7). Reflector D (Jongsma and Petkovic, 1977) was correlated to a seismic boundary below the volcaniclastic conglomerates (Fig. 7).

4.2 Dredging and sampling results

Composition of the two dredge samples (Elt55-12 and MD110-Dr11) on the Naturaliste Plateau has been discussed earlier in Chapter 3.3. In the light of dredging results on the southern flank of the plateau (MD110-Dr11, Fig.3), which demonstrated the presence of continental crust, the similarity of basalts dredged by the "*Eltanin*" (Elt55-12 on the northern margin of the plateau) to the Bunbury Basalts may indicate that they were formed as part of continental flood basalt province, rather than as a result of an oceanic hotspot.

The only sedimentary core on the Naturaliste Plateau was taken by the "*Robert Conrad*" (Fig. 3, Appendix 2). The core recovered 23 cm of Upper Cretaceous Turonian white chalk followed by 119 cm of Pleistocene to Recent coarse-grained foraminiferal sand. The Turonian age of the chalks is determined by assemblages of planktonic foraminifera (Burkle et al., 1967). The total absence of Tertiary sediments at this location indicates that local erosion may have been significant for some parts of the plateau in the Pleistocene.

4.3 Correlation with the southern Perth Basin stratigraphy

The Perth Basin is bounded in the east by the Darling Fault and contains sediments of Permian to Tertiary age (Hocking, 1994). The sediments are thickest in the east (Dandaragan Trough, Bunbury Trough), where they locally reach 15000 m. Deposited in continental and shallow marine environments, they are represented by sandstones, shales and siltstones.

The Perth Basin consists of a series of northwest striking sub-basins, troughs and highs, generally bounded by large transfer faults (Song and Cawood, 2000). The Vlaming Sub-basin is a major Jurassic-Cretaceous depocentre closest to the study area. The stratigraphy of the Vlaming Sub-Basin is based on a number of petroleum wells, three of which, Sugarloaf 1, Challenger 1 and Parmelia 1 (Fig. 8, Plate 2), were used in the current study for correlation to the stratigraphy of the basins of the Naturaliste Plateau and Mentelle Basin to the east.

The Vlaming Sub-basin started to develop as a rift basin in the Permian. Permian-aged sandstones and siltstones were recently drilled by Felix 1 (Woodside Offshore Petroleum, 1998; Fig. 3) on the uplifted western flank of the basin. The stratigraphy and regional framework of this basin has been described in some detail by Miyazaki et al. (1996). During the Middle Jurassic to Early Cretaceous, the major rift phase in the Vlaming Sub-basin, thick fluvial sediments of the Yarragadee Formation, followed by lagoonal and lacustrine sediments of the Parmelia Formation (Fig. 8) were deposited in the basin. Breakup in the Perth Abyssal Plain was preceded by regional uplift, which resulted in a major unconformity (Valanginian). Following breakup and the onset of thermal subsidence, depositional environments began to change from shallow marine to open marine conditions.

Below is a brief description of the stratigraphy from wells in the Vlaming Sub-basin used in this study:

Parmelia 1

Parmelia 1 (Plate 2) recovered 1250 m of Early Cretaceous to Recent sediments (West Australian Petroleum, 1983). The oldest sediments intersected by the well are 177 m of Carnac Formation (Parmelia Group; Berriasian) which are represented by sandstones, shales and siltstones. A major unconformity separates this part of the section from the overlying mostly sandy Leederville Formation (485 m) and the silty Osborne Formation (83 m). Another major unconformity separates the Osborne Formation from the overlying undifferentiated Late Cretaceous Coolyena Group (152 m) represented mostly by calcareous rocks and some shales.

Challenger 1

Challenger 1 (Plate 2) intersected 1785 m of Mid-Jurassic to Eocene sediments (West Australian Petroleum, 1975). The bottom 410 m are represented by sandstones of Yarragadee and Otorowiri formations, followed by 412 m of Parmelia Group sandstones (Jervoise Sandstone). The South Perth Shale (319 m) overlies a breakup unconformity at the base of the Gage Sandstone (1429 m). The shales are followed by 242 m of Leederville Formation sandstones. Another major unconformity separates these Early Cretaceous rocks from the Late Cretaceous Coolyena Group (128 m). The Gingin Chalk at the top of the Coolyena Group is followed by 275 m of calcareous rocks ranging in age from Late Paleocene to Eocene.

Sugarloaf 1

Sugarloaf 1 (Plate 2) is located close to the axis of a major depocentre in the Vlaming Sub-Basin. The well intersected a 3286m thick succession of Jurassic to Early Cretaceous shales and sandstones followed by 136 m of Albian-Cenomanian (Coolyena Group) sandstones and Miocene carbonates (West Australian Petroleum, 1971). The main (breakup) unconformity (base Wanbro Group) was intersected at 875 m. It corresponds to an abrupt change from shales of the Parmelia Group to the Gaol Sandstone. Another major unconformity was intersected at the base of the Coolyena Group at 450 m. Late Cretaceous sediments of the Coolyena Group are overlain by 170 m of Miocene carbonates.

Overall, the stratigraphy of the southern Perth Basin suggests that sedimentary sequences in the basins on the Naturaliste Plateau and beneath the adjacent Naturaliste Trough (Mentelle Basin) are likely to contain thick Cretaceous and Jurassic successions. The presence of older sediments is possible, but their age would be highly uncertain.

4.4 Correlation with the Great Australian Bight stratigraphy

The stratigraphic and tectonic evolution of the Great Australian Bight has been recently revised by Totterdell et al. (2000). Plate 3 shows the major sedimentary sequences defined by these authors together with the depositional environment.

Extension and syn-rift deposition in the Great Australian Bight started in the Late Jurassic (Fraser and Tilbury, 1979; Hegarty et al., 1988; Stagg et al., 1990; Totterdell et al., 2000). The Jurassic to earliest Cretaceous (Callovian to Berriasian; Sea Lion and Minke supersequences) rift section contains fluvial-lacustrine clastic sediment represented mostly by sandstone, siltstone and claystone (Totterdell et al., 2000). The Valanginian to Albian section (Bronze Whaler supersequences, Plate 2) is characterised by sag-phase aggradational and progradational successions of fluvial and lacustrine sediments represented by sandstone, claystone and mudstone. In the Late Albian, due to an acceleration in the subsidence rate, marine conditions were established in the Great Australian Bight. The mid-Albian to Cenomanian section (Blue Whale supersequence, Plate 2) is dominated by restricted marine siltstones. It is overlain by Cenomanian (White Pointer supersequence, Plate 2) fluvial to lagoonal siltstone and mudstone with minor sandstone and coal. The Turonian to Santonian (Tiger supersequence, Plate 2) succession consists predominantly of marginal marine to marine mudstone. In the Late Santonian-Maastrichtian (Hammerhead supersequence, Plate 2) deposition occurred in dominantly deltaic environments and is represented by sandstone, mudstone and minor coal. This sequence is overlain by Paleocene to Early Eocene (Wobbegong supersequence, Plate 2) marginal marine to deltaic sandstone with minor siltstone followed by Mid-Eocene to Pleistocene (Dugong supersequence) carbonate shelf deposits.

The stratigraphy of the Bight Basin demonstrates that syn-rift deposition here occurred in the Late Jurassic to Early Cretaceous (Valanginian), which was followed by a period of thermal subsidence. Acceleration in the subsidence rate occurred in the Albian, culminating in continental breakup in the Late Santonian. An erosional unconformity between the Tiger and Hammerhead supersequences probably corresponds to a regional uplift associated with the breakup on the southern margin.

5. STRUCTURE

Jongsma and Petkovic (1977) noted the structural complexity of the plateau and the difficulties associated with mapping its structure from a widely spaced grid of seismic lines. They attributed the fault-controlled southern margin of the plateau to breakup along the southern Australian Margin. Petkovic (1975) noted the difference between the western part of the Naturaliste Plateau, characterised by a shallow basement, and its eastern "basin-like" part.

The tectonic provinces/structural elements mapped in the present study are shown in Plate 4 and Figure 9. Major structural subdivisions include:

- a large sedimentary basin (Mentelle Basin) underlying the Naturaliste Trough east of DSDP hole 258
- smaller rift basins on the Naturaliste Plateau itself;
- areas of shallow basement corresponding to uplifted parts of the plateau;
- small fault-controlled rift basins located mostly along the southern margin of the plateau;
- a large intrusive complex in the north-western part of the plateau; and
- a possibly Paleozoic basin in the central part of the Naturaliste Plateau overlain by a thin Cretaceous to Recent succession.

A marked continent-ocean transition (COT) zone flanks the plateau. To the south, the COT consists of inner and outer parts and a peridotite zone. To the north, it has volcanic nature and is part of West Australian volcanic rifted margin. Major fractures zones in the region are associated with up to 30 km of highly faulted basement and have been mapped as separate structural elements.

Several structural trends can be identified in the study area:

- NNW-SSE orientated features are typical of the south Perth Basin, landward from about 115^{o}E. This trend is attributed to reactivation of pre-existing northerly oriented basement faults (Song and Cawood, 2000).
- NW-SE oriented faults are typical of the Mentelle Basin and parts of the southern COT (Fig.9; Plate 4). Strike-slip faults of this orientation were formed during the Jurassic-Early Cretaceous extension between Australia/Antarctica and India (Song and Cawood, 2000). When breakup occurred in the Perth Abyssal Plain to the north of the Naturaliste Plateau the direction of extension changed from NW-SE to WNW-ESE and some of these faults, particularly in the Mentelle Basin, were reactivated as highly obliques extensional faults.
- ENE-WSW and E-W oriented features are mapped on the southern Naturaliste Plateau and the adjacent southern COT (Fig. 9; Plate 4). This trend is related to the breakup between Australia and Antarctica in the Campanian. Late Santonian-Campanian basin-forming extensional faults on the southern margin are typically ENE oriented high-angle normal faults (Stagg et al., 1999), similar to what is observed on the southern margin of the Naturaliste Plateau.

5.1 Major fracture zones

Major fracture zones in the area include the NW-SE trending Naturaliste and Leeuwin series of faults (Fig. 9). Their orientation corresponds to the initial spreading direction between India and Australia/Antarctica in the Early Cretaceous and is almost the same as the trend of transform faults in the Perth Abyssal Plain (Plate 4). The Naturaliste Fracture Zone defines the southwestern margin of the Naturaliste Plateau and separates the plateau from an area of possibly 120 to 90 Ma age oceanic crust (Munschy, 1998), known as the Gonneville Triangle. The Naturaliste Fracture Zone is intersected by Lines 18-98 and 187-1. It is marked by a narrow graben followed father seaward by a basement high.

The Leeuwin Fracture Zone defines the southwestern margin of the Mentelle Basin Plate 4) and separates the continent-ocean transitional zone off the Naturaliste Plateau from the Recherche Sub-basin (of the Bight Basin) to the east. This fracture zone was intersected by Lines 319 and 320. On these lines it is represented by a 30 km wide zone with narrow blocks bounded by steep normal faults, which deepens rapidly southwest. This fracture zone appears to displace the Naturaliste Plateau continent-ocean transition zone by at least 50 km to the south (Plate 4). The presence of these fracture zones to the south and west of the Naturaliste Plateau indicates that significant crustal extension took place between Australia and Antarctica at about the same time as the breakup in the Perth Abyssal Plain, i.e during the earliest Cretaceous.

Another major fault system has been mapped forming the steep southern flank of the plateau between the Naturaliste and Leeuwin Fracture Zones (Fig. 9; Plate 4). The fault orientation ranges from ENE-WSW to WNW to ESE. These faults are typically very steep normal faults with up to 4 s TWT throw and are arranged in an echelon pattern.

Metamorphic basement crops out on the southern scarp of the Naturaliste Plateau at dredge site MD110-DR11 (Fig. 9; Plate 4; Royer and Beslier, 1998; Beslier et al., 2001). These rocks may compose the bulk of a basement ridge mapped along the entire southern margin of the plateau (Plate 4). Their presence and age (Cambrian) clearly demonstrates a continental origin for at least part of the plateau (Beslier et al., 2001).

5.2 Mentelle Basin

The Mentelle Basin (Mentelle Sub-basin of Hocking, 1994) underlies the bathymetric Naturaliste Trough and is the largest sedimentary basin in the study area (Plate 4). It is about 220 km north-south and 200 km east-west and contains at least 3 s TWT of sedimentary section in its major depocentre. Its thickest sediments underlie the Naturaliste Trough, whereas to the west sediments progressively thin onto an uplifted block beneath the eastern flank of the Naturaliste Plateau (Plate 5, Lines n324 and n325). In the east, the major depocentre gives way to an area of shallow basement with a few small rift basins containing up to 1 s TWT of sedimentary section (Plate 4). Although not well imaged, the boundary between the main depocentre and this eastern flank appears to be fault controlled. Poor seismic resolution in this area could be due to multiple fault reactivation, accompanied by transpression (Song and Cawood, 2000). .

The shape of the Mentelle Basin can be seen in Figures 10 and 11, which show depth to basement and sediment distribution in the study area. In the west the basin sequences onlap on the shallow basement of the Naturaliste Plateau (Fig. 10). A NW oriented asymmetric basement block defines the southwestern extent of the basin (Plate 5, Line n325), while farther north the boundary is not well defined.

The Mentelle Basin was intersected by only three widely spaced EW seismic lines (Fig. 2), which is insufficient to map its structural elements in any detail. Although faults shown in Plate 4 were mapped from the seismic, their orientation has been inferred from the satellite gravity data. The gravity data indicate that many of the basin's bounding faults are NW-SE oriented (Fig. 11). This structural trend indicates that the Mentelle Basin was probably formed during Jurassic-Late Cretaceous extension rather than during earlier Permian rifting in the Perth Basin. This predominant trend also suggests that the basin was formed in a strike-slip setting and probably combines extensional and compressional elements (Plate 5, Line n324).

5.3 Small rift basins

The basement of the southern Naturaliste Plateau is highly faulted and more eroded in comparison to its northern part. A number of variable size rift basins are imaged on seismic profiles (Plate 5). Most of the individual rift basins are half-graben bounded by steep ENE oriented normal faults dipping S or SE. The basins are 10 to 30 km wide and up to 120 km long.

The largest basin (informally named here the Southern Rift basin) is located in the southeastern part of the plateau (Plate 4). The basin was intersected by Lines 18-90, 18-92, n321, n322and n325 (Plate 5). It consists of several en-echelon rift segments and gradually widens to the southeast. Most of rift segments are half-grabens with major normal faults controlling their northern boundary (Lines n321 and n322, Plate 5). Sediment thickness in individual half-grabens is up to 2.5 s TWT (Fig. 11), but the segments themselves are fairly narrow (about 5-10 km wide).

DSDP Site 264 on the southeastern flank of the basin recovered volcaniclastic conglomerates of Cenomanian or older age within the sag phase succession less than 200 m below the seafloor. In the central part of the same rift segment, sediments beneath the drilled conglomerates are about 1 s TWT thick and contain 2 prominent sequence boundaries of inferred Albian and Valanginian age. Poor seismic resolution of individual faults and seismic boundaries may be attributed to the possible presence of volcanics in the section. The structural orientation of the basin and comparison with similar structural elements along the Australian Southern margin suggest that this basin was probably formed in the Jurassic – Early Cretaceous in response to NW-SE extension between Australia and Antarctica.

Two smaller rift basins have been mapped in the northwestern and southwestern parts of the Naturaliste Plateau. The Southwestern Rift, intersected by lines n323, 187-1, 18-96 and 18-94 (Plate 5), has a similar structural trend to the Southern Rift Basin (Plate 4). However, seismic records show that it is more symmetrical with steep bounding faults on both flanks. The sag section in this basin is less than 1 s TWT thick. Beneath the interpreted Valanginian unconformity, the sedimentary origin of the section is questionable, as its seismic character is similar to some parts of the Naturaliste Plateau "basement" (Chapter 5.5). Possible composition of the Naturaliste Plateau basement will be discussed later.

The Northwestern Rift is located to the southeast of the volcanic complex (Plate 4). It was crossed by lines n323 and 18-94 (Plate 5). The orientation and structural style of this basin is similar to the SWR. The basin is bounded by steep normal faults and only the upper part of the sedimentary fill has reasonable seismic resolution. The lower part of the syn-rift section is similar in seismic character to laminated "basement" observed in other parts of the plateau (Chapter 5.5).

Overall small rift basins of the Naturaliste Plateau seem to be structurally similar to Late Jurassic-Early Cretaceous basins of the Southern margin, for example the Eyre Sub-Basin (Willcox and Stagg, 1990; Totterdell et al., 2000).

5.4 Volcanic/intrusive complex

A large circular-shaped bathymetric and gravity high on the northwestern flank of the Naturaliste plateau has been mapped as a possible volcanic/intrusive complex (Plate 4). This feature is separated from the main part of the plateau by a marked bathymetric low. Its central part corresponds to an area of negative magnetic anomalies and its outer part to strong positive anomalies (Fig. 12).

Eltanin dredge 12 (Fig. 3) from the steep northeastern flank of Naturaliste Plateau recovered slabs of manganese crust, incorporating conglomerates at their base. Cobbles from this conglomerate range in size from 0.5 to 15 cm, and have been shown to consist of altered tholeiitic basalts closely correlating with Bunbury Tholeiitic Suite (Coleman et al., 1982). It was suggested that these conglomerates are the same as at DSDP Site 264 and covered large areas of the plateau in the Cenomanian (Jongsma and Petkovic, 1977).

An interpreted volcanic/intrusive province along the northern flank of the plateau was intersected by Lines 18-101, 18-98, 18-96 and 18-94. All sections display dome-shaped seismically transparent basement (Fig. 13). Faulting occurs throughout the feature, however fault density is greater in the west. Small grabens imaged on lines 18-101 and 18-96 contain up to 1 s TWT of syn-rift section. As Survey 18 lines have poor seismic resolution, it is not clear whether the basement here has magmatic origin or represents an uplifted block of the Naturaliste Plateau crust. However, its domed shape and clear expression in potential field data (gravity and magnetics) support the view that this feature has a magmatic origin.

5.5 Possible older basins

Basement over a large area in the central part of the Naturaliste Plateau is highly laminated and structured (Fig. 14). Its seismic character is markedly different from that of basement along the southern margin of the plateau, which is seismically bland. As was discussed in section 5.1, the basement high along the southern margin of the

Naturaliste Plateau is composed at least partly of metamorphic rocks. Composition of the laminated basement is likely to be different. Seismic data from the south Perth Basin (Survey 81) indicates that the Jurassic and older section can be strongly laminated and deformed. Although differences in acquisition and processing prevent direct comparison of the seismic character from the Shell "Petrel" Survey lines and GA Survey 81 lines, the observed similarities indicate the possible presence of Jurassic and older Perth Basin equivalent sedimentary sequences on the Naturaliste Plateau. The area of this "sedimentary" basement is shown in Plate 4 as a sag basin occupying most of the central part of the plateau.

5.6 Continent-ocean transition

The location of the continent-ocean transition in the Naturaliste Plateau area is ambiguous. Along most of its northern margin, faulted basement of the plateau gradually descends towards the Perth Abyssal Plain with little apparent change in basement structure (Fig. 15). On most lines the boundary with the unequivocal oceanic crust cannot be defined and clearly lies seaward of the seismic coverage used in this study. Only lines 18-90 and 18-92 possibly reach true oceanic crust. The boundary between the volcanic complex (Plate 4) and the Perth Abyssal Plain basement is well defined by a steep slope and large intrusions at its base. The continent-ocean transitional zone adjacent to this province appears to be fairly narrow (Plate 4). In the area adjacent to the Naturaliste Trough/Mentelle Basin (Plate 5, Lines n321and n320), transition to the Perth Abyssal Plain is gradual. Transitional zone crust is characterised by the presence of igneous rocks both as intrusive bodies and lava flows. In the northeast, in the area adjacent to the northern part of the Mentelle Basin, basement lying at about 7 s TWT is characterised by a very strong bright reflection and reflective crust underneath (Fig. 16), which may indicate volcanic flows. Overall the continent-ocean transition zone to the north of the Naturaliste plateau is 20 to 90 km wide and contains many of the features common to volcanic rifted margins, particularly those off the western Australian margin (Symonds et al., 1998).

To the south, the Naturaliste Plateau is adjoined by highly faulted basement alternating with large intrusive-looking bodies (Fig. 17). The southern part of this province belongs to the Diamantina Zone, which stretches from the Broken Ridge (104^{o}E) eastwards to about 120^{o} E (Plate 1). The crustal origin of the Diamantina Zone is unknown. It has been variously interpreted as an oceanic fracture zone (Markl, 1978), rerifted Early Cretaceous oceanic crust (Munschy, 1998), the result of ultra-slow spreading in the Late Cretaceous to Eocene (Tikku and Cande, 2000), or highly extended continental crust (Chatin et al., 1998; Borissova et al., 2002).

In this study we classify the whole of the area to the south of the Naturaliste Plateau up to the boundary with the Eocene oceanic crust as a continent-ocean transition zone (COT). It is further subdivided into the inner COT extending from the foot of slope to about 35^{o} 40' S, the outer COT stretching further 70-80 km to the south, and the zone of peridotite ridges separating Naturaliste Plateau COT from the young oceanic crust of Australian-Antarctic Basin (Fig. 9; Plate 4).

