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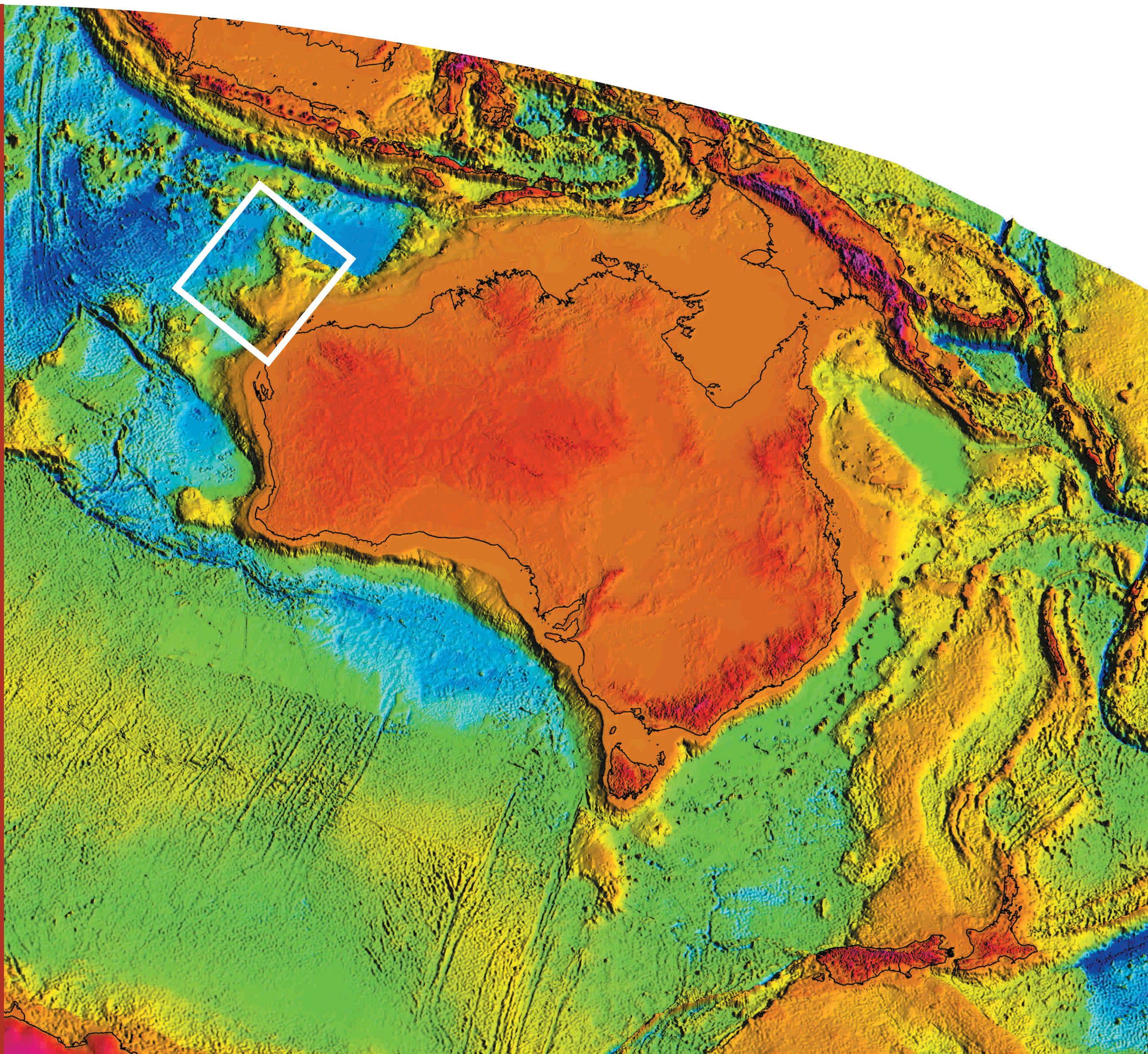
Record
2004/13