The inner COT was crossed by seismic lines n321, n322 and 187-1 (Plate 5). Morphologically it looks like a terrace off the plateau especially in its western part. The basement in the inner COT lies between 6.5 and 7 s TWT and the sediments are about 0.5 s TWT thick. The seaward boundary of the province is marked by a basement high, which could represent densely faulted uplifted basement block or intruded basement (Fig. 17). The basement in this zone has not been sampled.

The outer COT and peridotite zone were crossed only by line 187-1, therefore the outlines of these provinces have been interpreted from satellite gravity and magnetic anomaly images. The basement in the outer COT zone is highly faulted and lies deeper than that in the inner COT, between 7 and 8 s TWT. Sediment cover is very thin, only 0.2 to 0.5 s TWT thick. The basement has been sampled in two locations (MD110-DR08 & 10, Fig. 3, Appendix 2) recovering vesicular basalt.

The peridotite zone consists of intrusive-looking ridges separated by a very deep basin lying at about 7.5 s TWT and containing up to 2.5 s TWT of sediment. Basement ridges in this province were sampled in several locations (including sites outside the study area) yielding along with basalts, upper mantle rocks including perodotite, lherzolite, harzburgite and pyroxenite (Nicolls et al., 1981; Chatin et al., 1998; Royer and Beslier, 1998). Sediments in the deep basin have never been drilled or cored. Observations from seismic data in the Labuan Basin (Borissova, et al., 2002) and on the Antarctic margin to the west of the Bruce Rise (Stagg, pers. comm., May 2002) suggest the presence of a similar very deep linear basin on the conjugate margin. Geochemical evidence from peridotites dredged in the Diamantina Zone provides evidence for emplacement in a rift setting, allowing rapid exhumation and consequently limiting the degree of melting, rather than formation at a slow-spreading oceanic ridge (Chatin et al., 1998).

The total width of the southern COT is about 250 km. The possible origin of this unusually wide and complex zone will be discussed in Chapter 8.1.

6. SEISMIC SEQUENCES

6.1 Introduction

The first seismic stratigraphic scheme for the Naturaliste Plateau was developed by Jongsma and Petkovic (1977) as part of their landmark study of the plateau. It was based on regional unconformities identified from an examination of all available seismic data and correlation to DSDP Sites (Fig.6 and 7). Based on this interpretation, a more detailed seismic stratigraphy is presented below.

6.2 Sedimentary sequences

Sediment thickness over most of the Naturaliste Plateau does not exceed 1 s TWT (Fig. 11, Plate 5). Thicker successions occur only in small rift basins and in the Mentelle Basin. Tentative correlation of the Vlaming Sub-basin sequences of the southern Perth Basin (Plate 3) to seismic packages in the Mentelle Basin indicates that the Mentelle Basin syn-rift sequences probably consist of Upper Jurassic to Valanginian sediments.

Eight major sequences have been identified on the Naturaliste Plateau and the adjacent Mentelle Basin (Fig. 18). Correlation to horizons described by Jongsma and Petkovic (1977) is shown in Appendix 3. Only the post-Albian sequences are reasonably well constrained in age. An interpretation of the age of older section relies on regional correlation and comparison to the Vlaming Sub-basin.

The Valanginian breakup unconformity has been mapped in all basins of the Naturaliste Plateau. The sedimentary successions below the breakup unconformity in small rift basins have been broken into two sequences, upper (*Syn2*) and lower (*Syn1*) often separated by a pronounced unconformity (Fig. 18). The base of *Syn1* corresponds to acoustic basement of the plateau. In many cases only the base of *Syn2* is imaged on the seismic. Early Cretaceous sag-phase sediments are absent on the uplifted southern and western parts of the plateau and have a detrital origin (DSDP 258) in the east. The stratal geometry of the sag section of the Mentelle Basin is quite complex and it contains sedimentary units that occur only in this basin. The Mid-Late Cretaceous to Eocene section is mostly thin (less than 0.5 s TWT) and is represented by pelagic sediments (chalk and limestone). The Tertiary section is incomplete with Paleocene and Eocene sediments often absent. Base Tertiary corresponds to a consistent seismic boundary reflecting the change from Cretaceous chalks to nannofossil oozes. The hiatus at this boundary sometimes spans the Late Cretaceous to the Miocene (DSDP 258, Fig. 6). The youngest part of the section (the Tertiary to Recent) has poor seismic stratification and ranges in thickness from 0.2 to 0.8 s TWT. These sediments are unusually thick over most of volcanic complex province (Plate 4).

The following eight sedimentary sequences ranging in age from Late Jurassic to Recent (Fig.18, Plate 3) have been identified in the Naturaliste Plateau region:

Ju?-Parm /Syn1

The oldest sequence mapped in the Mentelle Basin (*Ju?-Pam*) has been tentatively correlated with the upper part of the Otorowiri Formation in the Vlaming Sub-Basin (Upper Jurassic to Base Parmelia Group). In the Vlaming Sub-basin the sequence has been intersected by petroleum wells Challenger 1 (Plate 5, Line 81-35) and Sugarloaf 1 (Plate 5, Line 81-40) and corresponds to highly deformed and faulted section represented mostly by sandstones. Interpretation of the Lines 81/40 and n319 suggests that the thickness of the Jurassic sediments rapidly decreases to the west across a few large faults bounding the Vlaming Sub-Basin. However, further to the west, in the Mentelle Basin, there is up to 2 s TWT of sediments below the breakup unconformity, which suggests the possible presence of sequences equivalent to older succession within the Vlaming Sub-basin (Plate 5, Lines n324, n325). The sequence is characterised by high amplitude and low frequency reflections and its base is poorly defined.

The oldest sequence identified on the Naturaliste Plateau is the lower part of the syn-rift section in the Southern Rift Basin (*Syn1*). It is bounded by the acoustic basement and a pronounced seismic boundary in the middle of rift fill. It is faulted (Plate 5, Lines n321, n325) and is characterised by high amplitude, low frequency reflections. Judging by the seismic character and general basement architecture the sequence may be equivalent in age to Ju?-Pam sequence in the Mentelle Basin.

Parm-Val/Syn2

The sequence beneath the major breakup unconformity (Valanginian) in the Mentelle Basin (*Parm-Val*) has been correlated to the Parmelia Group in the Vlaming Sub-Basin. The equivalent sequence on the Naturaliste Plateau has been mapped as *syn2*. In the Mentelle Basin the sequence is characterised by high amplitude, medium frequency reflections and in the other basins by medium amplitude, medium to low frequency reflections, which probably indicates differences in depositional environment. The sequence is often gently folded (Plate 5, Line 325) and at places is highly faulted (Plate 5, n321, n324). Seismic character and stratal geometry on the northern parts of lines n320 and 321 (Plate 5) indicate that it could be partly volcanic in origin.

Val-Barr

A prominent angular unconformity above the *Parm-Val* sequence has been mapped on seismic lines 81-35 and 81-40 (Plate 5) In Parmelia 1 this unconformity lies at about 1145 ms and falls within the Leederville Formation. No unconformity has been documented in the well, however there is a marked lithological change from mostly sandstones underneath to mostly siltstones above (Plate 2). *O. Operculata* (2c <115Ma, Aptian) has been recovered 100 m above this unconformity and *S. Areolata* (3c >133 Ma, Valanginian) about 80 m below. The inferred age of this unconformity is Barremian (~120 Ma?).

The Val-Barr sequence has been mapped in the Mentelle Basin and in the northwestern part of the Naturaliste Plateau. It was probably formed in response to regional subsidence that followed breakup in the Perth Abyssal Plain. The sequence has mostly horizontal bedding on the Naturaliste Plateau and is slightly deformed in the Vlaming Sub-basin and in the Mentelle Basin (Plate 5). It is characterised by medium to high amplitude and medium frequency reflections.

Barr-M.Alb

The mid-Albian unconformity at the top of this sequence has been intersected by DSDP Hole 258 (Chapter 4.1). It is the most prominent and widespread unconformity on the Naturaliste Plateau (Plate 5). *Barr-M.Alb* sequence below this unconformity has low to medium amplitude, medium frequency reflectors but typically weak seismic signature, which makes it appear transparent in places (Plate 5, Line 321). The seismic character and geometry of the sequence varies across the plateau. The sequence typically shows clear onlap at the depocentre edges. In the Mentelle Basin, an intermediate sequence boundary of probable Lower Albian age has been mapped within this sequence. The *Barr-M.Alb* sequence is faulted in the northeastern part of the plateau (Plate 5, Lines n321, n320) and is relatively undisturbed elsewhere on the plateau. Over most of the plateau the sequence is absent from uplifted and eroded blocks, indicating that up to the mid-Albian large areas of the plateau were still subaerial.

Basal sequences to the north and south of the Naturaliste Plateau were interpreted to be the same age as the *Val-M.Alb* sequence on the plateau. The Valanginian age of breakup in the Perth Abyssal Plain and an interpreted start of crustal extension between the Naturaliste Plateau and the Bruce Rise in the Barremian suggest that the oldest sediments overlying COT basement are likely to be of Valanginian to Barremian age. Correlation with the *Val-M.Alb* sequence on Line 320 (Plate 5) and its semi-transparent seismic character similar to that of the *Val-M.Alb* sequence, also indicate that it is likely to be Valanginian/Barremian to Albian in age.

M.Alb-San

The thickness of Mid Albian to Santonian sequence (Plate 5) ranges from less than 100 m on the uplifted southern part of the plateau to about 800m in its northern part and in the Mentelle Basin. Although very thin at places, it blankets most of the plateau. The sequence is characterised by low to medium amplitude reflections of higher frequency than the underlying section. Well data (Chapters 4.1 and 4.3) indicates that it consists of chalk and limestone both on the Naturaliste Plateau and in the Vlaming Sub-basin. The sequence displays an onlapping geometry similar to the *Val-M.Alb* sequence, which indicates continuing thermal subsidence during this period.

San-Pal

The Santonian to Early Paleocene sequence (Plate 5) is very thin (les than 100m) or absent on basement highs and up to 500 m thick in the depocentres. Its seismic character ranges from parallel with distinct reflections to chaotic reflections, particularly in the Mentelle Basin area. Well data (Chapters 4.1 and 4.3) shows widespread hiatuses during this period, which may reflect pre-breakup uplift of the southern margin. On the northern margin, however, the geometry of this sequence indicates continuing subsidence and deposition.

Pal-Eoc

The Late Paleocene to Early Eocene sequence is 300 to 500m thick on the plateau and less than 200 m thin in the Mentelle Basin (Plate 5). Its seismic character is similar to the underlying section, although parallel bedding becomes more prevalent. The sequence reaches a maximum thickness (about 500-600 s TWT) in the northwestern part of the plateau, which may have resulted from sediment transport from the uplifted southern part.

Eoc-Recent

Middle Eocene to Recent sediments are fairly thin (0.2-0.3 s TWT) over most of the plateau increasing to the northeast up to 0.4 s TWT. The sequence is characterised by medium amplitude, high frequency reflections (Plate 5). It has been deposited at depths similar to present day and is represented by nannofossil oozes. The Eocene section is missing on some parts of the plateau (Chapter 4.1).

The overall geometry of the mapped sequences indicates that there were several episodes of faulting on the Naturaliste Plateau. Major basement involved faults were probably active in the Jurassic or even earlier. Both *Syn1* and *Syn2* sequences are faulted (Plate 5, Lines n321 and n324) indicating at least two unrelated periods of faulting: one probably in the Valanginian and the other after the breakup, possibly in the Barremian. Sag phase faulting appears to be largely restricted to localised reactivation of major faults. A prominent fault on Line n324 was probably reactivated several times and shows displacement even at the sea floor. However, over most of the Naturaliste Plateau, the last fault reactivation probably took place sometime between the Paleocene and Middle Eocene.

7. RESOURCE POTENTIAL

7.1 Introduction

The study area lies adjacent and has a similar geological history to the southern Perth Basin, which has proven hydrocarbon occurrences. Exploration of the Perth Basin has led to the discovery of several commercial onshore oil and gas fields. Until now no commercial fields have been discovered in the southern Perth Basin, even though hydrocarbon shows have been encountered in several wells. Gas has flowed on test from the Permian in wells near Whicher Range 1, and commercial production is being considered (WA Dept. of Resource Development, 2001).

It has been proposed (Dept. of Industry, Science and Resources, 2001) that several active petroleum systems are present in the Perth Basin with petroleum accumulations coming from four different sources. The most prolific petroleum system is sourced by the Early Triassic Kockatea Shale. In the Vlaming Sub-basin an oil occurrence at Gage Roads 1 is thought to originate from the Late Jurassic rift-related sediments of the Yarragadee and/or Parmelia Formations (Dept. of Industry, Science and Resources, 2001).

7.2 Major depocentres

In comparison to the southern Perth Basin, where the sedimentary section within the major depocentres is 10 to 15 km thick (Vlaming Sub-Basin, Bunbury Trough), sedimentary packages in the Naturaliste plateau area are much thinner (typically up to 3 km) and most are confined to narrow grabens (Figs 19, 20). Sediment thickness in these basins is marginal for hydrocarbon generation (Deming, 1994).

The presence of structured laminated basement (Plate 5, Lines n321 and n322 at approximately 4.0s TWT) in the central part of the plateau indicates the possible presence of older sedimentary sequences. If present, this succession may have a significant thickness, similar to that in the southern Perth Basin and may contain rocks ranging in age from Permian to Jurassic.

The Mentelle Basin is the largest depocentre in the area and contains 4 to 5 km of sedimentary section. It includes about 1 km of Early Cretaceous rocks and at least 1.5 km of Jurassic section (Fig. 20). Overburden above the Cretaceous section is insufficient for petroleum generation, however Jurassic rocks beneath may be within the oil window.

Two heat flow measurements on the Naturaliste Plateau provided little information on possible source rock maturity. An extremely high value of 220 mW/m^2 registered in the northwestern part of the plateau (Von Hersen and Langseth, 1965) has doubtful accuracy (Symonds and Willcox, 1989). The measurement taken near DSDP site 264 of about 60 mW/m^2 corresponds to world average values (Jongsma and Petkovic, 1977). The tectonic history of the Naturaliste Plateau indicates the possibility of increased heat flow in the past. In the Late Cretaceous, it was close to the Kerguelen

Hotspot in the west and a volcanic rifted margin to the north. Moreover, the Naturaliste Plateau lithosphere was reheated twice, once prior to the breakup in the Perth Abyssal Plain, and the second time prior to the southern margin breakup. If the Naturaliste Plateau did have higher than average heat flows in the past, it could have resulted in maturation at relatively shallow depths.

7.3 Potential source rocks

The ***Permian*** sequence contains proven hydrocarbon source rocks (Iasky, 1993) and has been the principal target for petroleum exploration in the onshore Perth Basin. Upper Permian units with petroleum occurrences (Wagina and Dongara Formations) are represented by medium- to coarse-grained sandstone and shale with minor coal beds deposited in terrestrial environment in the east and open marine in the west and southwest (Cawood and Nemchin, 2000). The closest location to the study area, where Permian rocks were reached by drill is the Vlaming Sub-basin. Felix 1 on the northwestern flank of the basin sampled an interbedded sandstone, siltstone and claystone succession of Kungurian (Early Permian) age. No hydrocarbons were encountered in the well (Woodside Offshore Petroleum, 1998). Permian-aged rocks may by present below the Jurassic/Mesozoic section in the Mentelle Basin and in the areas of laminated basement of the central Naturaliste Plateau.

In the northern Perth Basin, the Early Triassic ***Kockatea Shale*** overlies Upper Permian sediments and forms both a source and regional seal (Mory and Isaky, 1996). The Kockatea Shale accumulated in a shallow marine environment and thickens to the south (Mory and Isaky, 1996). Triassic sediments potentially could be present in the Naturaliste region in the same areas as Permian rocks.

In the southern Perth Basin, the fluvial Early Jurassic ***Cockleshell Gully Formation*** has been shown to possess reasonable source rock potential (Iasky, 1993). The ***Yarragadee Formation*** (Middle to Late Jurassic, Plate 3) is a fluvial deposit consisting thin shaly sequences interbedded between major channel sandstone units (Marshall et al., 1993). Shaly units of this formation commonly contain more than 1.5 % total organic carbon (TOC), and in Wanbro 1 and Sugarloaf 1, TOC values in some units are over 2.5% (Marshall et al., 1993). Yarragadee Formation equivalents are likely to underlie the deeper parts of the Mentelle Basin. It could also be present in *Syn1* sequence in parts of the Naturaliste Plateau.

In the northern Perth Basin, the best Mesozoic source rock interval occurs near the base of the Middle to Late Jurassic Yarragadee Formation (around Houtman 1 and Gun Island 1). The two principal source facies containing oil-prone kerogen occur in the lower part of the Yarragadee Formation, which is marginal marine at its base.

The Parmelia Group (Plate 3) consists of continental, deltaic and shallow marine sediments. Fluvial facies contain less organic matter than in the Yarragadee Formation (<1-3 % TOC). On the basis of pyrolysis data, Marshall et al. (1993) estimated that in the Vlaming Sub-basin this unit has the potential to contain mixed oil and gas source material. However, in the Naturaliste Plateau basins, this sequence is likely to be immature due to insufficient depth of burial.

7.4 Potential reservoir and seal

Sandstones in Jurassic and Early Cretaceous successions may possess good reservoir properties. Porosities in the Perth Basin reservoir sandstones typically vary from 5-20% offshore and up to 40% onshore (Tupper et al., 1994). The Warnbro and Parmelia Groups both have good reservoir potential with porosities in some units of these formations reaching 22% (Crostella and Blackhouse, 2000).

Both regional and local seals are present at many stratigraphic levels within the Perth Basin. In the Cretaceous section, the Otorowiri Member and the South Perth Shale provide good seals, but their areal extent is limited (Dept. of Industry, Science and Resources, 2001). Stratigraphically equivalent units on the Naturaliste Plateau are likely to contain more shales as the area was bathymetrically lower than the adjacent Perth Basin, at least since the Early Cretaceous.

7.5 Potential plays and exploration risks

The most prospective area in the Naturaliste Plateau region is the Mentelle Basin. Possible plays include horst and tilted fault blocks and structural-stratigraphic traps. The greatest discouragement to exploration at present in the region is the water depth: most of the plateau and the Mentelle Basin lie in greater than 2500m of water. However, if oil has been generated in the Mentelle Basin, it may have migrated to the east into traps at much shallower water depths.

Other exploration risks in the region include immature source rocks, the potentially localised nature of seals, and the loss of hydrocarbons through fault reactivation. Reservoir/seal geometries are likely to be critical for the discovery of significant hydrocarbon accumulations.

8. DISCUSSION

8.1 Extent of continental crust in the Naturaliste Plateau region

The debate about the origin of the crust beneath the Naturaliste Plateau has spanned almost 30 years. Some authors (e.g. Coleman et al., 1982; Storey et al., 1992; Colwell, et al., 1994) inferred an oceanic magmatic origin for the plateau, whereas others (e.g.Jongsma and Petkovic, 1977; Symonds and Willcox, 1989) have favoured a continental origin. With the recovery of continental rocks on its southern margin (Beslier et al., 2001; Chatin et al., 1998) it is now clear that the Naturaliste Plateau is at least partly continental, however, the areal extent of the continental crust beneath the plateau remains unclear. The evidence for the extent of continental crust is given below.

MD110 dredge 11, which recovered high-grade gneisses, is located on a prominent basement ridge extending along almost the whole southern margin of the plateau. On the seismic data this ridge looks fairly uniform and is characterised by chaotic seismic reflections. We suggest that the southernmost part of the plateau is composed of continental rocks similar to those recovered by dredge 11.

To the north of the southern margin ridge, the seismic character of basement changes. On most lines (n321, n322, n325) it becomes characterised by areas of parallel, dipping reflectors of varying amplitude offset by faults, which alternate with featureless basement highs. A number of small rift basins formed within this crustal province. The age of the syn-rift section in the larger of the rift basins is interpreted to be Late Jurassic - Early Cretaceous. The seismic character of the laminated basement indicates that it is likely to be Paleozoic rocks, rather than volcanic sequences.

The northwestern part of the plateau (Chapter 5.4) is probably underlain mostly by magmatic crust. However, the presence of shallow half-grabens with syn-rift fill indicates that this province is more likely to represent highly-intruded continental crust, rather than a magmatic complex formed on oceanic crust.

The proportion of continental crust beneath the northern continental-ocean transition zone (COT) is difficult to estimate. Seismic data are relatively sparse and on lines that do cross the probable COT (n323, n321), the presence of volcanics partly obliterates basement character underneath.

This study indicates that continental crust off the southern margin of the Naturaliste Plateau underlies at least the inner part of the COT (Plate 4). The outer part of the COT may be in part underlain by old oceanic crust, but most likely is a mixture of highly extended continental and magmatic crust. The alkaline nature of basalts sampled in this zone (Chatin et al., 1998) suggests that they were not formed through normal mid-ocean ridge spreading and are more likely to have been formed in a continental rift setting. The peridotite zone seaward of the outer COT probably represents exposed continental mantle unroofed prior to the onset of spreading along the southern margin.

8.2 Age and origin of the rift structures on the Naturaliste Plateau

It is not possible to directly tie sequences in rift basins on the Naturaliste Plateau to Perth Basin successions. The regional unconformity at the top of the syn-rift section on the Naturaliste Plateau has been correlated with reasonable confidence to the Valanginian breakup unconformity in the Perth Basin. *Syn1* and *Syn2* sequences could be both Early Cretaceous in age, or may contain older (?Jurassic) sediments.