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GEOSCIENCE AUSTRALIA
DEPARTMENT OF INDUSTRY, TOURISM & RESOURCES

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GEOLOGICAL FRAMEWORK OF THE OUTER EXMOUTH PLATEAU AND ADJACENT OCEAN BASINS

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CANBERRA 2004

Department of Industry, Tourism & Resources

Minister for Industry, Tourism & Resources: The Hon. Ian McFarlane MP
Parliamentary Secretary: The Hon. Warren Entsch, MP
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Geoscience Australia

Chief Executive Officer: Neil Williams

ISSN: 1039-0073
ISBN: 1 920871 08 X

GeoCat No. 60864

Bibliographic reference: Stagg, H.M.J., Alcock, M.B., Bernardel, G., Moore, A.M.G., Symonds, P.A. & Exon, N.F., 2004. Geological framework of the outer Exmouth Plateau and adjacent ocean basins. *Geoscience Australia Record 2004/13*

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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.

PREFACE

This report is a summary of an interpretation of the deep-water outer Exmouth Plateau and adjacent ocean basins that was carried out during 1998 to provide background to Australia's submission on the region under the United Nations Convention on the Law of the Sea. Due to unanticipated delays, the report was not completed until late 2003. In this period between interpretation and publication, a number of major papers and reports have appeared in the scientific literature. Most of these papers have been focussed on the inboard part of the margin and do not significantly affect the interpretation of the more remote parts of the margin. Therefore, we have updated this report to refer to the more recent papers but, in the interest of getting this report published, we have not attempted to modify our interpretation in any major way.

EXECUTIVE SUMMARY

Analysis of the extent of Australia's legal continental shelf under the United Nations Convention on the Law of the Sea (UNCLOS) has shown that there are nine areas of seabed that extend beyond the 200 M Exclusive Economic Zone around Australia and its island territories. One of these areas includes the physiographic and geologic province of the Exmouth Plateau, off northwest Australia, including its margins and the adjacent deep-ocean basins. Information on the geological framework of the area is available from a number of sources including high-resolution and deep-penetration reflection seismic profiling, seismic refraction studies, potential field and heat-flow data, and geological samples from exploration and scientific drilling and from seabed dredging and coring.

The Exmouth Plateau, a marginal plateau lying at water depths of 800 m to more than 3000 m, is a major element of the Northern Carnarvon Basin. This basin is the southernmost component of the late Palaeozoic to Cainozoic Westralian Super-basin that underlies the continental margin of Australia from North West Cape to the Timor Sea. Most of the plateau is underlain by 10-15 km of generally flat-lying, faulted sedimentary section that was mainly deposited during the extension that preceded breakup of Argo Land and Australia in the Middle Jurassic, and Greater India and Australia in the Early Cretaceous. Since the second breakup episode, the Exmouth Plateau and its environs have largely been sediment-starved, with only a few hundred metres of mid-Cretaceous to Cainozoic marine sediment being present.

The margins of the plateau are geologically very distinctive, reflecting their differing origins, and they are strongly influenced by volcanics whose emplacement is generally closely related to continental breakup. The northern (Argo) margin is structurally the most complex, reflecting its interpreted origin in a mixed rift-transform setting in combination with the influence of underlying early Palaeozoic structures related to the E-W trending onshore Canning Basin. The major manifestation of volcanic activity on this margin is the 3000+ m-high edifice of the Joey Rise, which connects with the northernmost extremity of the Exmouth Plateau via the low-relief volcanic buildup of the Platypus Spur.

The northwest (Gascoyne) margin is characterised by a rugged, commonly low-gradient slope that is generally concave in profile. Volcanic extrusions and intrusions dominate this margin, strongly influencing the physiography and masking the underlying sedimentary section. A number of volcanic provinces can be recognised on this margin, including landward flows, slope volcanics, seaward-dipping reflector sequences (SDRS), buildups of varying styles and origins, and thickened magmatic crust. Within this latter zone, there are strong indications that SDRS wedges may overlie highly extended continental crust; that is, the crust may be vertically partitioned and not readily classified as being either clearly continental or oceanic. True oceanic crust lies oceanwards (west) of this zone.

The southwest (Cuvier) margin is strongly linear, reflecting its genesis as a transform margin between the Exmouth Plateau and the Cuvier Abyssal Plain. This margin has undergone major uplift and erosion (*ca.* 2+ km) of the Triassic-Cretaceous sedimentary section, largely as a result of the presence of the Cuvier spreading centre which abutted the continent for some 10 Ma after margin breakup.

The inboard portion of the Northern Carnarvon Basin is currently Australia's prime hydrocarbon province, with production deriving from super-giant gas-condensate fields and a number of small- to medium-size oil fields. Hydrocarbons have also been encountered on the Exmouth Plateau, with the most important discovery being the super-giant Scarborough gas field on the central-southern part of the plateau. It is likely that other substantial hydrocarbon discoveries remain to be made on the plateau, including on the deep-water outer margin. However, it is likely that development of any such discoveries will only occur in the long term, due to the water depths (typically deeper than 2000 m) and the considerable distance from land.

Deep-sea mineral deposits, in the form of polymetallic nodules and crusts, have also been recovered from the Exmouth Plateau and adjacent deep-water areas. However, metals of potential economic interest (manganese, cobalt, nickel and copper) are only present in low concentrations compared to areas of high economic potential, such as in the Pacific Ocean. Consequently, the deep-sea mineral deposits of the Exmouth Plateau region are unlikely to have any economic value, in at least the short- to medium-term.

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 (see Fig. 1; Appendix 1)[1]. Where the continental margin of a nation extends beyond 200 nautical miles, the outer limit of the "legal" Continental Shelf 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 characteristics, may be used to support the definition of the outer limit.

A preliminary analysis of the extent of Australia's Continental Shelf under UNCLOS (Symonds & Willcox, 1989) indicated that it could be at least 14.8 million square kilometres in area, including offshore the Australian Antarctic Territory – nearly twice the area of the continent and one of the worlds largest. Nine areas of Continental Shelf, totalling an area of about 3 million km^2, extend beyond the 200 nautical mile Australian Exclusive Economic Zone (AEEZ). Several of these areas lie along the continental margin of Western Australia (Symonds et al., 1998b). Geoscience Australia[2] has the responsibility for ensuring that Australia has the necessary technical information to fully define its Continental Shelf under UNCLOS. Australia has decided to adopt a 'safe minimum' approach to Continental Shelf definition in which bathymetric and seismic data are acquired on profiles spaced about 30 nautical miles apart over areas of the margin extending beyond the AEEZ. Internal Geoscience Australia assessments in the early 1990s indicated that further data collection and analysis was needed in about six areas of potential extended Continental Shelf beyond the AEEZ. One of the areas requiring such analysis was the segment of the continental margin encompassing the Exmouth and Wallaby Plateaus off northwest Australia (Fig. 2). Two surveys for Law of the Sea purposes were undertaken in this area by Geoscience Australia, in 1994 (Survey 135) and 1995 (Survey 162).

The continental margin off northwest and west Australia extends for some 3400 km from the Naturaliste Plateau in the south to Darwin and the Timor Trough in the north, and encompasses an area of approximately 1.3 million km^2 (Fig. 3). The basin systems that underlie the margin formed over more than 500 million years as a result of multiple tectonic events and culminated with the development of a collisional margin in the north in the past 20 million years. Although the margin has been extensively studied since the late 1960s, particularly because of the presence of a major petroleum province on the North West Shelf, a comprehensive understanding of its nature and evolution remains somewhat elusive.

[1] The 'legal' Continental Shelf' (LCS), defined by a complex series of rules or formulae contained within Article 76 of UNCLOS, 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. The part of the LCS that extends beyond the 200 nautical mile Exclusive Economic Zone is commonly referred to as the 'Extended' Continental Shelf (ECS).