Formation of rift basins on the Naturaliste Plateau probably occurred at much the same time as in the Vlaming Sub-basin, that is during the Middle Jurassic to Early Cretaceous. The orientation of normal faults bounding rift basins changes from WSW-ENE in the southern part of the plateau to SW-NE in its northern part, which indicates differences in the stress field across the plateau. With the currently available data, it is not possible to determine whether there is an age progression in the initiation of rifting in different parts of the plateau; however, it is apparent that faulting episodes and periods of maximum sedimentation vary in different areas.

Regional inversion of the Perth Basin associated with the Valanginian breakup resulted in extensive uplift and erosion of the pre-breakup section throughout the basin. Song and Cawood (2000) estimated that about 3.2 km of pre-breakup succession was removed from the Vlaming Sub-basin. In the major depocentres, basin inversion led not only to uplift and erosion, but also to folding. On the Naturaliste Plateau, local inversion along faults and the presence of folded strata (Plate 5, Lines n320, n323, n325) indicate that similar processes took place there. Because of the localised nature of this deformation and the sparse seismic grid, these structuring events are still poorly understood.

9. GEOLOGICAL EVOLUTION OF THE NATURALISTE PLATEAU REGION

Although the geological history of the Naturaliste Plateau goes back to the Cambrian (high-grade gneisses on its southern flank), the data available to date allow us to interpret its evolution only since about the Permian. Results of this study suggest that tectonic development of the Naturaliste Plateau was affected by rifting on both the Australia's western and southern margins. The structural characteristics of the plateau were first determined by the breakup between Australia/Antarctica and India and then modified by the breakup between Australia and Antarctica.

The main tectonic and depositional events in the study area and surrounding regions are summarised in Plate 3 and described below.

9.1 Permian intracratonic rifting

In the Permian, the Naturaliste Plateau was part of Gondwana and was above sea level. Intracratonic rifting in the Perth Basin (and elsewhere) possibly extended to the Naturaliste Plateau and may have resulted in the deposition of terrigenous sediments. Permian-aged sedimentary successions may be present at shallow depths in the central part of the plateau.

9.2 Jurassic-Early Cretaceous rifting

At the end of the Jurassic to the beginning of the Cretaceous, a large extensional terrane formed around the incipient plate boundaries between Greater India, Australia and Antarctica. In the southern Perth Basin (Vlaming Sub-basin) very thick Jurassic sediments of mostly fluvial origin were deposited in its depocentres. On the Naturaliste Plateau, a large number of small rift basins formed. The largest depocentre was located in the Naturaliste Trough area (Mentelle Basin). Its N-S orientation indicates that it could have formed over a pre-existing structure. Rift basins probably filled up with largely clastic terrigenous sediments during this period. Syn-rift deposition continued up to the Valanginian.

9.3 Valanginian breakup between Australia/Antarctica and India

In the Valanginian (Chron M13), seafloor spreading started in the Perth, Gascoyne and Cuvier Abyssal Plains as well as on parts of the Antarctic margin (Enderby Basin) that were conjugate to India. Regional uplift and erosion, as indicated by the erosional nature of the Valanginian unconformity, preceded the breakup. Movement along the large strike-slip zones, the Naturaliste and Leeuwin Fracture Zones, resulted in reactivation of Jurassic faults, with strike-slip movement on some normal faults. Faulting occurred mostly on the northern part of the plateau.

9.4 Barremian-Albian basaltic volcanism

The earliest known volcanism in the region, the Bunbury Basaltic Province (Colwell et al., 1994), began in the Valanginian. Ar-Ar data indicates that it evolved in two stages: Carusiana basalts erupted at about 132 Ma (Coffin et al., in press) and Gosselin basalts at about 123 Ma (Frey et al., 1996). The Rajmahal Traps in Northeastern India formed at about 117 Ma (Coffin et al., in press), at the same time (117 Ma) that massive volcanism commenced on the Southern Kerguelen Plateau (Duncan and Pringle, in press). Several large volcanic provinces, which developed close to the locus of the breakup, affected the evolving west Australian continental margin, including the northern margin of the Naturaliste Plateau. Seismic data suggests the presence lava flows and intrusions in the northern continent-ocean transition zone; volcaniclastic sediments may been deposited in the basins. Basaltic magmatism probably affected significant parts the plateau and it is likely that the volcanic complex in the northwestern part of the plateau was emplaced at this time.

9.5 Albian-Campanian amagmatic extension between Australia and Antarctica

After the Valanginian breakup, the locus of extension moved to the south of the Naturaliste Plateau. It is not clear when the extensional faulting started between the Naturaliste Plateau and its conjugate feature on the Antarctic margin, the Bruce Rise. The presence of ?Albian sediments in the Labuan Basin (Borissova et al., 2002), which is conjugate to the Diamantina Zone west of the Naturaliste Plateau, and the Barremian-Cenomanian age of the oceanic crust underpinning the Gonnevile Triangle (Munschy, 1998) suggest that by the Albian extension was underway. It is possible that very limited spreading (which later failed) took place in the western part of this extensional terrane. An Early Eocene satellite gravity reconstruction of the region (Fig. 21) shows the location of major continental blocks to the west of the Australian continent and the wide extensional terrane that existed between Australia and Antarctica at that time. The COT to the south of the Naturaliste Plateau, including the Diamantina Zone, represents a part of this extensional terrane.

9.6 Breakup along the southern margin (Campanian-Eocene)

Extension and seafloor spreading between India, Antarctica, and Australia continued uninterrupted to about 85 Ma. In the Santonian (85 Ma) a significant plate reorganisation took place resulting in a change of spreading direction and the rapid movement of India to the north (Royer and Coffin, 1992). At about the same time in the Late Santonian Early Campanian (~83Ma,) spreading started in the Great Australian Bight (Sayers et al., 2001), while the Naturaliste Plateau/Diamantina Zone and the Bruce Rise remained connected.

Seafloor spreading between Australia and Antarctica in the Campanian to Eocene was extremely slow (Tikku and Cande, 1999). Magnetic lineations along the Australian and Antarctic margins (Cande and Mutter, 1982; Tikku and Cande, 1999), as well as plate tectonic reconstructions, indicate that towards the west, in the study area, it was accommodated by amagmatic extension and diffuse deformation (Tikku and Cande, 2000). In the Naturaliste Trough area, pre-breakup tectonic reactivation resulted in strike-slip movement and compression along some segments of major normal faults and inversion of some basin structures. Between 90 and 84 Ma, extension in the Diamantina Zone reached a critical point resulting in the exhumation of peridotites (Chatin et al., 1998).

9.7 Eocene breakup and post-Eocene subsidence

The next major tectonic event in the region was the separation of the Diamantina Zone and the Labuan Basin at about 43 Ma (anomaly 20) in the mid-Eocene (Royer and Coffin, 1992). This breakup coincided with the start of fast spreading in the Southeast Indian Ocean. The breakup was preceded by uplift on the southern part of the Naturaliste Plateau, resulting in very steep faults along the whole southern margin of the plateau. The southernmost parts of the margin may have been emergent at the time. Thick sediments of Paleocene to Eocene age on the northern and northwestern parts of the plateau suggest that the southern margin was bathymetrically higher and sediment transport was generally in a northerly direction.

Since the Eocene breakup, the Naturaliste Plateau has been gradually subsiding. Although there have been no major tectonic events since the Eocene, movements along some faults continued until the Recent. These intermittent fault movements could be related to intraplate stress.

10. CONCLUSIONS

The Naturaliste Plateau is a westward extension of the Australian continent composed of Paleozoic rocks overlain by Mesozoic sedimentary and volcanic successions and thin Cainozoic sediments. Its development was controlled by tectonic processes on both the western and southern margins of Australia and includes:

- continental extension and rifting in the Jurassic-Early Cretaceous with formation of several rift basins;
- uplift and erosion preceding the Valanginian breakup of India and Australia/Antarctica followed by breakup-related volcanism on its northern margin;
- thermal subsidence accompanied by deposition of carbonate shelf sediments in the Late Cretaceous;
- uplift of the southern flank of the plateau preceding the breakup of the Naturaliste Plateau/Diamantina Zone and the Bruce Rise in the Eocene, fault reactivation in the Naturaliste Trough in settings varying from transtensional to transpressional, resulting in inversion of some basin structures; and
- continuing subsidence from the Eocene to Recent; reactivation of individual faults in the eastern part of the plateau and in the Naturaliste Trough area.

Jurassic-Early Cretaceous rift basins on the Naturaliste Plateau are typically small grabens or half-graben containing up to 2.5 km of sedimentary section. The petroleum potential of these basins is probably negligible, unless they are floored by older (?Permo/Triassic) strata. The largest sedimentary basin in the study area is the Mentelle Basin underlying the Naturaliste Trough, which contains up to 5 km of sediments. This basin may be potentially prospective for oil and gas, particularly in the long-term.

The continental nature of part of the Naturaliste Plateau has been confirmed by recent dredge results. Analysis of the seismic data as part of the present study indicates that most of the plateau is underlain by continental crust adjoined by a wide zone of continent-ocean transitional crust. On the northern margin of the Naturaliste Plateau, this zone is of volcanic origin and is 20 to 90 km wide. On the plateau's southern margin, it is almost 200 km wide and is represented by a highly–faulted and extended terrane alternating with intrusions that form high basement ridges. The inner part of this zone, adjacent to the Naturaliste Plateau, is probably underlain by extended continental crust. The outer part of the continent-ocean transition zone, known as Diamantina Zone, could be floored either by highly extended continental, or Early Cretaceous slow-spreading crust or a mixture of both, including exhumed peridotites on its southern side. The geochemical characteristics of dredged peridotites indicate that at least the eastern part of the continent-ocean transition zone is underpinned by exhumed continental upper mantle.

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APPENDICES

Appendix 1

1982 United Nations Convention on the Law of the Sea (UNCLOS)

Article 76 : Definition of the continental shelf

1. The continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance.

2. The continental shelf of a coastal State shall not extend beyond the limits provided for in paragraphs 4 to 6.

3. The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof.

4. (a) For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by either:

   (i) a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or

   (ii) a line delineated in accordance with paragraph 7 by reference to fixed points not more than 60 nautical miles from the foot of the continental slope.

(b) In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base.

5. The fixed points comprising the line of the outer limits of the continental shelf on the seabed, drawn in accordance with paragraph 4 (a) (I) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depths of 2,500 metres.

6. Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from

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which the breadth of the territorial sea is measured. This paragraph does not apply to submarine elevations that are natural components of the continental margin, such as its plateaux, rises, caps, banks and spurs.

7. The coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by coordinates of latitude and longitude.

8. Information on the limits of the continental shelf beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured shall be submitted by the coastal State to the Commission on the Limits of the Continental Shelf set up under Annex II on the basis of equitable geographical representation. The Commission shall make recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. the limits of the shelf established by a coastal State on the basis of these recommendations shall be final and binding.

9. The coastal State shall deposit with the Secretary-General of the United Nations charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf. The Secretary-General shall give due publicity thereto.

10. The provisions of this article are without prejudice to the question of delimitation of the continental shelf between States with opposite or adjacent coasts.

Appendix 2

Details of gelogical sampling sites in the study area.

	Year	Survey	Sampl e -ID	Latutude-start	Latutude - finish	Longitude -start	Londitude -finish	Type	Penetr ation (m)	Volume (kg)	Surface sediments
1	1972	Eltanin 55	DR12	-32.9100		110.9700		dredge			Slabs of manganese mat with conglomerate sediment at its base
2	1966	Robert Conrad	56	-33.6667		112.6667		core	2.2200		pinkish-gray calcilutite and foraminiferal lutite
3	1977	Diamantina	DR11	-36.6333		112.2666		dredge			Blocks of ultra-mafic rocks covered by manganese crust
4	1998	Marion Dufresne 110	DR01	-37.0600	-37.0560	119.1500	119.1750	dredge		2.0000	Dolerite basalts (fresh), gabbro, sediments, charts and nodules
5	1998	Marion Dufresne 110	DR02	-37.6160	-37.5800	119.9000	119.8900	dredge		43.6000	Perodotite, lherzolite, gabbro, pyroxenite, basalt
6	1998	Marion Dufresne 110	DR03	-37.3390	-37.2410	118.2288	118.2100	dredge		76.0000	Basalt, dolerite, gabbro
7	1998	Marion Dufresne 110	DR04	-37.3483	-37.3287	117.8166	117.7706	dredge		17.0000	Olivine basalt and basalt with plagioclase
8	1998	Marion Dufresne 110	DR05	-37.0465	-37.0370	117.0788	117.0672	dredge		9.8000	(Vesicular)Basalt, manganese crusts
9	1998	Marion Dufresne 110	DR06	-36.3000	-36.3000	115.9667	115.9500	dredge		313.5000	Lherzolite, harzburgite, basalt
10	1998	Marion Dufresne 110	DR07	-35.6666	-35.6500	115.0500	115.0500	dredge		66.5000	Gneiss and granite
11	1998	Marion Dufresne 110	DR08	-36.3938	-36.4058	112.2338	112.2427	dredge		49.2000	(Vesicular)Basalt
12	1998	Marion Dufresne 110	DR09	-36.6167	-36.6417	112.2417	112.2417	dredge		15.1000	peridotite, gabbro harzburgite
13	1998	Marion Dufresne 110	DR10	-36.0116	-36.0265	111.4132	111.4085	dredge		17.2000	Basalt
14	1998	Marion Dufresne 110	DR11	-35.0933	-35.0812	110.3500	110.3437	dredge		77.3000	Metamorphic rocks, granite, diorite, gabbro-basalt
15	1994	Marion Dufresne 80	DR3	-36.5000		106.9000		dredge			Highly altered peridotites in a manganiferous matrix
16	1994	Marion Dufresne 80	DR5	-34.3000		103.1333		dredge			Slightly porphyritic alkaline basalts
17	1994	Marion Dufresne 80	DR7	-34.3000		103.1333		dredge			Slightly porphyritic alkaline basalts

	Age of the SS	Age of oldest sediments	Lithology of oldest sediments	Source
1	Unknown	Pre-Cenomanian	basalt cobbles in a mineral suite derived from granite-gneiss terraine	Coleman, P.J., Michael, P.J. and Mutter, J.C., 1982
2	Plestocene	Turonian	Pelagic ooze and clay, mostly coccolith plates and forams	Burkle, L.H., Saito, T. and Ewing, M., 1967
3	Pleistocene (?)	Neocomian	Ultramafic blocks containing lherzolites,clinopyroxenite and serpentinite	Nicholls, I.A., Ferguson, J., Jones, H., Marks, G.P. and Mutter, J.C., 1981
4	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
5	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
6	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
7	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
8	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
9	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
10	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
11	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
12	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
13	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
14	Unknown	n/a	n/a	Royer J.-Y., Beslier, M.-O. Rapport de campagne MD110/MARGAU, 1998
15	Unknown	n/a	n/a	Chatin, F., Robert, U., Monyigny, R. and Whitechurch, H., 1998
16	93+-4Ma	n/a	n/a	Chatin, F., Robert, U., Monyigny, R. and Whitechurch, H., 1998
17	93+-4Ma	n/a	n/a	Chatin, F., Robert, U., Monyigny, R. and Whitechurch, H., 1998

Appendix 3

Interpreted seismic sequences and correlation with previous work on the Naturaliste Plateau.

Sequence (this study)	**Boundary horizon**		**Age**	**Lithology from the wells, seafloor cores and dredges**	**Correlations**
	upper	lower			(Jongsma and Petkovic, 1977)
Eo-Q	wb	Eo	Mid Eocene to Recent	Nannofossil ooze	A to Recent
Pal-Eo	Eo	Pal	Paleocene to Mid Eocene	Nannofossil chalk	Horizons B to A
San-Pal	Pal	San	Santonian to Paleocene	Chalk and limestone	
Alb-San	San	Alb	Mid Albian to Santonian	Chalk and limestone, detrital clay, volcaniclastic conglomerate	Horizons C to B
Barr-Alb	Alb	Barr	Barremian to Mid Albian	Sandstones, shales and siltstones (Perth Basin)	Horizons D to C
Val-Barr	Barr	Val	Valanginian to Barremian	Sandstones, shales and siltstones (Perth Basin)	
Syn2/Parm-Val	Val	Syn2/Parm	~ 140 Ma. Equivalent to Parmelia Group (?)	Sandstones, shales and siltstones (Perth Basin)	
Syn1/Ju?-Parm	Syn2/Parm	NP_base/Ju?	~ 145-140 Ma. Equivalent to the top part of the Otorowiri Formation	Mostly sandstone with some claystone (Perth Basin)	

FIGURES

Fig. 1. Bathymetric image showing location of the study area (red box). Green line is the Exclusive Economic Zone (EEZ) boundary and pink line is the preliminary boundary of the extended Continental Shelf (after Symonds et al., 1998). The latter line is not necessarily indicative or representative of the final outer limit of the Continental Shelf that might be used by Australia in any submission it makes to the Commission on the Limits of the Continental Shelf. NP – Naturaliste Plateau, WP – Wallaby Plateau, and EP – Exmouth Plateau.

Fig. 2. Location of seismic lines used in the study. DSDP wells shown as red circles. AEEZ is shown as light green area, preliminary area of Extended Continental Shelf beyond the AEEZ shown as pink area. This area are not necessarily indicative or representative of the area of Extended Continental Shelf that Australia may include in any submission it makes to the Commission on the Limits of the Continental Shelf. Bathymetric contours from the GEBCO data set.

Fig. 3. Satellite gravity image showing location of geological sampling sites. Petroleum exploration wells (Perth Basin) shown as red circles, DSDP holes – green circles, dredges – blue triangles and a sedimentary core – yellow circle.

Fig. 4. Plate tectonic setting of the Naturaliste Plateau. Magnetic lineations after Cande et al. (1989). Predicted bathymetry from Smith and Sandwell (1997). NP- Naturaliste Plateau; BR – Broken Ridge; KP – Kerguelen Plateau; BRR – Bruce Rise, LB – Labuan Basin, DZ – Diamantina Zone and SEIR – Southeast Indian Ridge.

Fig. 5. Geological setting of the Naturaliste Plateau in relation to major basins of Australian Continental margin. Outlines of sedimentary basins from National Geoscience Datasets (http://www.ga.gov.au/map/national/).

Fig. 6. Lithostratigraphic column at Site 258 (after Davies et al., 1974) showing sequence picks and correlation with the seismic. Equivalent Jongsma and Petkovic (1977) horizon names are shown in brackets.

Fig. 7. Lithostratigraphic column at Site 264 (after Hayes et al., 1975) showing sequence picks and correlation with the seismic. Equivalent Jongsma and Petkovic (1977) horizon names are shown in brackets.

Fig. 8. Stratigraphy of the southern Perth Basin (compiled by V. Passmore, 2001)

Fig. 9. Tectonic provinces and structural elements of the Naturaliste Plateau region.

Fig. 10. Depth to basement (in s TWT) over the Naturaliste Plateau region derived from the seismic data.

Fig. 11. Sediment thickness (in s TWT) over the Naturaliste Plateau region derived from the seismic data.

Fig. 12. Magnetic anomalies over the Naturaliste Plateau and surrounding areas with outlines of basement provinces (shown as yellow lines).

Fig. 13. Seismic line across the possible volcanic/intrusive complex on the northern part of the Naturaliste Plateau (Line 18-94).

Fig. 14. Example of an area with laminated basement, central part of the Naturaliste Plateau (Line n321).

Fig. 15. Seismic line across the northern slope of the Naturaliste Plateau showing basement character (Line 18-88).

Fig. 16. Seismic character of the northern continent-ocean transition (COT) zone adjacent to the continental margin off South Perth Basin (Line n317).

Fig. 17. Seismic character of the southern continent-ocean transition zone (Line 187-1).

Fig. 18. Correlation between seismic sequences, drilled stratigraphy and regional tectonic events in the Naturaliste Plateau area.

Fig. 19. N-S cross-section through the Naturaliste Plateau based on interpreted seismic line N322.

Fig. 20 W-E cross-section through the Naturaliste Plateau based on interpreted seismic line N325.

Fig. 21. Satellite gravity pre-breakup (Early Eocene) reconstruction of the Naturaliste Plateau region. Continental blocks are shown by yellow hatch, possible continental blocks - by green hatch and Diamantina Zone is outlined by a thick red line. NP - Naturaliste Plateau; BrR - Bruce Rise; DZ - Diamantina Zone; GTr - Gonneville Triangle; BR - Broken Ridge; WR - William's Ridge; CKP - Central Kerguelen Plateau; SKP - Southern Kerguelen Plateau; EB - Elan Bank.

PLATES

Plate 1. Bathymetric image of the Naturaliste Plateau and surrounding basins (Petkovic and Buchanan, 2002). The image is based on compilation of ship track and swath mapping data. Predicted bathymetry (Smith and Sandwell, 1997) was used where other data were not available.

Plate 2. Lithostratigraphic columns for DSDP holes 258 and 264 on the Naturaliste Plateau and petroleum wells Sugarloaf 1, Parmelia 1, Challenger 1 in the Vlaming Sub-basin.

Plate 3. Stratigraphic correlation and tectonic events on the Naturaliste Plateau, in the southern Perth Basin and the Ceduna Sub-Basin (Great Australian Bight).