[2]Geoscience Australia was previously called the Australian Geological Survey Organisation (AGSO) from 1993 to 2001, and prior to that, the Bureau of Mineral Resources (BMR) from its founding in 1946 to 1993.

The margin can be broadly divided into four tectonic-physiographic provinces. From north to south, these are (Fig. 3) :

The **Argo province**, extending from the Timor Trough to the Joey and Roo Rises, and including the Scott Plateau, Rowley Terrace and northern Exmouth Plateau, and the adjacent Argo Abyssal Plain. The embedded sedimentary basins include the Browse and Roebuck (formerly offshore Canning) Basins and the northern margin of the Northern Carnarvon Basin.

The **Gascoyne province**, extending from the Joey and Roo Rises to the Cape Range Fracture Zone (CRFZ), and including the central Exmouth Plateau and adjacent Gascoyne Abyssal Plain. This province is dominated by the highly hydrocarbon-rich Northern Carnarvon Basin.

The **Cuvier province**, bounded by the CRFZ to the north and the Wallaby-Zenith Fracture Zone (WZFZ) to the south, and including the Carnarvon Terrace, Cuvier Abyssal Plain, Wallaby Plateau and Zenith Seamount. The sedimentary basin geology is dominated by the Southern Carnarvon Basin.

The **Perth province**, bounded by the WZFZ to the north and the Naturaliste Plateau to the south, and including the Perth Basin beneath the continental shelf and slope and the Perth Abyssal Plain.

This report provides the background geological framework interpretation and data relevant to the claimable area covering the western Exmouth Plateau.

2. DATA SETS USED IN THE STUDY

The interpretation contained in this report is based on a wide range and vintage of geophysical and geological data sets, including seismic and potential field data, heat-flow data and geological samples acquired from scientific and petroleum exploration drilling and from dredging and shallow sediment coring. Detailed listings of the seismic surveys used and the recording parameters are included in Appendix 2. The following text comprises a brief summary of the most important of these data sets.

2.1 Bathymetry

While bathymetric data have been routinely acquired on all research cruises and surveys in the Exmouth Plateau region, the density of coverage is highly variable, ranging from dense in shallow water and on the Exmouth Plateau, to moderate on the plateau margins and sparse to non-existent in the abyssal environment. The bathymetric data presented in this report has been integrated from all available sources, including conventional bathymetry profiling, multi-beam swath-mapping, and satellite predicted bathymetry (Sandwell & Smith, 1997) where ship-board data are effectively non-existent (Petkovic & Buchanan, 2002).

2.2 Seismic Reflection

The most important data sets used in this report are the deep-seismic data acquired by Geoscience Australia on its former research vessel *Rig Seismic* between 1991 and 1995, and comprising the following surveys:

Survey 101 (1991): 1659 km of data along 10 lines, mainly in the nearshore part of the Northern Carnarvon Basin (Stagg et al., 1991). Three lines from this survey were used in transects of the continental margin for this report.

Survey 110 (1992): 2888 km of data along 13 lines that in-fill and extend the Survey 101 data (Stagg & Survey 110 Shipboard Party, 1992).

Survey 128 (1994): 3424 km of data along 11 lines on the outer continental margin of the Exmouth Plateau, Roebuck Basin and Scott Plateau and adjacent abyssal plains (Struckmeyer & Survey 128 Shipboard Party, 1994). Four lines from this survey were integral to this interpretation.

Survey 135 (1994): 4243 km of data along 21 lines on the Wallaby Plateau, Cuvier Abyssal Plain and southwest Exmouth Plateau. These lines are also the primary tie between the LOS projects on the Exmouth and Wallaby Plateaus.

Survey 162 (1995): 4097 km of data along 15 lines on the northwestern and northern margins of the Exmouth Plateau. These data form the primary data set used in this interpretation.

A single line from the Shell *Petrel* roving reconnaissance seismic survey was also integrated into the interpretation (line N211). A total of more than 7900 km of seismic data were interpreted and digitised for the project.