Plate 4. Tectonic provinces and structural elements of the Naturaliste Plateau region.

Plate 5. Interpreted seismic sections from Shell "Petrel" Survey GA Survey 187 and GA Survey 81.

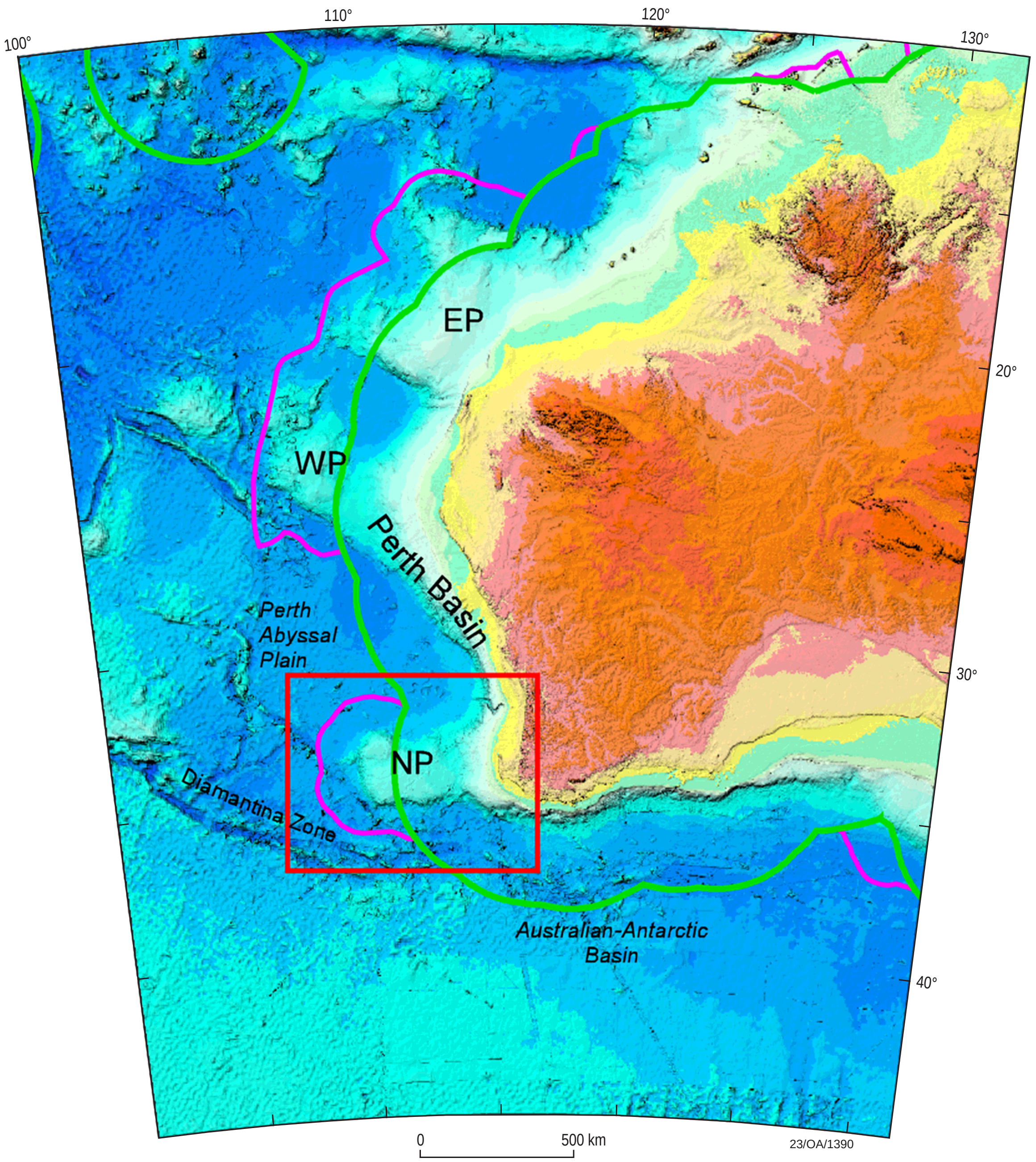

Fig. 1. Bathymetric image showing location of the study area (red box). Green line is the Exclusive Economic Zone boundary and pink line is the preliminary boundary of the extended Continental Shelf (after Symonds et al., 1998). The latter line is not necessarily indicative or representative of the final outer limit of the Continental Shelf that might be used by Australia in any submission it makes to the Commission on the Limits of the Continental Shelf.
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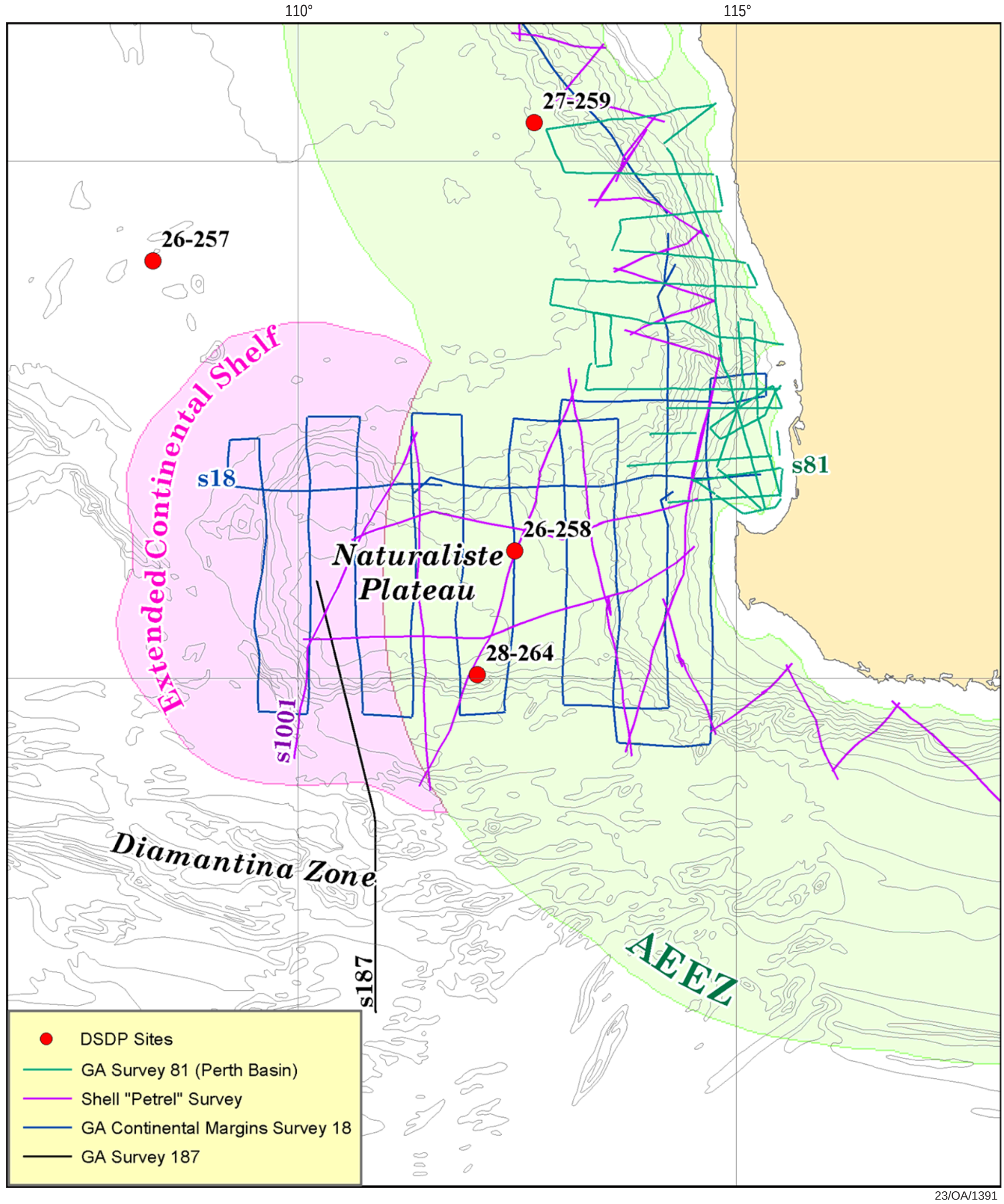

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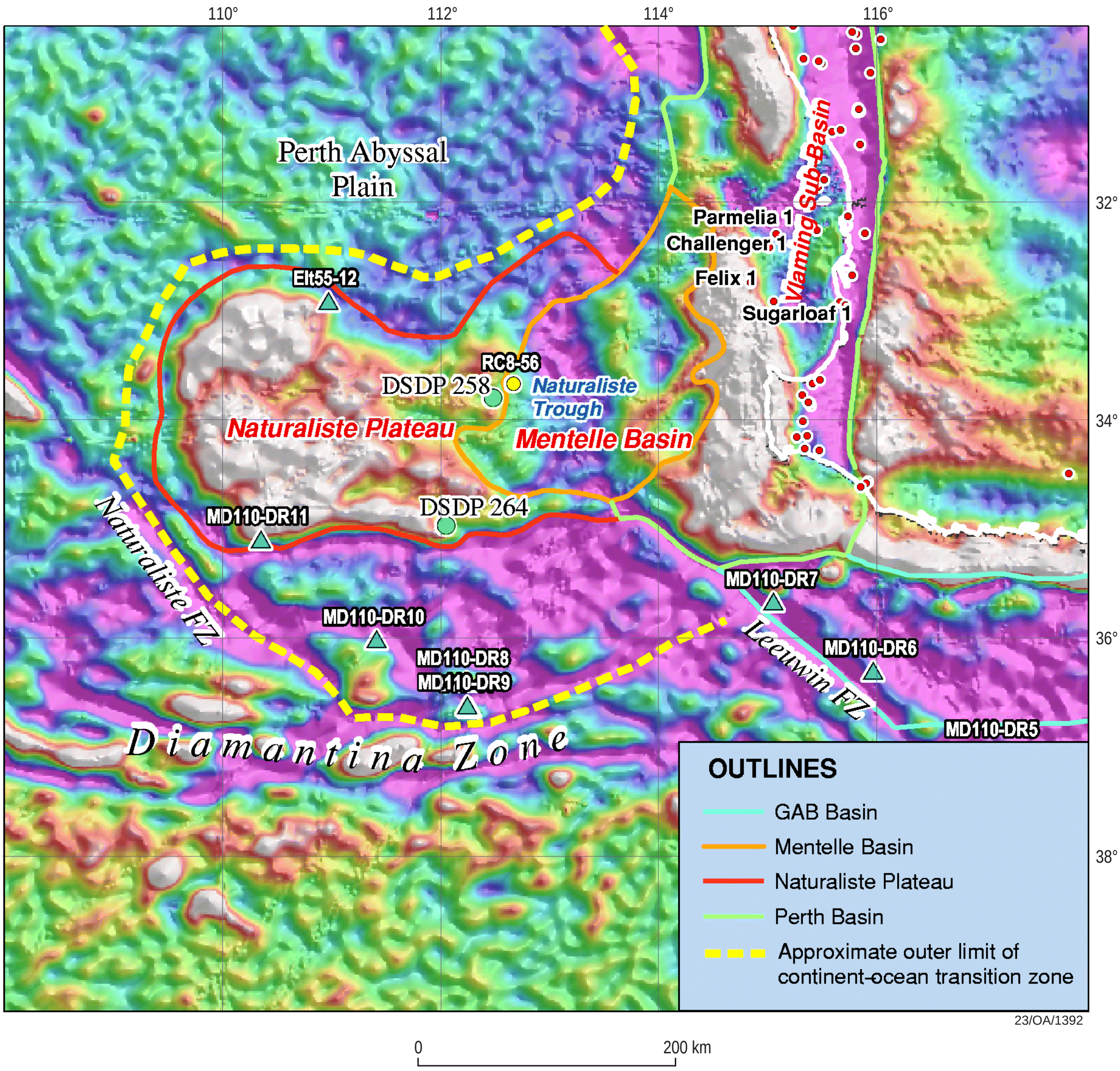

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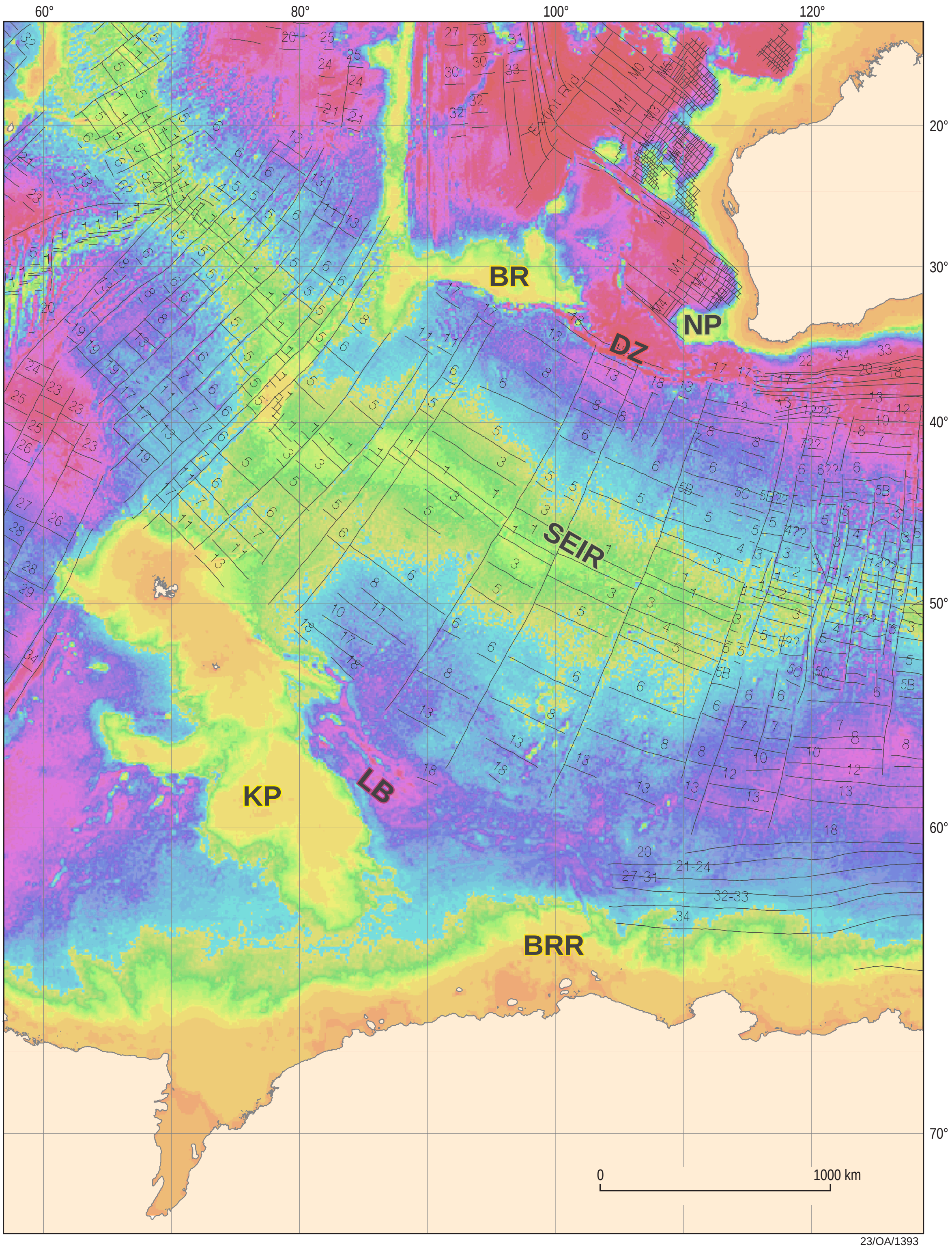

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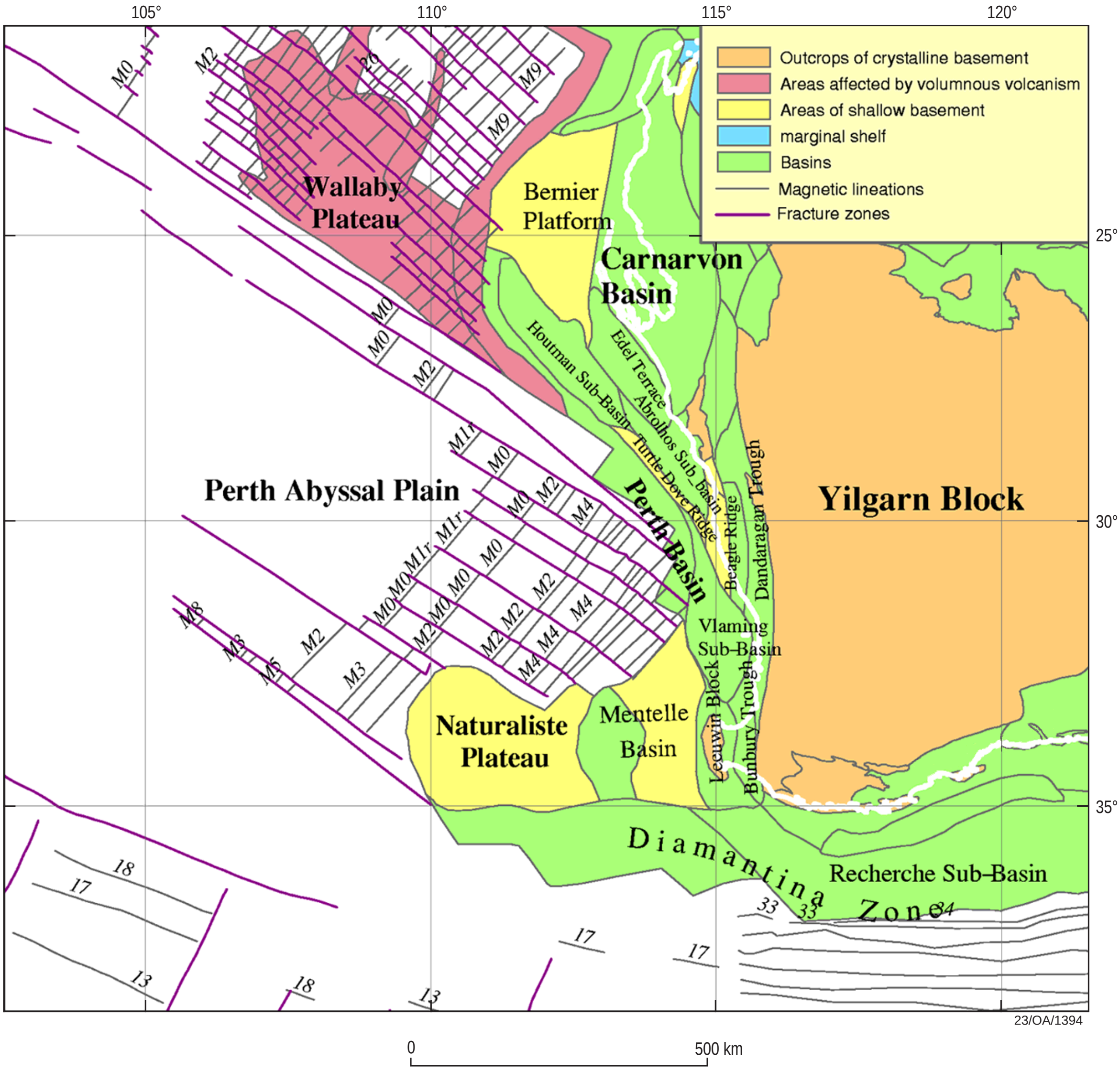

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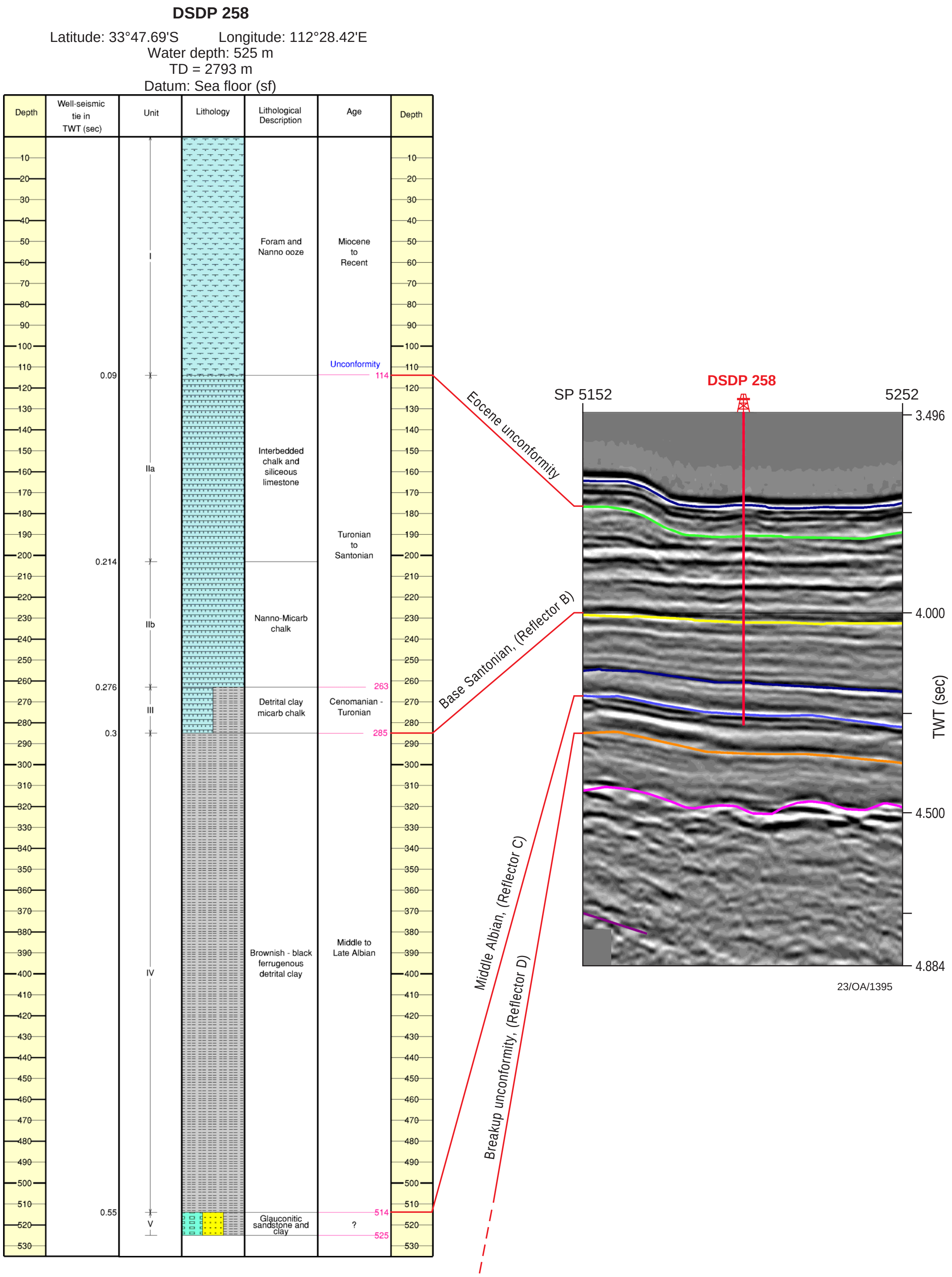