In addition to these high-quality seismic data sets, a number of older seismic surveys were used to constrain aspects of the interpretation. These surveys, which were not systematically interpreted and digitised, include:

Geoscience Australia Surveys 17 & 18 (1972): These surveys (CGG, 1975) were recorded along a grid of E-W lines from continental shelf to abyssal plain at a regular 20 M (~36 km) spacing, complemented by regional tie-lines. The seismic data were recorded from a sparker system and are generally only available in analogue form. While the data are of inferior quality, compared to modern multichannel seismic data, they are valuable in the correlation of major geological structures where modern data are absent.

Geoscience Australia Surveys 55 & 56 (1986): These surveys were recorded by Geoscience Australia on the RV *Rig Seismic* as site surveys for Ocean Drilling Program Legs 122 and 123 (Exon et al., 1988; Williamson & Falvey, 1988). The data are of fair quality and have been used to constrain interpretations of the Wombat Plateau on the northern margin of the Exmouth Plateau and on the southwest Exmouth Plateau.

The locations of these seismic lines are shown in Figure 4 and in Plate 2.

2.3 Velocity Data

Seismic velocity information is available from a number of surveys, including:

- Sonobuoy refraction data (Francis & Raitt,1967);
- Two-ship wide-angle reflection and expanding seismic profile (ESP) recording (Mutter et al., 1989; Lorenzo et al., 1991; Hopper et al., 1992);
- Refraction and wide-angle reflection data recorded by arrays of ocean bottom seismometers (OBS) along selected deep-seismic profiles; and
- Interval velocities computed from processing of multichannel seismic data.

The analysis of velocity data is integral to the interpretation presented here, and the above data sources will be dealt with in more detail later in this report.

Following completion of the draft of this report, a five-week research cruise using the R/V *Maurice Ewing* was undertaken along the Exmouth and Cuvier margins in November 2001 by a NSF-funded consortium of US agencies including Lamont-Doherty Earth Observatory and Scripps Institute of Oceanography. This cruise, which was planned with Geoscience Australia assistance, aimed to acquire data relevant to the tectonic, stratigraphic, volcanic and magmatic development of the margins using, amongst other techniques, ocean bottom seismometers (OBS) and deep-seismic profiling. Initial results of the work were presented by Sugimoto et al. (2002) and Tischer et al. (2002).

2.4 Potential Field Data

Gravity and magnetic data are routinely acquired on marine geophysical surveys. Analysis of magnetic profiles has provided the basis for plate kinematic interpretations in the past, and these interpretations will be summarised later in this report. In recent years, shipboard gravity data has largely been supplanted by high-resolution satellite gravity data sets (eg Sandwell & Smith, 1997), and the accent on the interpretation of gravity data has changed from profile-based two-dimensional modelling to regional structural interpretations; these are particularly important in contemporary studies of the plate kinematics. Gravity data available to this study are shown in Figure 5.

2.5 Geological Samples

Geological samples are derived from three main sources: petroleum exploration drilling; scientific drilling; and seabed sampling through dredging and coring. Locations of sample stations are shown in Plate 3.

Interpretation of the stratigraphy of the Exmouth Plateau and its margins has made extensive use of exploration wells drilled in the period 1979-80. The wells of most relevance to this study include Brigadier-1, Eendracht-1, Investigator-1, Jupiter-1 and Vinck-1. Digital log data were available for all of these wells and composite well logs for most of these and other nearby wells are included as Plates 4 and 5.

Scientific drilling carried out by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) provide critical sedimentary and igneous information on the abyssal plains and invaluable stratigraphic information on the Upper Cretaceous and Cainozoic sequences on the Exmouth Plateau, which were typically not cored by exploration drilling. Digital log data for ODP Sites 759-766 are displayed in Plates 6 and 7. There are no digital log data for DSDP Sites 260 and 263, and we have therefore been restricted to the information available in the post-cruise report for these sites (Plate 7; Veevers, Heirtzler et al., 1974).