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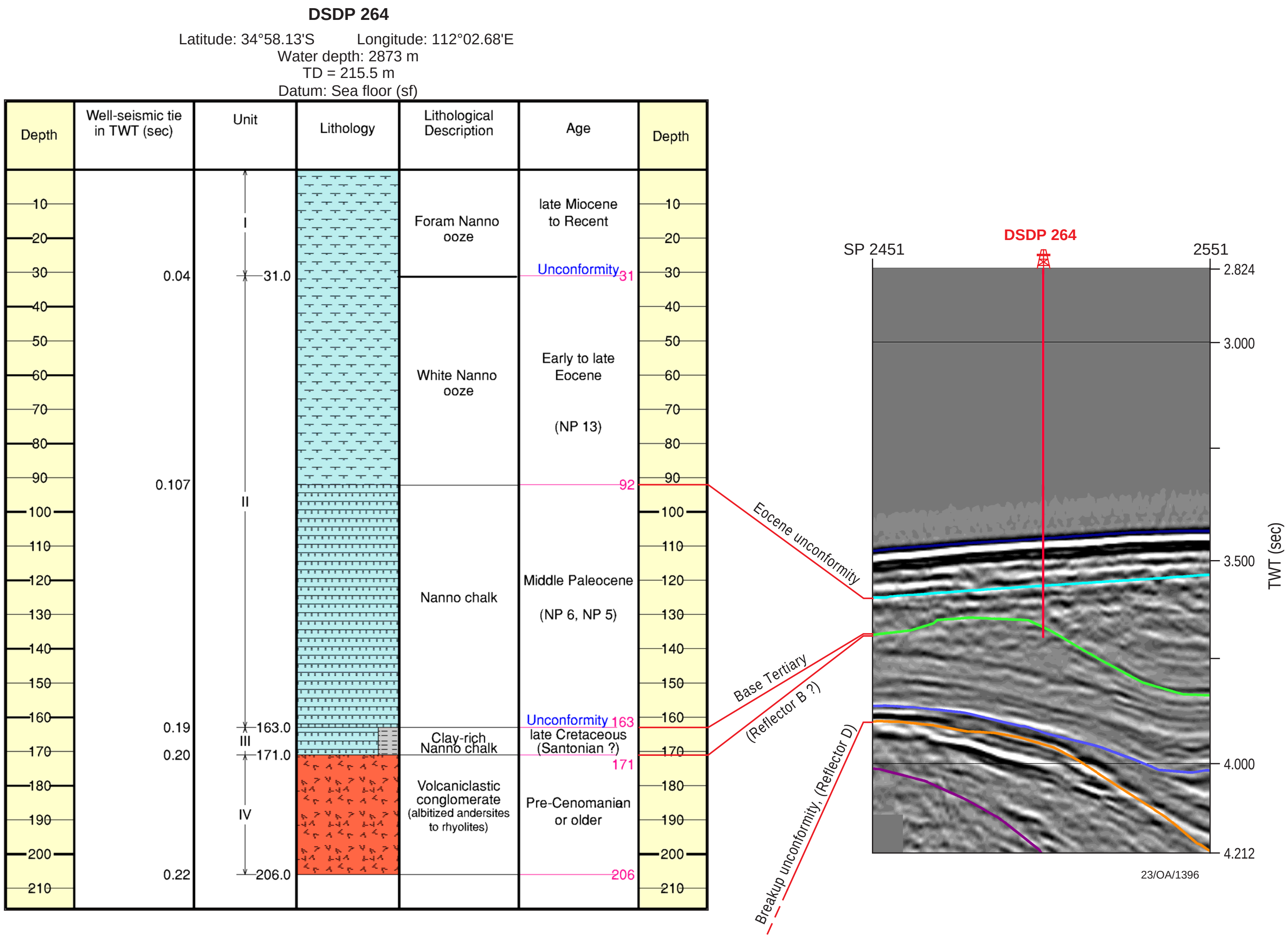
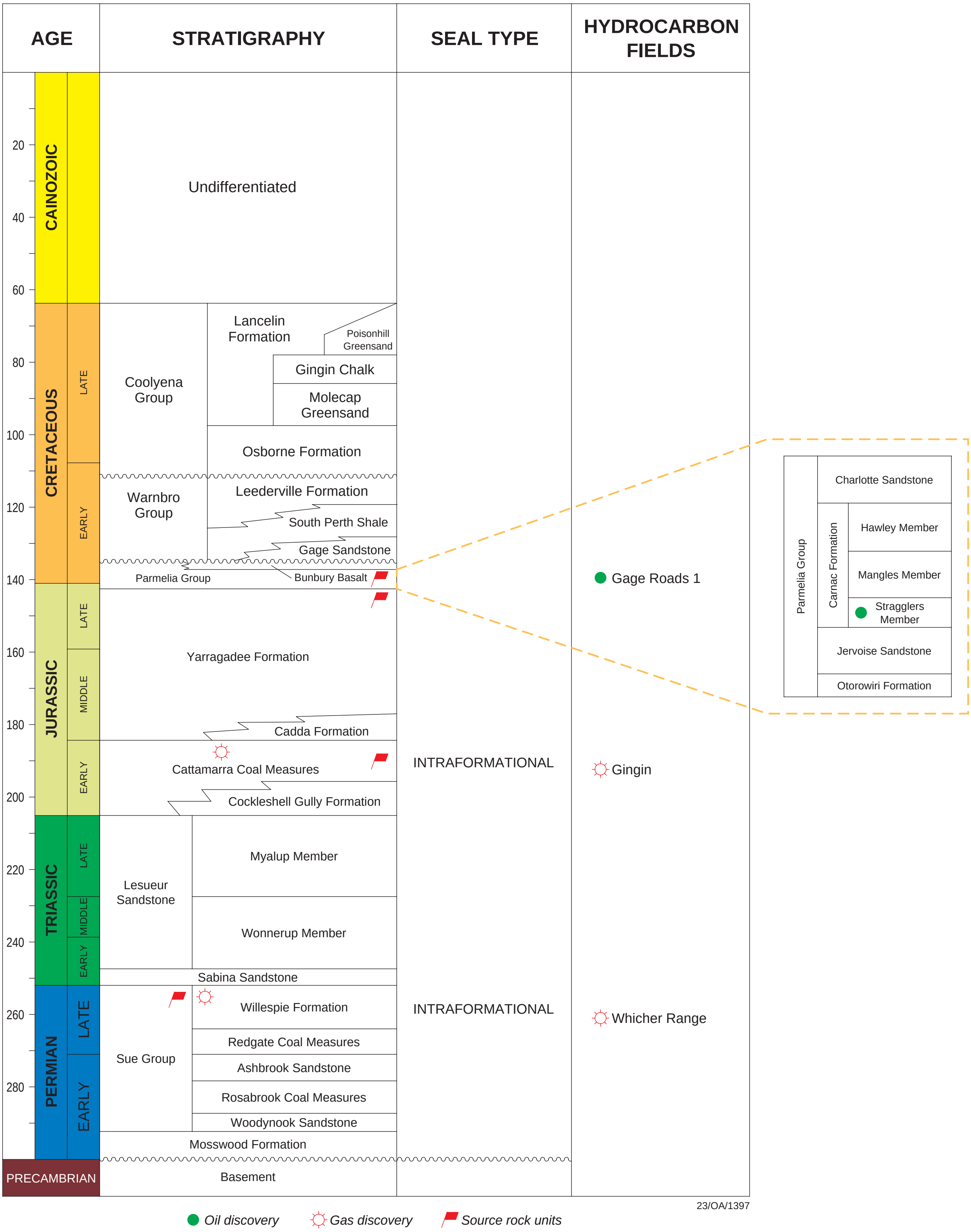


Fig. 7. Lithostratigraphic column at Site 264 (after Hayes et al., 1975), showing sequence picks and correlation with the seismic. Equivalent Jongsma and Petkovic (1977) horizon names are shown in brackets



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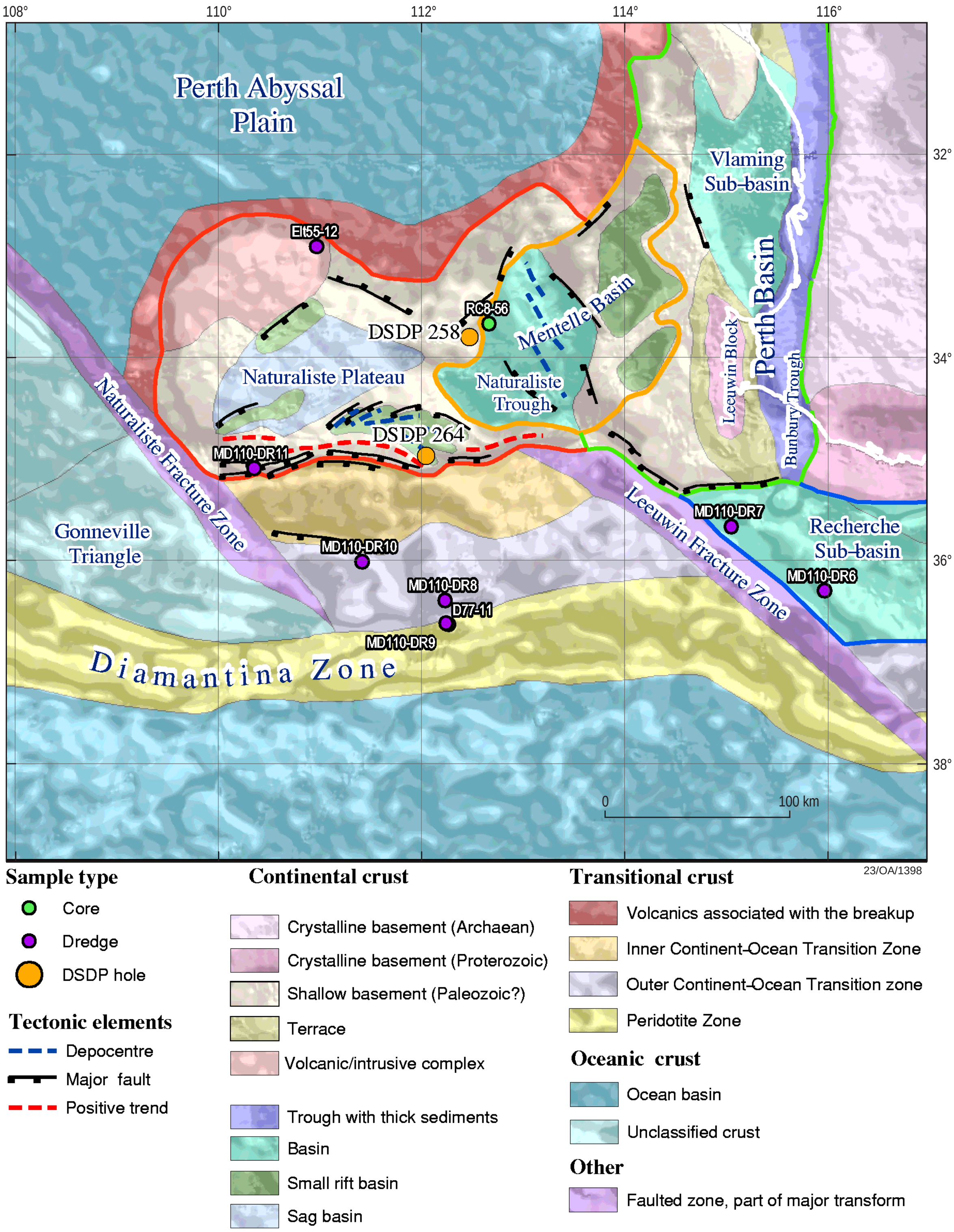


Fig. 9. Tectonic provinces and structural elements of the Naturaliste Plateau region.

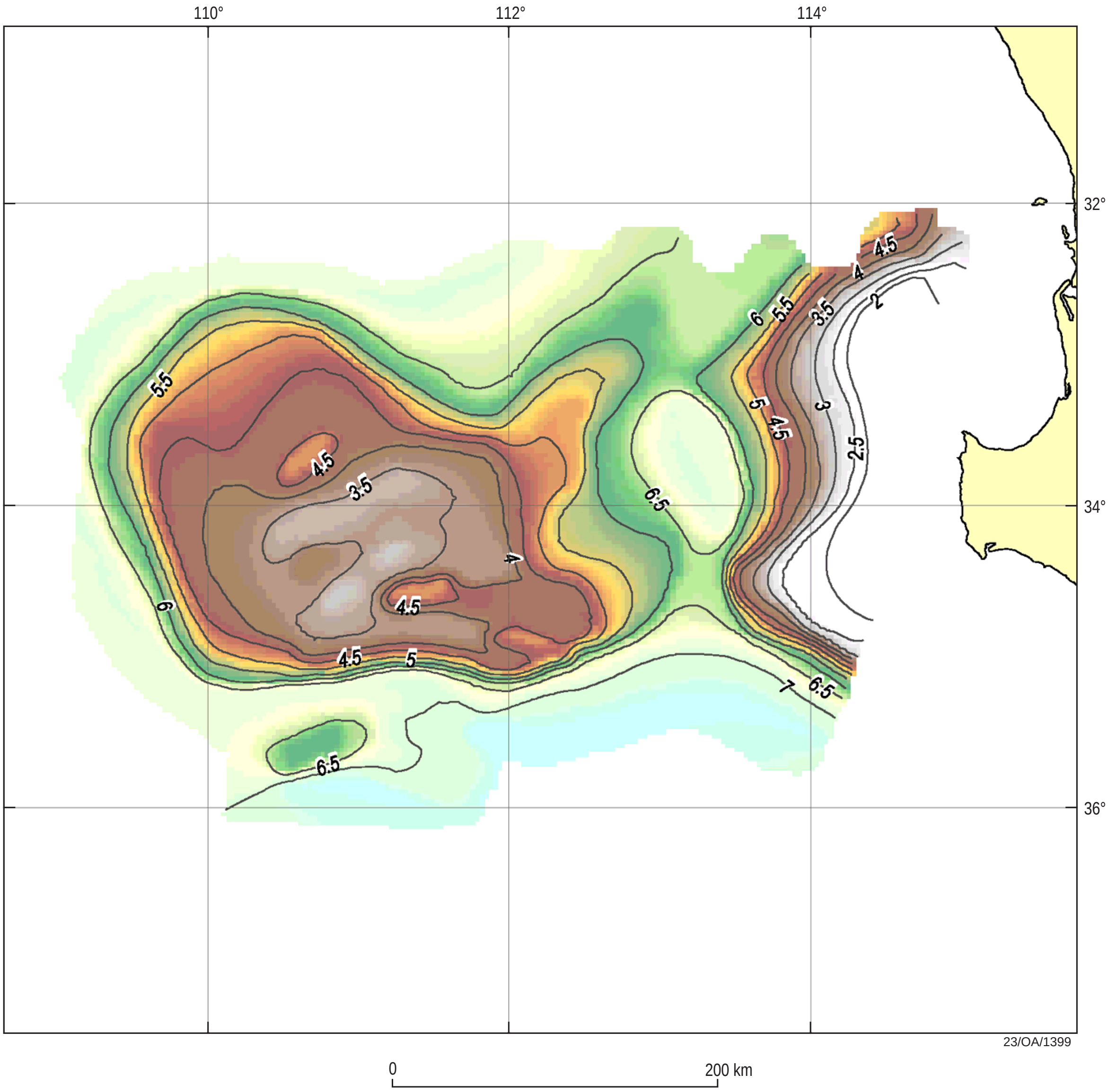


Fig. 10. Depth to basement (in s TWT) over the Naturaliste Plateau region, derived from the seismic data

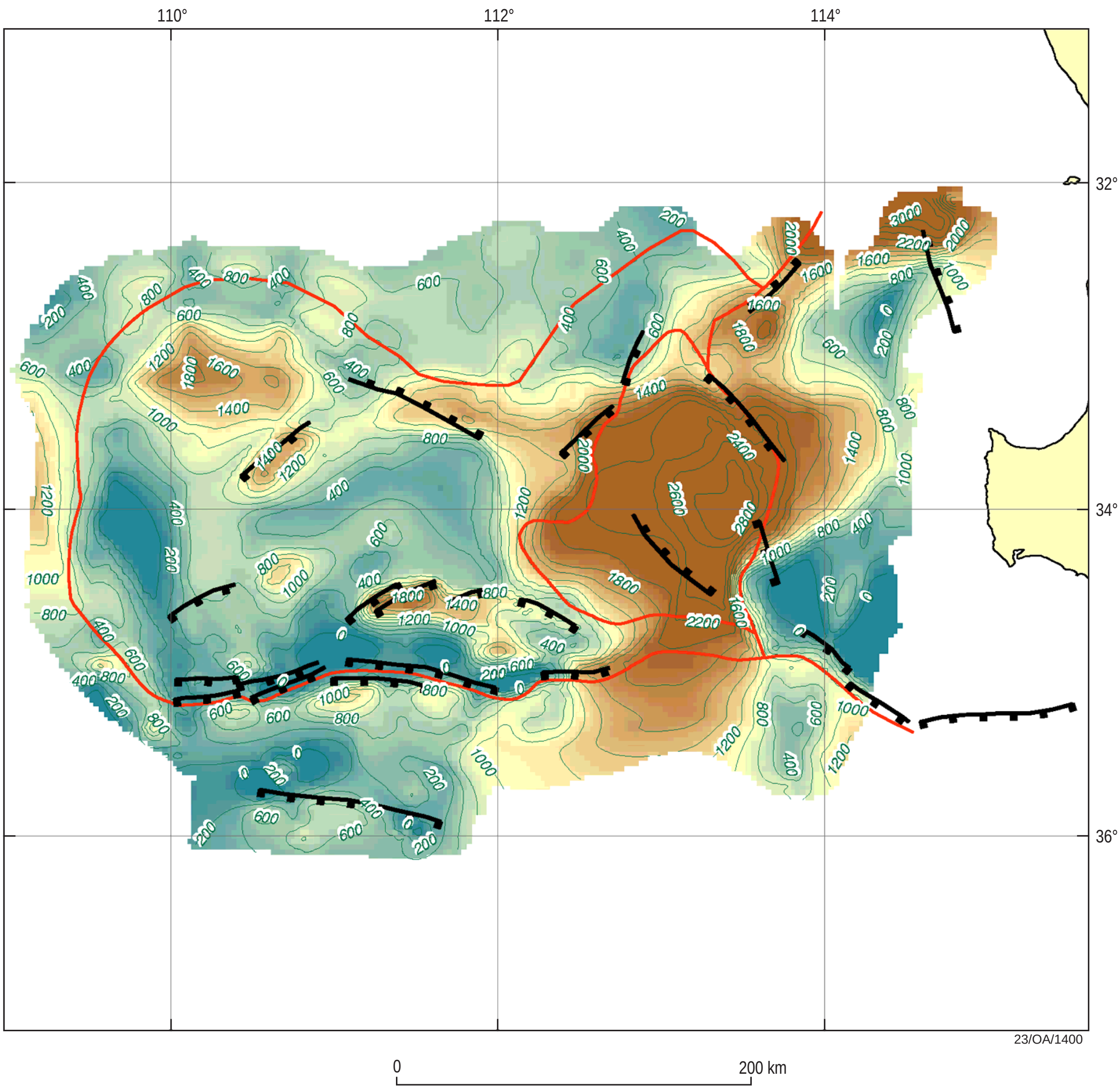
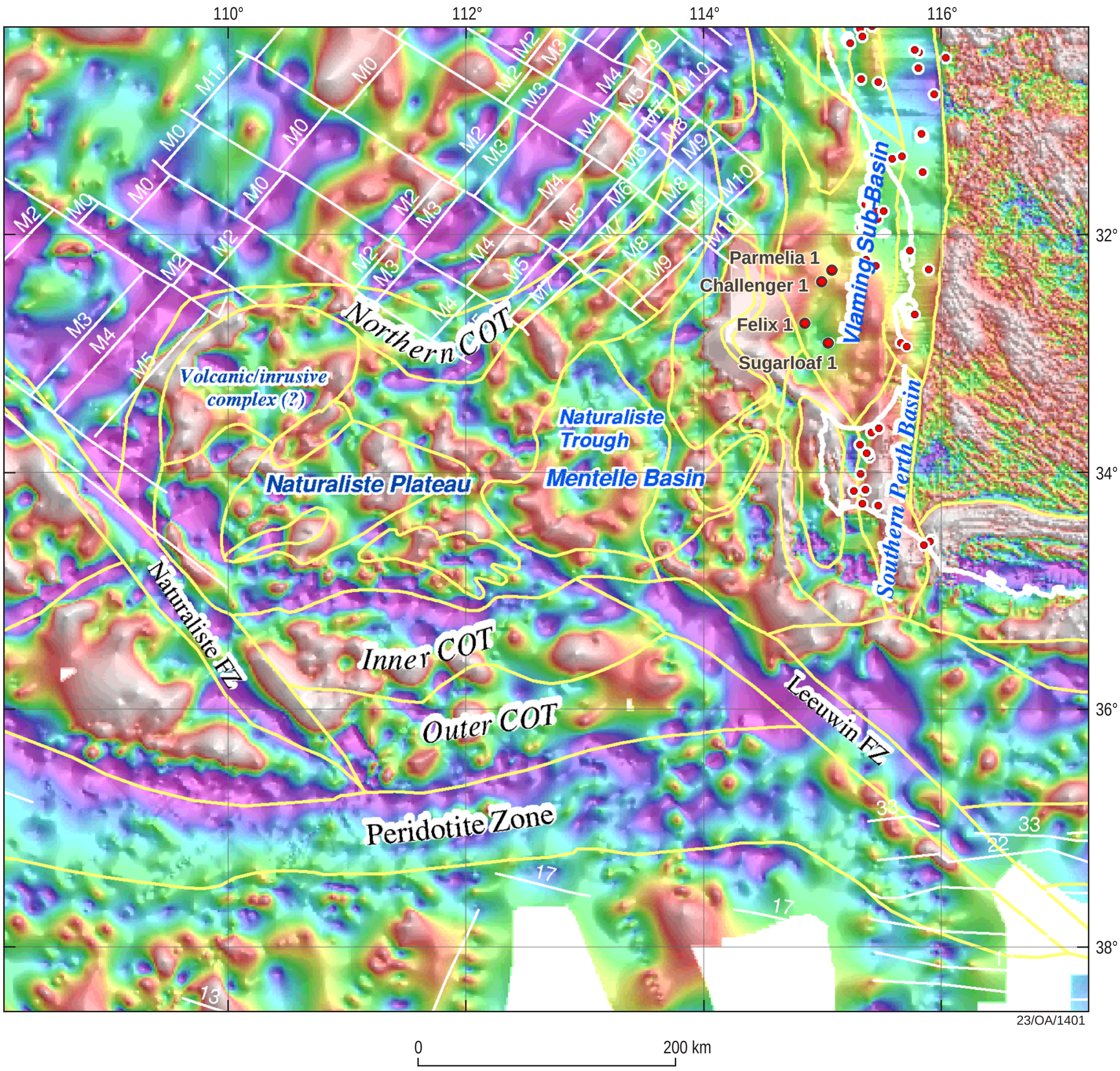


Fig. 11. Sediment thickness (in msec TWT) over the Naturaliste Plateau region, derived from the seismic data



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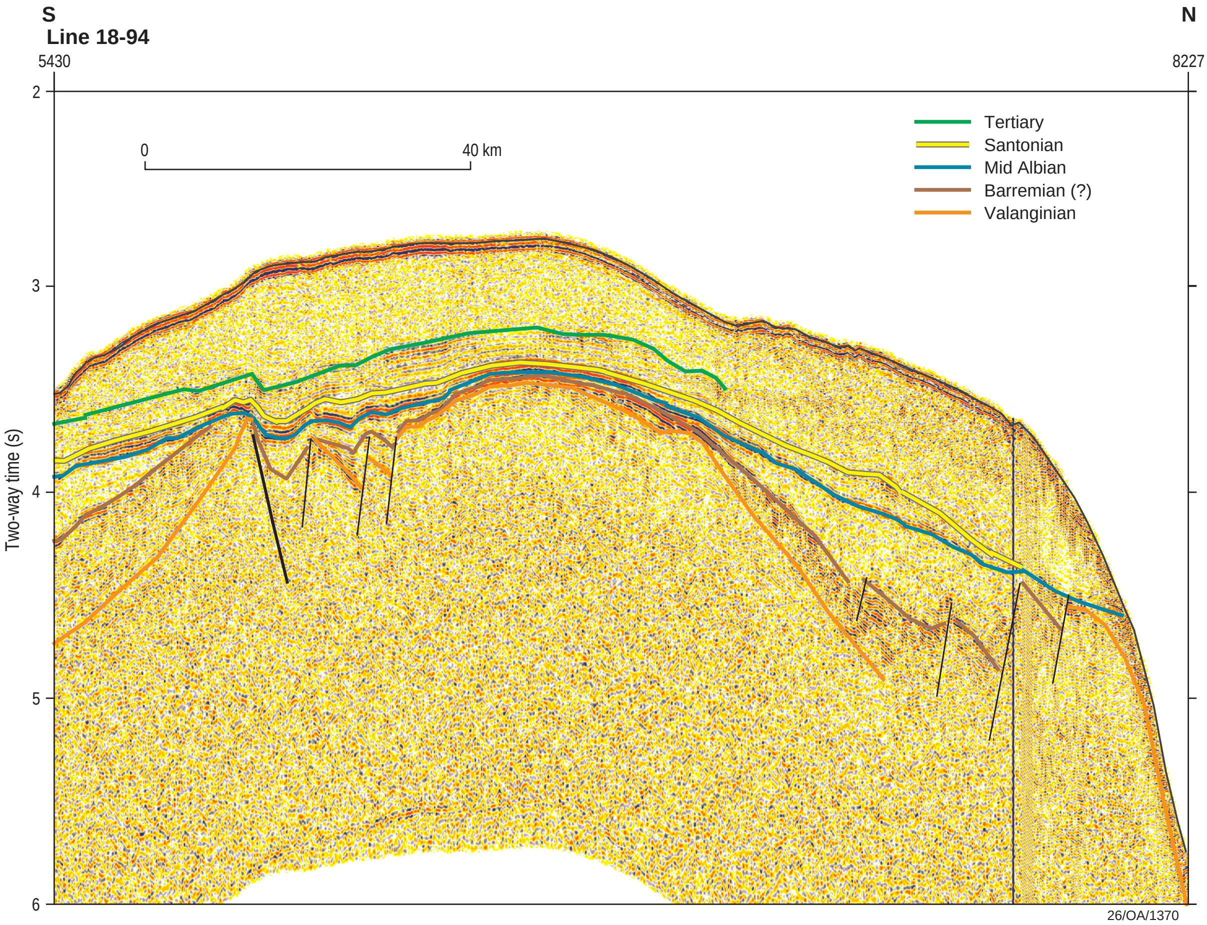

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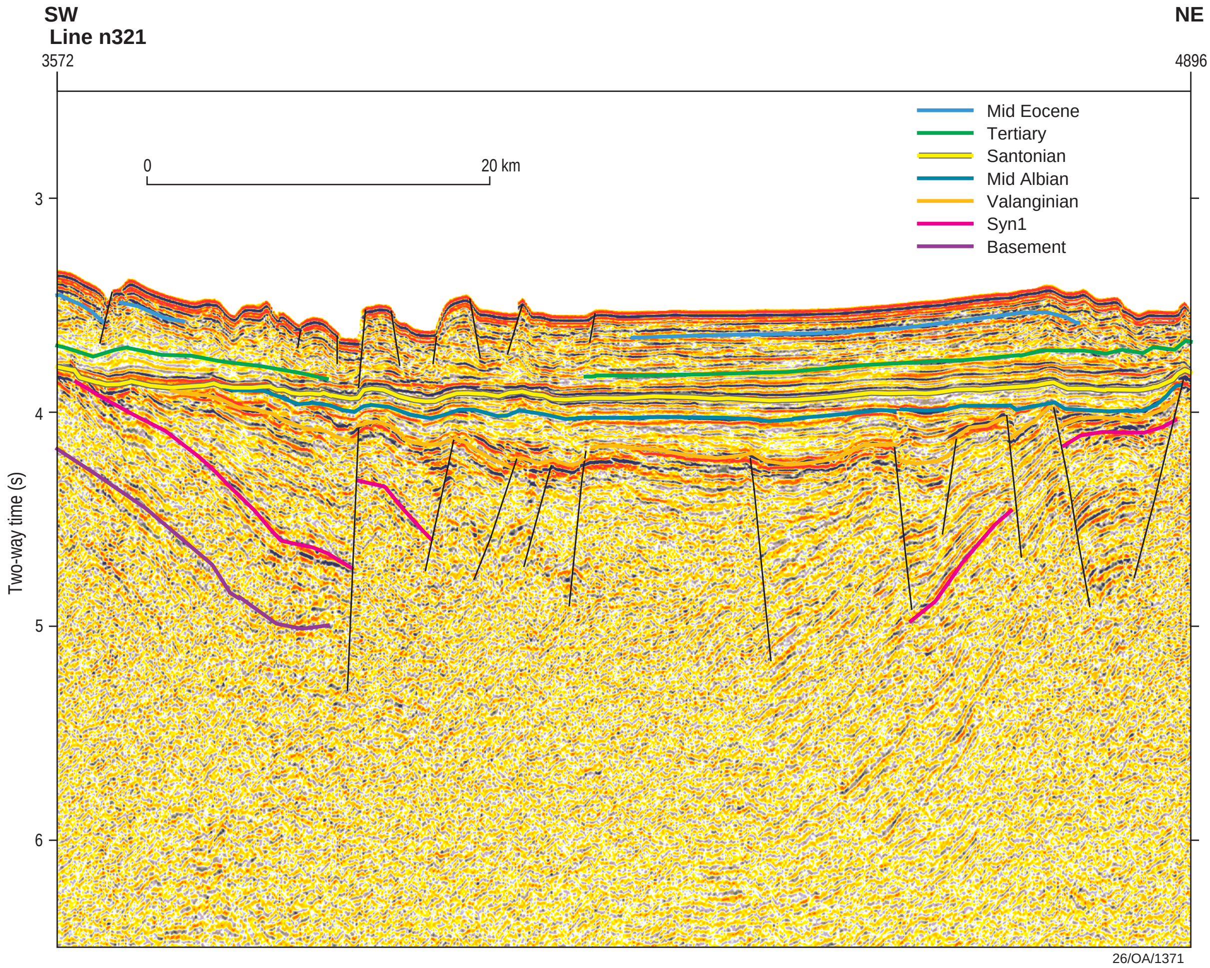


Fig. 14. Example of an area with laminated basement, central part of the Naturaliste Plateau (line n321)

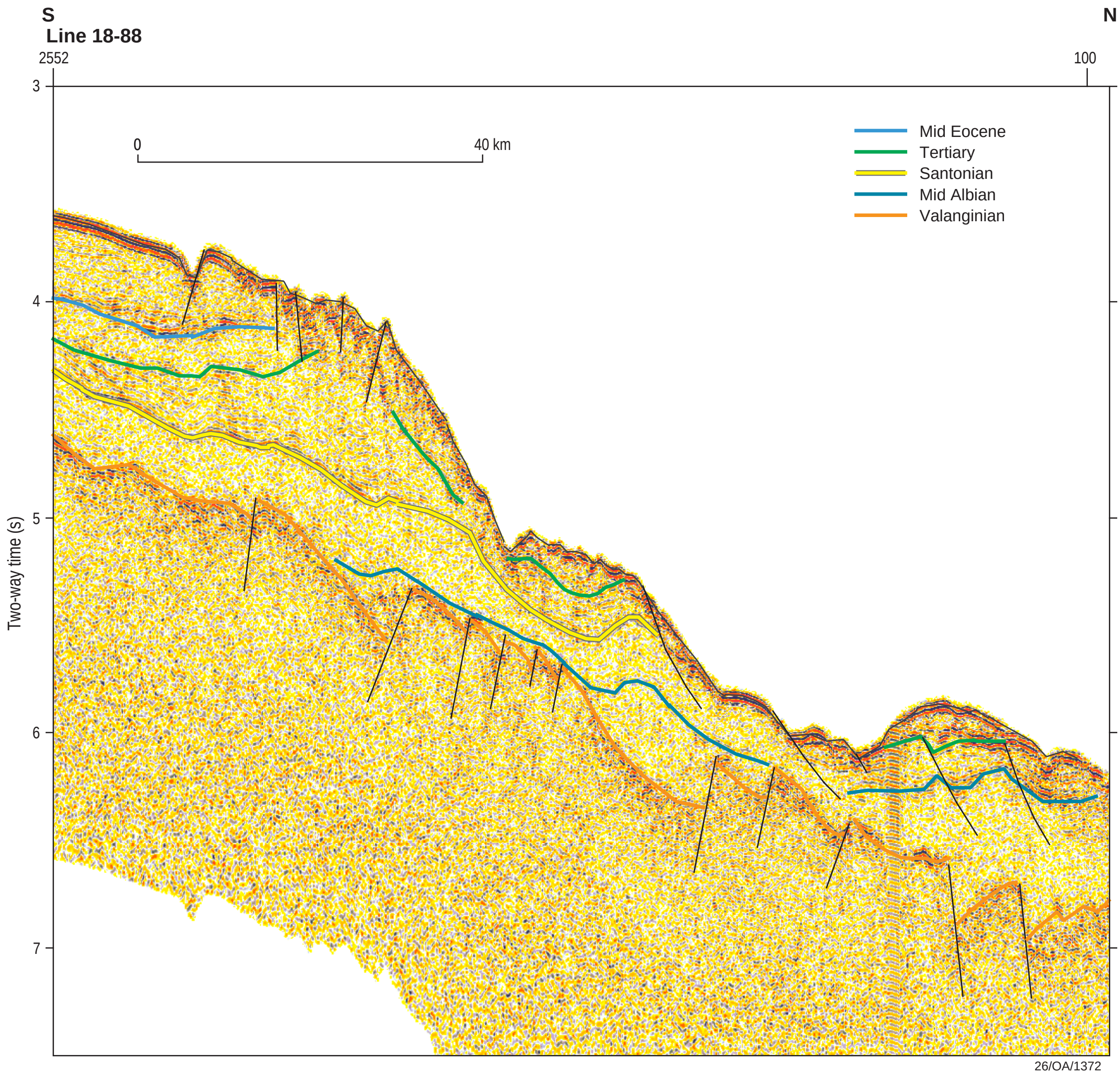


Fig. 15. Seismic line across the northern slope of the Naturaliste Plateau, showing basement character (Line 18-88)

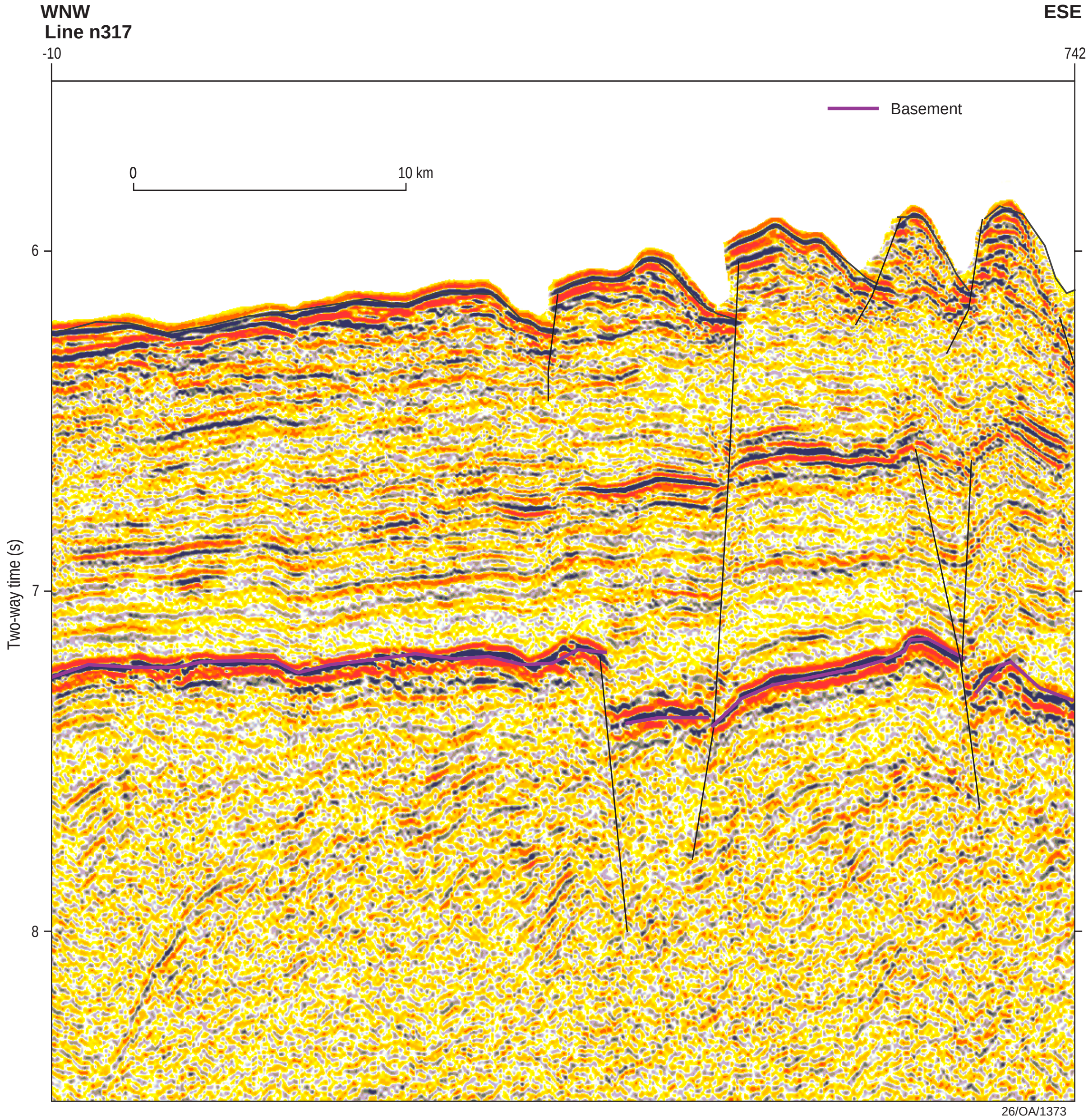


Fig. 16. Seismic character of the northern continent-ocean transition zone, adjacent to the continental margin off South Perth Basin (Line n317)