In the past three decades, a large number of samples have been retrieved from the Exmouth Plateau region by a variety of research institutes and vessels. These samples range from shallow sediment cores which have been taken from the seabed to provide the physical properties measurements required to compute heat-flow data, to dredges of consolidated sedimentary and volcanic rocks taken mainly from steep slopes on the plateau margins. These latter samples are of most value to this report and provide essential complementary information to the exploration and scientific drilling. A summary of seabed sample stations is contained in Appendix 3.

2.6 Heat-flow Data

Swift (1990) compiled all the available heat-flow data for the Exmouth Plateau and adjacent ocean basins available at that time in an interpretive study of the heat-flow regime on the Exmouth Plateau (Appendix 4; Plate 3). These data were primarily acquired from measurements made in the sediments immediately below the seabed, but also include some values computed from exploration wells. Most of the data were acquired on Geoscience Australia Survey 53 (Choi, Stagg et al., 1987) and on a 1987 research cruise of the RV *Franklin* (Swift, 1990).

3. PREVIOUS WORK

As scientific and industry exploration of the continental margin of northwest Australia dates back to the 1960s and is currently highly active, a comprehensive account of this history is beyond the scope of this report. This section will therefore be confined to a historical summary of exploration in the region, concentrating on the most valuable modern work that has been undertaken. A recent paper (Bussell et al., 2001) contrasts and compares deepwater petroleum exploration plays of the Northern Carnarvon Basin (including the Exmouth Plateau) with deepwater plays in the Gulf of Mexico and Mauritania.

3.1 Petroleum Exploration

The initial oil exploration permits on the North West Shelf were granted to Ampol Petroleum Ltd in 1946. While these leases were primarily onshore, they did cover the offshore Carnarvon Basin out to a water depth of 100 fathoms (<200 m). In 1952, Ampol combined with Caltex to form West Australian Petroleum Pty Ltd (Wapet), and the new company drilled its first well (Cape Range-1) on a surface anticline in 1953. This well flowed oil from a small pool and provided a major impetus to exploration on the southern North West Shelf. The first offshore seismic work was carried out by Wapet in 1961. In 1964, Wapet drilled a wildcat well on Barrow Island that discovered oil in Upper Jurassic sands. Subsequent appraisal drilling on Barrow Island showed the presence of a major oil field, principally reservoired in Cretaceous sands. Barrow Island provoked a major expansion of exploration in the region, with a number of super-giant gas-condensate fields (eg North Rankin, Goodwyn) being discovered from the start of the 1970s.

In the subsequent three-and-a-half decades, while industry exploration has waxed and waned from year to year in response to oil prices and the degree of exploration success, there has been a steady increase in knowledge of the sedimentary basins of the North West Shelf, particularly on the morphologic shelf. By late 1998, much of the North West Shelf was being actively explored, particularly in the Carnarvon, Browse and Bonaparte Basins. The Carnarvon Basin has surpassed the Gippsland Basin as Australia's premier hydrocarbon producing province, while production is also underway in the Bonaparte Basin, and likely to commence in the Browse Basin in the future.

The tools used in the exploration industry on the North West Shelf have also undergone radical development, particularly in the 1990s. While the principal tools continue to be reflection seismic recording (particularly 3-D seismic) and exploration drilling, new tools such as satellite, airborne and ship-board hydrocarbon detection, and new applications of existing tools, such as satellite gravity, and new data compilations are revealing invaluable new information about the margin.

For contemporary interpretations of the hydrocarbon-related geology of northwest Australia, the reader is referred to the proceedings of the North West Shelf and Sedimentary Basins of Western Australia symposia conducted by the Petroleum Exploration Society of Australia in 1988, 1994, 1998 and 2002 (Purcell & Purcell, 1988, 1994, 1998; Keep & Moss, 2002). Some of the more relevant regional studies of northwest Australia include those by AGSO North West Shelf Study Group (1994), Bradshaw et al. (1998), Stagg et al. (1999), O'Brien et al. (1999), Longley et al. (2002), and Norvick (2002).