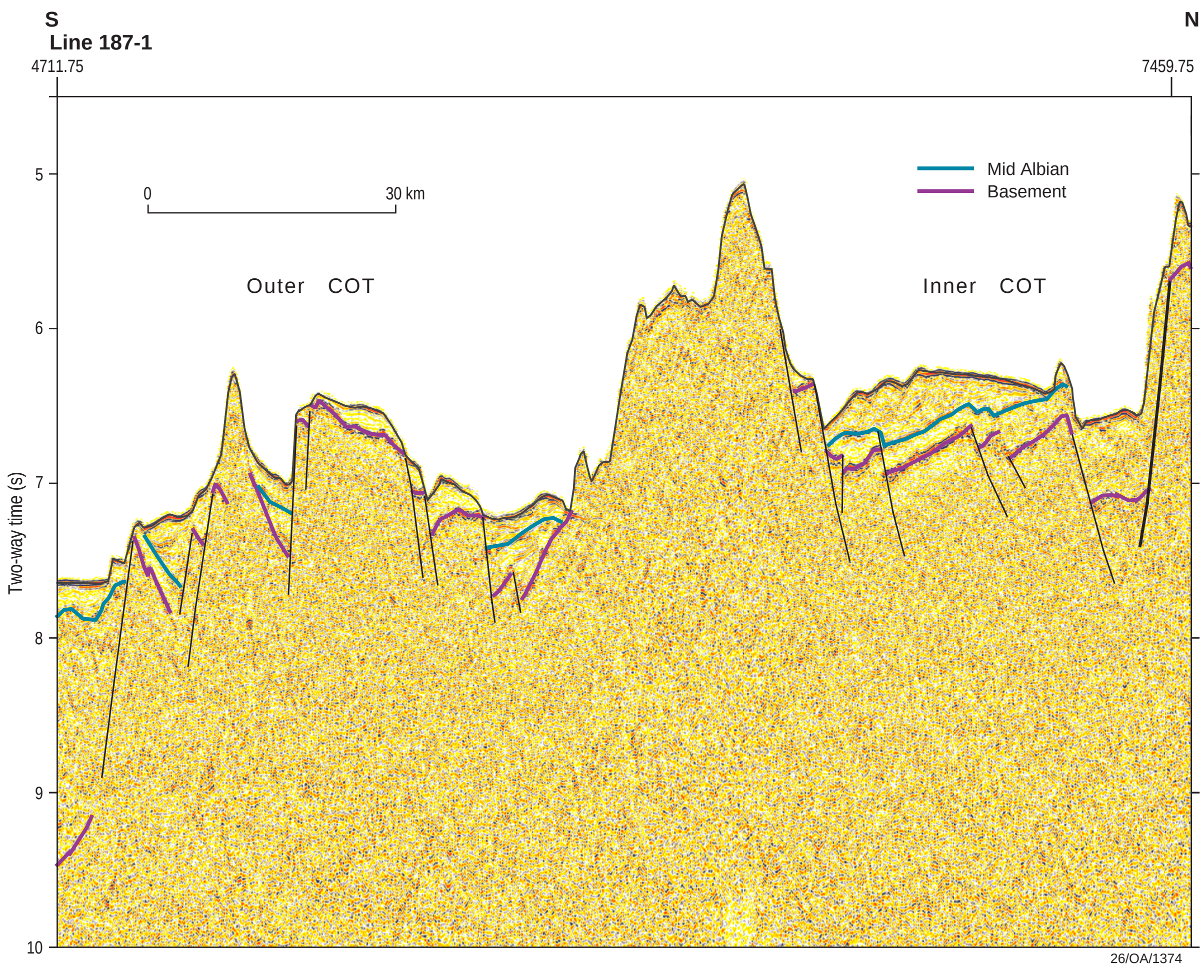
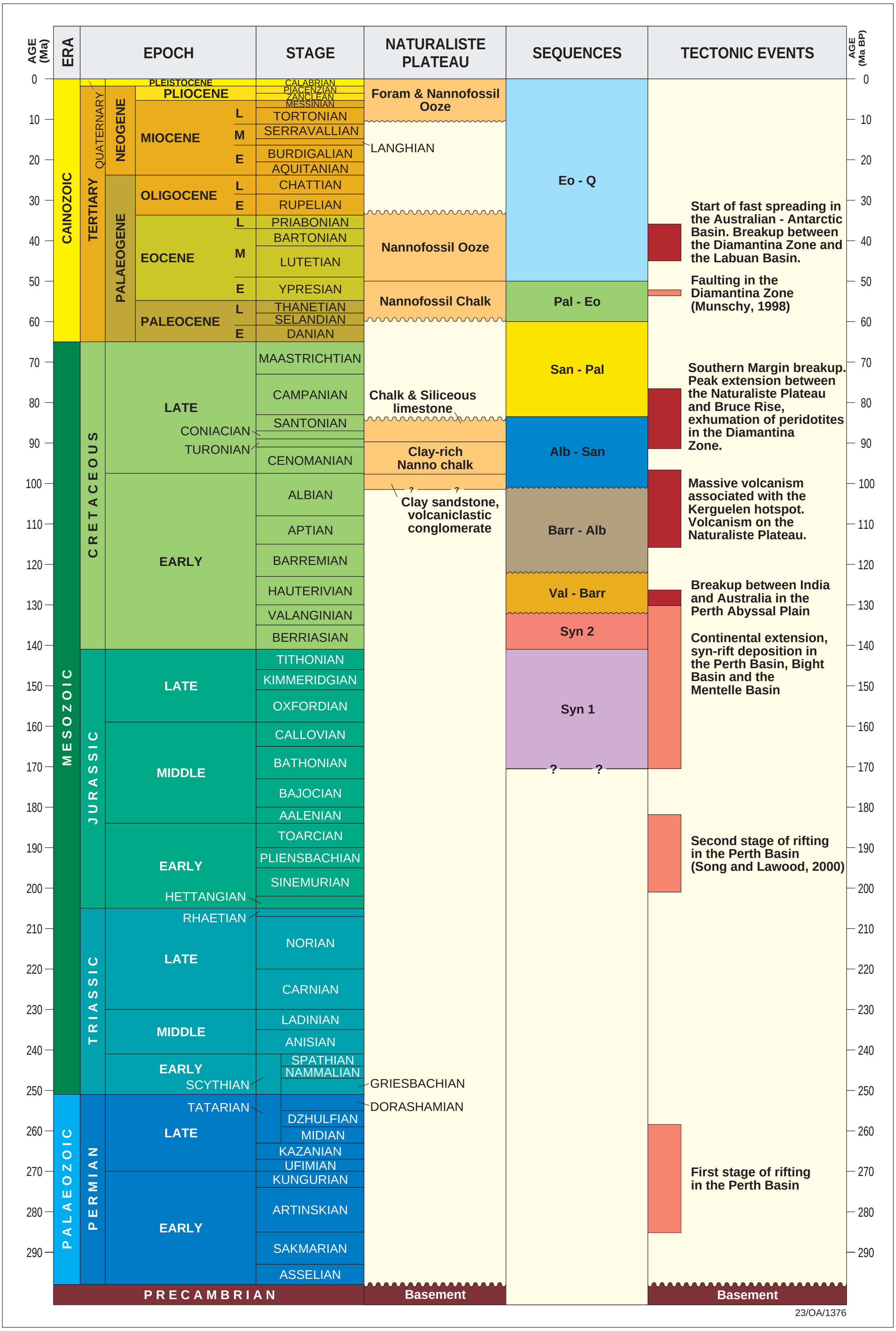


Fig. 17. Seismic character of the southern continent-ocean transition zone (Line 187-1)



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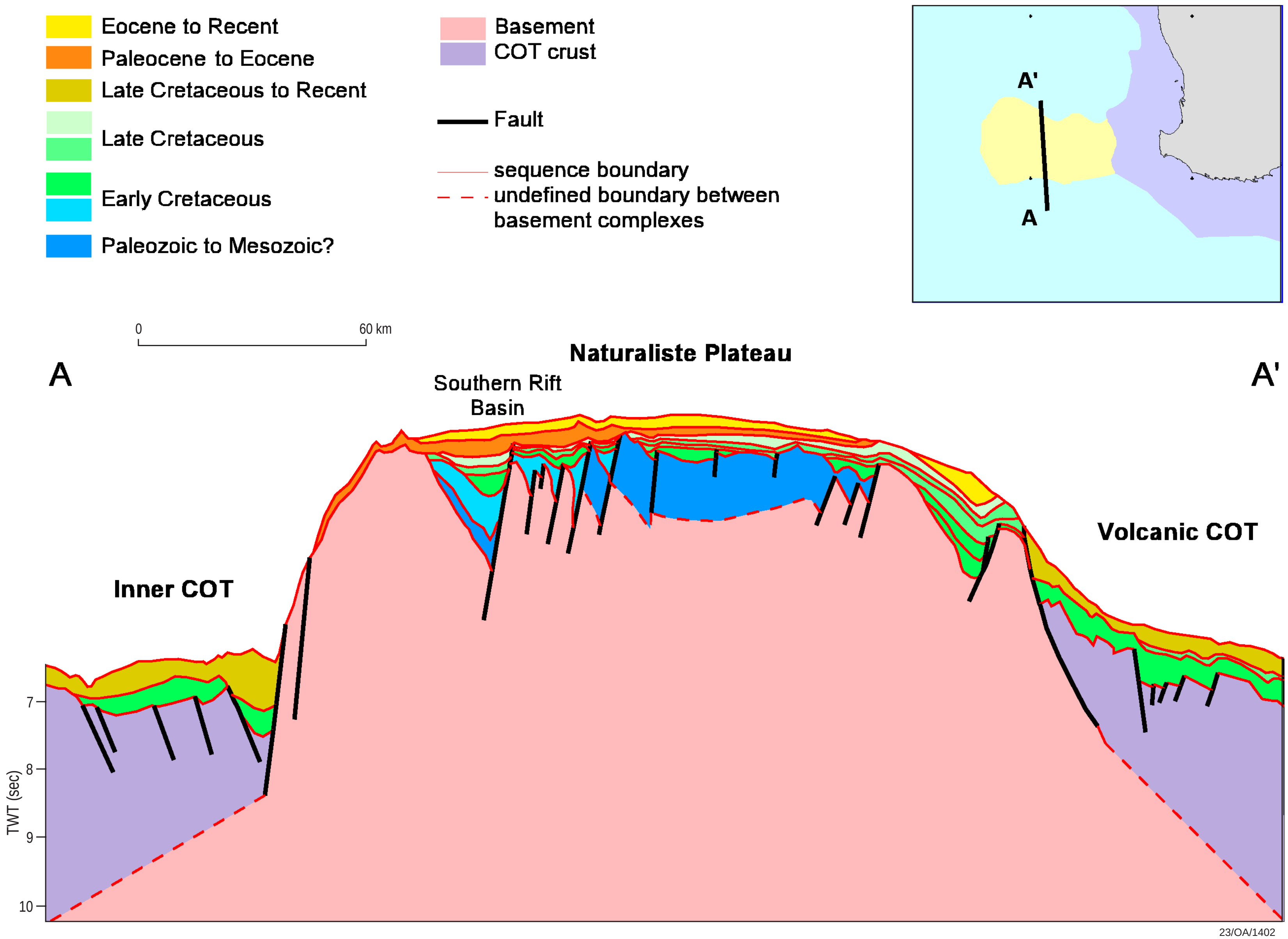


Fig. 19. N-S cross-section through the Naturaliste Plateau based on interpreted seismic Line N322

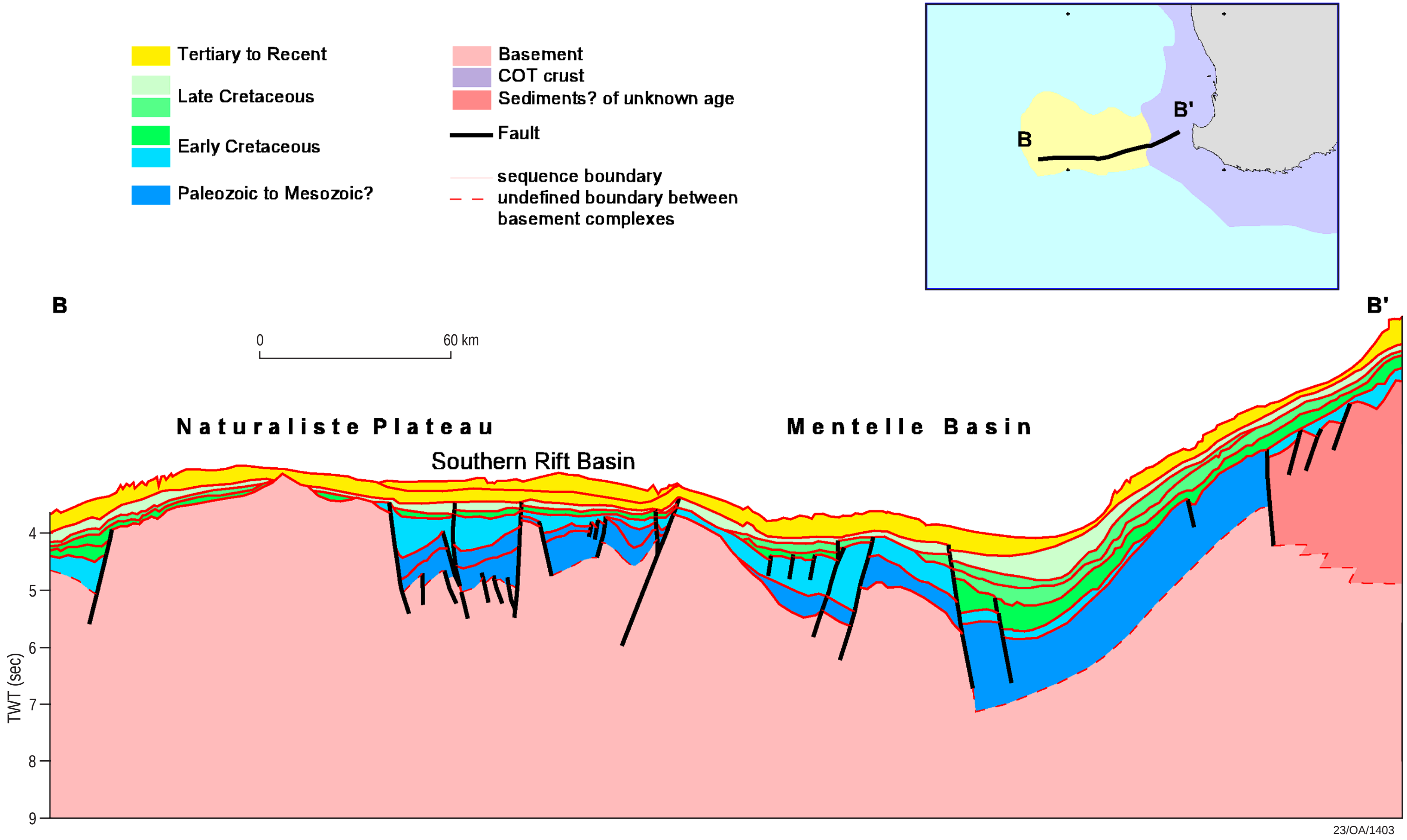
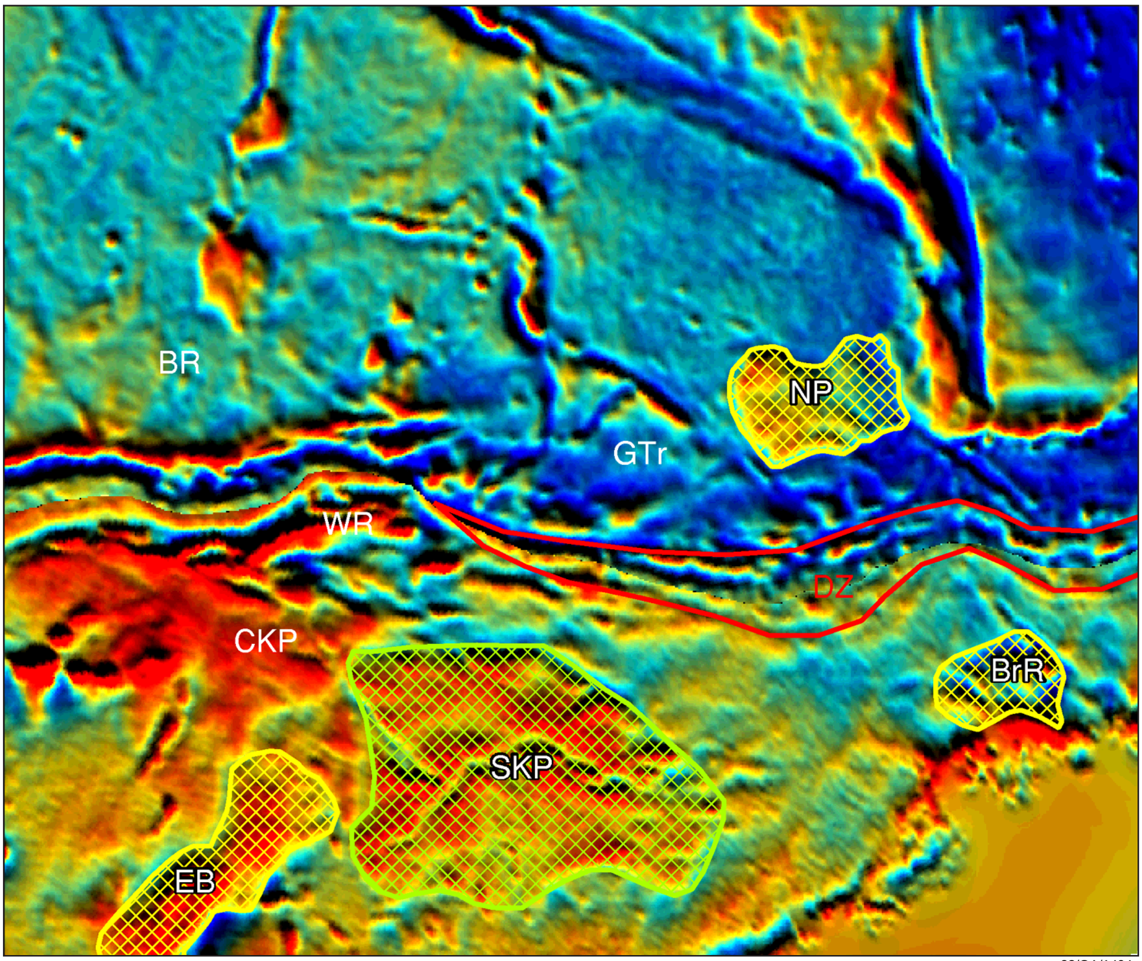


Fig. 20. W-E cross-section through the Naturaliste Plateau based on interpreted seismic Line N325



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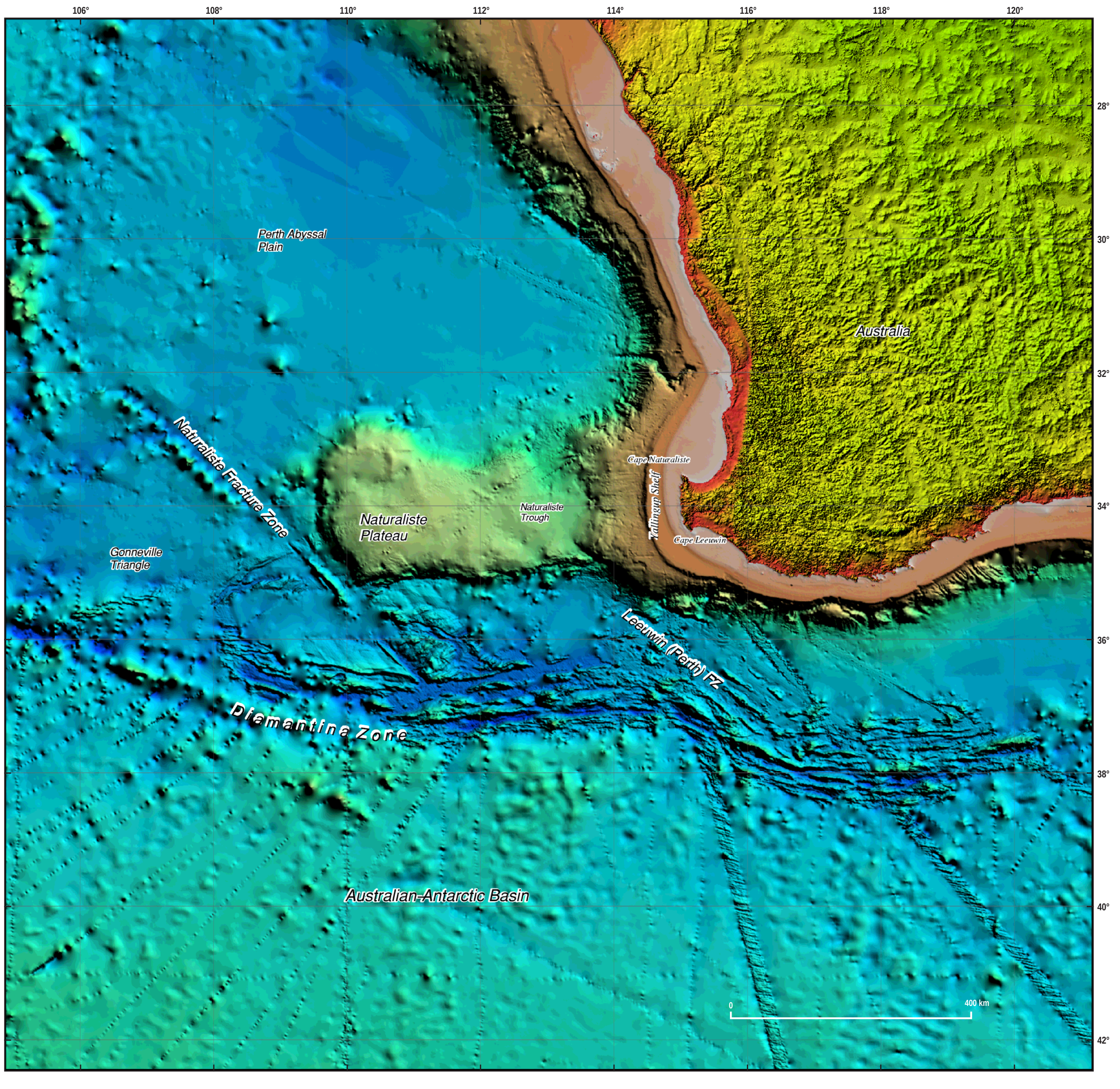

High resolution plot files of Plates 1-5 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

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Plate 1

Bathymetric image of the Naturaliste Plateau and surrounding basins (Petkovic and Buchanan, 2002). The image is based on compilation of ship track and swath mapping data. Predicted bathymetric grid (Smith and Sandwell, 1997) was used where other data were not available.

GEOSCIENCE AUSTRALIA

Borissova, I., 2002

Geological framework of the Naturaliste Plateau.
Geoscience Australia Record, 2002/20

23/OA/1405

Lithostratigraphic columns for DSDP holes 258 and 264 on the Naturaliste Plateau and petroleum wells Sugarloaf 1, Parmelia 1, Challenger 1 in the Vlaming Sub-basin.

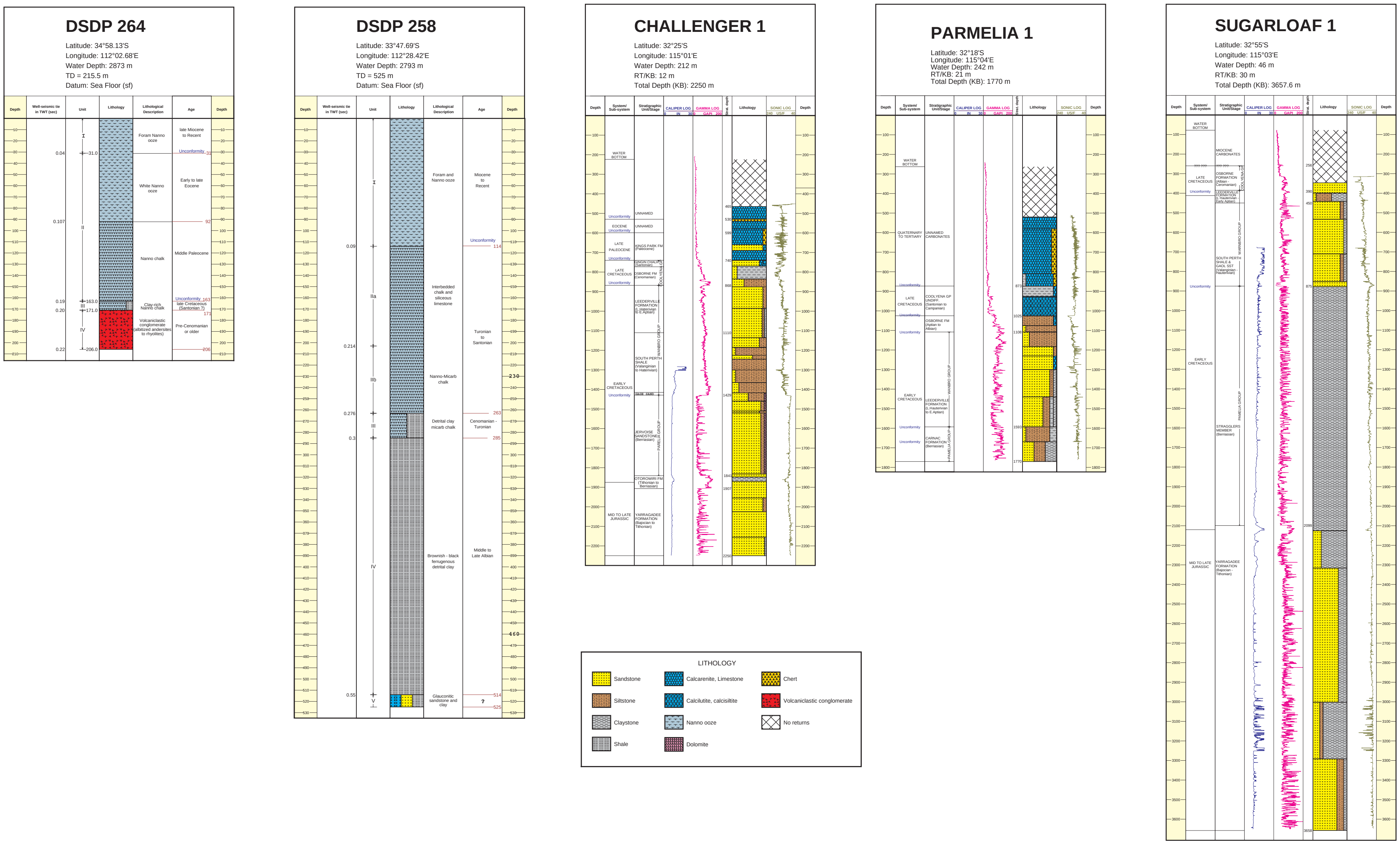

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Plate 2

Lithostratigraphic columns for DSDP holes 258 and 264 on the Naturaliste Plateau and petroleum wells Sugarloaf 1, Parmelia 1, Challenger 1 in the Vlaming Sub-basin

GEOSCIENCE AUSTRALIA

Borissova, I., 2002

Geological framework of the Naturaliste Plateau
Geoscience Australia Record, 2002/20

23/OA/1369

STRATIGRAPHIC CORRELATION BETWEEN THE NATURALISTE PLATEAU, SOUTHERN PERTH BASIN AND CEDUNA SUB-BASIN

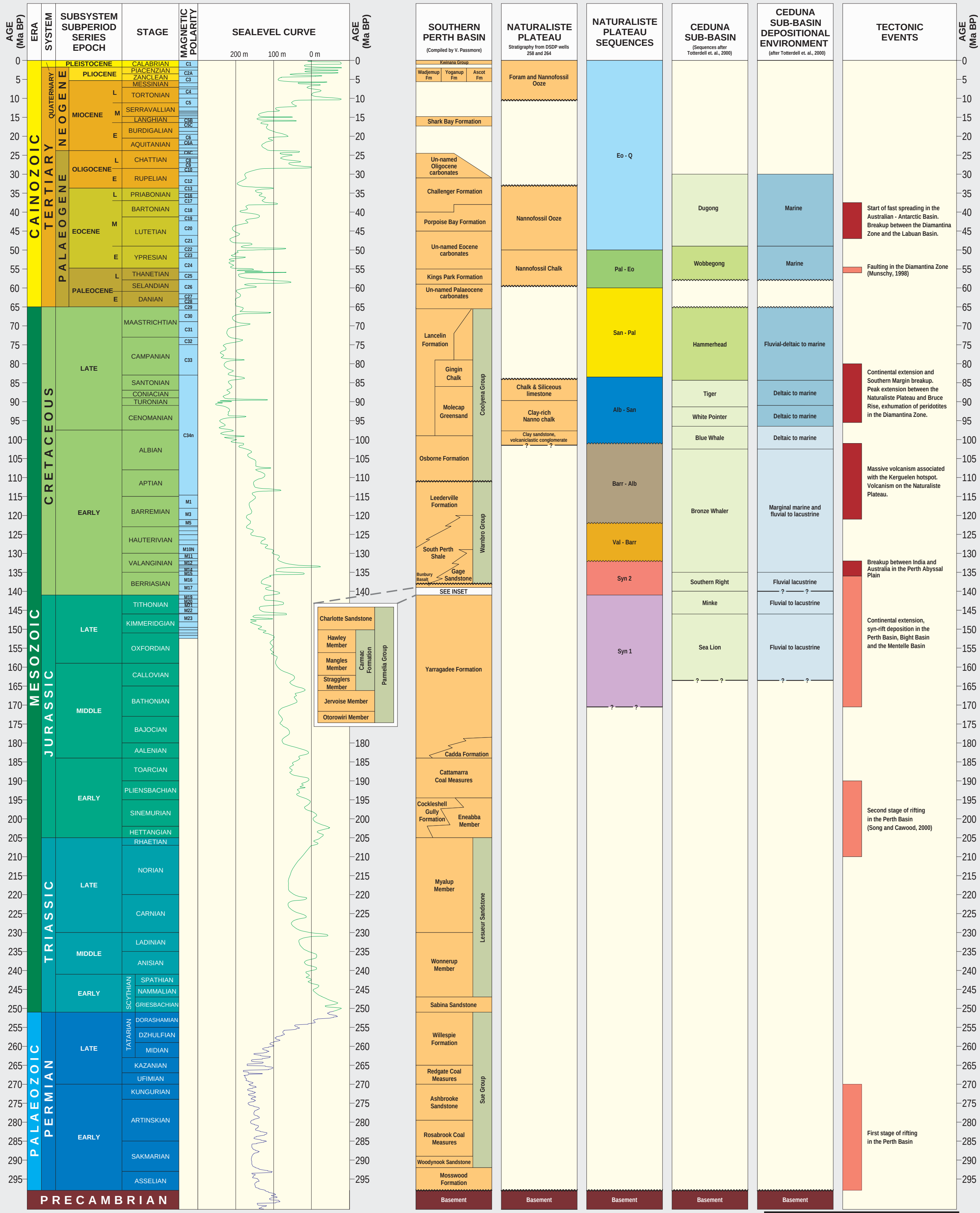

Chart Stratigraphy and tectonic history compilation: Irina Borissova

Digital compilation: Neville Montgomerie

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Plate 3

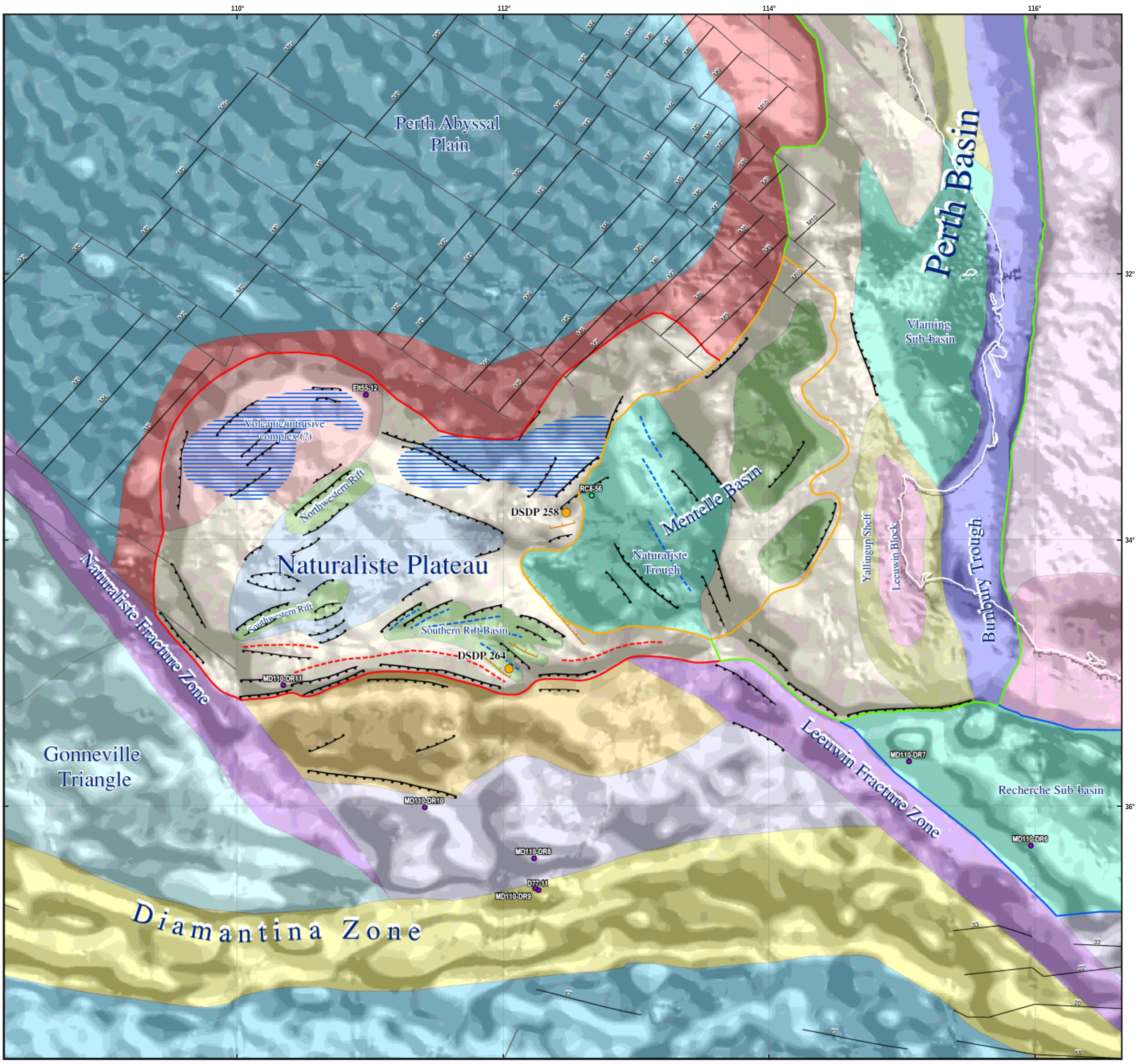
Stratigraphic correlation between the Naturaliste Plateau, southern Perth Basin and Ceduna Sub-basin

Borissova, I., 2002

Geological framework of the Naturaliste Plateau. Geoscience Australia Record, 2002/20

23/OA/1377

High resolution plot files of Plates 1-5 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD



Sample type

- core
- dredge
- DSDP drill hole

Tectonic elements

- Depocentre
- Major Fault
- Positive trend

Continental crust

- Crystalline basement (Archaean)
- Crystalline basement (Proterozoic)
- Shallow basement (Paleozoic?)
- Terrace
- Volcanic/intrusive complex
- Basement ridge
- Trough with thick sediments
- Basin
- Small rift basin
- Sag basin

Transitional crust

- Volcanics associated with breakup
- Inner Continent-Ocean Transition Zone
- Outer Continent-Ocean Transition zone
- Peridotite Zone

Oceanic crust

- Ocean basin
- Unclassified crust

Other

- Faulted zone, part of major transform
- Thick Cenozoic buildup
- 13 Magnetic lineations (after Cande et al., 1989)

0 — 200 km

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Plate 4

Tectonic provinces and structiural elements of the Naturaliste Plateau

GEOSCIENCE AUSTRALIA

Borissova, I., 2002
Geological framework of the Naturaliste Plateau.
Geoscience Australia Record, 2002/20

23/OA/1406

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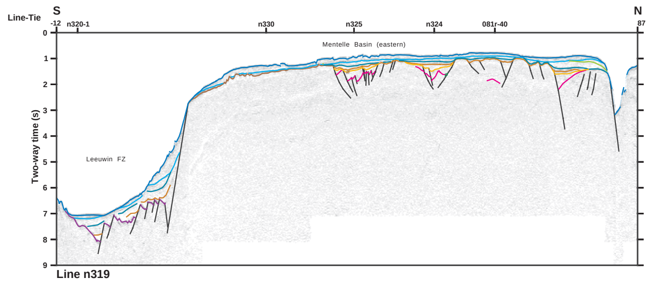
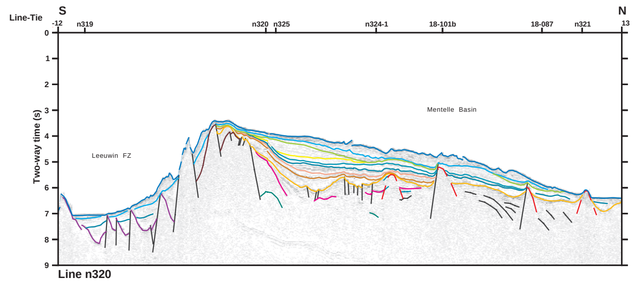
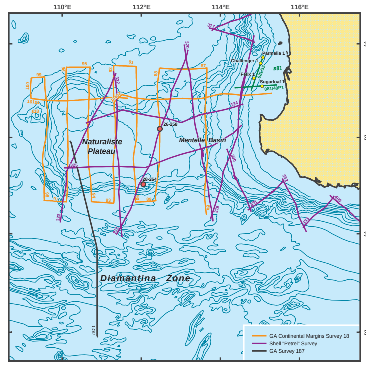
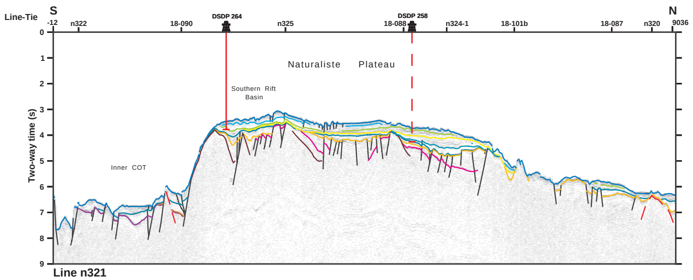
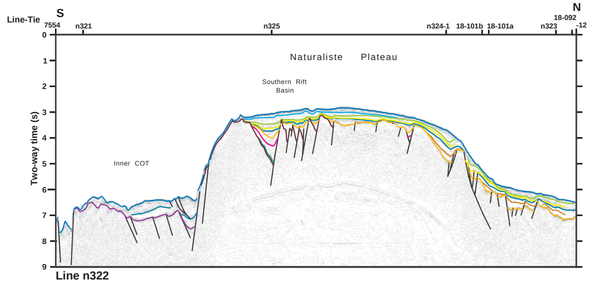
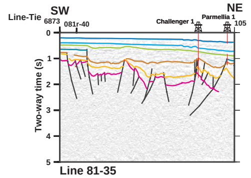


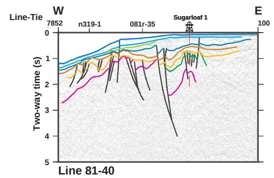






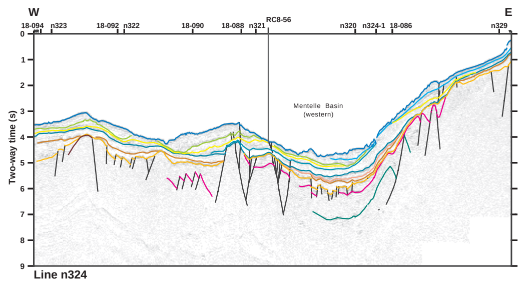


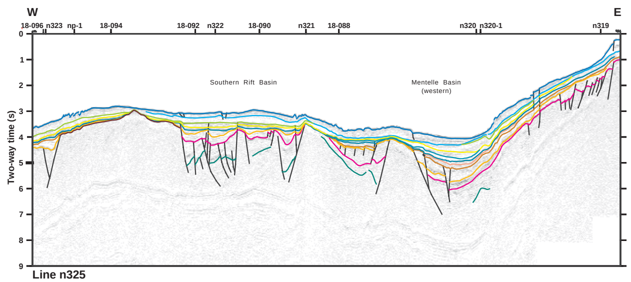


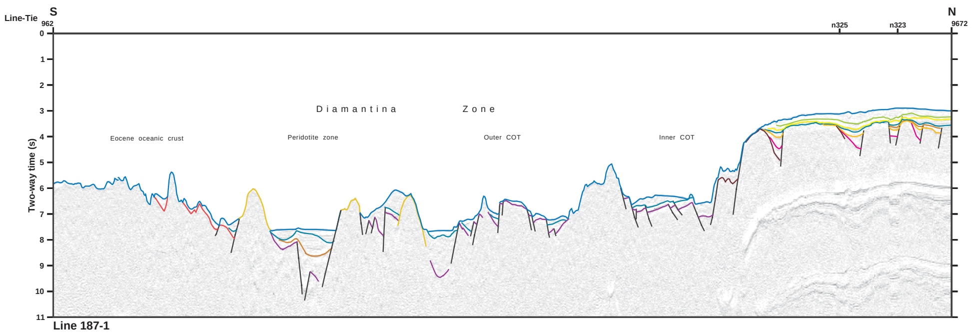


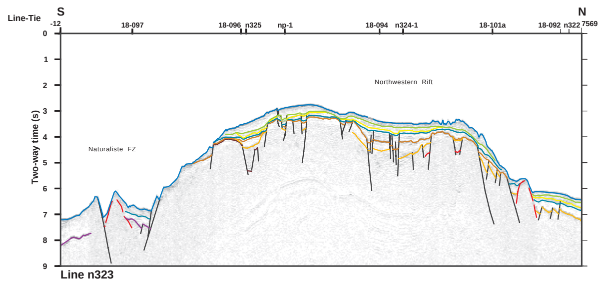
Horizon	Description
wb	Water bottom
eoc	Base Eocene
Pal	Base Paleocene (Tertiary)
san	Base Santonian
u-alb (?)	Base Upper Albian
m-alb	Base Mid Albian
l-alb (?)	Base Lower Albian
barr (?)	Base Barremian
val	Base Valanginian
berr (?)	Base Berriassian
syn2/parmelia (?)	Base upper part of syn-rift section
syn1	Possible base Jurassic
vol	Volcanics
np-base	Top Naturaliste Plateau basement
cot-base	Top continental-ocean transition zone basement
oc-crust	Top oceanic crust basement
Mentelle-base	Top shallow basement of eastern Mentelle Basin
p (?)	Top possible periodotites
intrabas	Intrabasement reflectors

0 100 km









High resolution plot files of Plates 1-5 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

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Plate 5

Interpreted Seismic Sections from Shell "Petrel" Survey, GA Survey 187 and GA Survey 81

Borissova, I., 2002

Geological framework of the Naturaliste Plateau.
Geoscience Australia Record, 2002/20

23/OA/1368

Instructions for the CD-ROM

Geological framework of the Naturaliste Plateau

This CD-ROM contains the above-titled document as GeoscienceAustraliaRecord2002_20.pdf

To view this document on PC, install the Adobe Acrobat Reader v4.0 located in the Acrobat\Win_NT sub-directory on this CD, double click on the file Acrd4enu.exe and follow the installation prompts.

Once the reader is installed, go to the Record directory, double click on the GeoscienceAustraliaRecord2002_20.pdf to launch the document.

Please note:
Additional readers for Macintosh and Unix are also supplied on this CD
For Macintosh use, Acrobat\Macintosh\ar405eng.bin
For Unix use, Acrobat\Unix\sunsparc-rs-405.tar.gz

Directories on this CD

Acrobat directory:
Sub-directories of Adobe Acrobat Reader installation files for Win_NT, Macintosh, Unix and Help, which includes © Acrobat copyright, Adobe Acrobat Reader Guide and information on Adobe.

Plot files directory:
With sub-directories containing A1 and A0 Postscript (.PS) plot files and Raster Transfer Language (.RTL) plot files of the 5 plates used in this Record. All these are suitable for plotting to large format plotters.

Record directory:
GeoscienceAustraliaRecord2002_20.pdf