3.2 Continental Margin Research

Our present understanding of the regional geology of the continental margin of northwest and west Australia and the eastern Indian Ocean comes from a number of sources, other than petroleum exploration:

- Papers dealing with the breakup history of the margin, based largely on sea-floor spreading magnetic lineations. Some of the key papers are those of Markl (1974, 1978), Larson (1975, 1977), Heirtzler et al. (1978) and Fullerton et al. (1989). Most recently, Müller et al. (1998) and Mihut & Müller (1998) have reinterpreted all the magnetic lineation data available in the region and refined the plate kinematics of the region; their work will be discussed in more detail later in this report.

- Papers dealing with the continental margins and their evolution, based largely on seismic reflection profiling and seabed sampling data. Key papers include those of Symonds & Cameron (1977), Hinz et al. (1978), Exon & Willcox (1978, 1980), von Stackelberg et al. (1980), Stagg & Exon (1981), Exon et al. (1982), von Rad & Exon (1983), Exon et al. (1988), Mutter et al. (1989), Exon & Ramsay (1990), Colwell et al. (1990) and von Rad et al. (1990). Exon (1994a), a thematic issue of the AGSO Journal on the geology of the outer North West Shelf, contains a selection of papers that summarise much of the state of knowledge of the geology of the region. The most recent papers dealing with the regional geology include AGSO North West Shelf Study Group (1994), Stagg et al. (1999) and Longley et al. (2002). A number of recent papers have been directed at the volcanic aspects of the evolution of the margin (Symonds et al., 1998a; Frey, 1998; Planke et al., 2000).

- Reports dealing with the results of scientific drilling by the Deep Sea Drilling Project (DSDP) and its successor, the Ocean Drilling Program (ODP). Results of DSDP Leg 27, which drilled holes on the Argo, Gascoyne and Cuvier Abyssal Plains, are contained in Veevers, Heirtzler et al. (1974). The principal results of ODP Leg 122, which drilled Sites 759-764 on the Exmouth Plateau, are contained in Haq et al. (1990) and von Rad, Haq et al. (1992), while the results of ODP Leg 123, which drilled Sites 765 on the Argo Abyssal Plain and Site 766 off the southwest corner of the Exmouth Plateau, are discussed in Gradstein, Ludden et al. (1990, 1992).

4. REGIONAL SETTING

4.1 Physiography

The study area covered by this report is focussed on the physiographic and geologic provinces of the Exmouth Plateau, its margins, and the adjacent deep ocean basins (Figs 6-8). These provinces have evolved during a complex multi-phase rifting history, particularly during the past 300 Ma. All the provinces have been extensively modified through the emplacement of large volumes of igneous and volcanic rocks during and subsequent to breakup of the margin in the Mesozoic.

The physiography of the Exmouth Plateau and adjacent areas is shown in Figures 6 and 7 and Plates 1 and 3.

The Exmouth Plateau is a major continental margin plateau and is elongated northeast-southwest, parallel to the coast and the North West Shelf. The plateau proper is bounded by the 800 m isobath to the southeast, and by the lower continental slope (water depths from 2000-4000 m) to the north, northwest, and southwest. Morphologically, the plateau is bound by the Montebello Trough (minimum axial water depth less than 1100 m) and the continental shelf to the southeast, the Argo Abyssal Plain to the north, the Gascoyne Abyssal Plain to the northwest and the Cuvier Abyssal Plain to the southwest. The shallowest area of the plateau is the NNE-trending and centrally located Exmouth Plateau Arch, which culminates at about 815 m water depth.

The E-W trending northern margin of the plateau is morphologically complex, being dominated by a minor plateau (the Wombat Plateau), the Echidna and Emu Spurs and intervening canyons. The plateaus and spurs lie at water depths of 2000-2500 m, while the canyons have incised the seabed by 1000-2000 m. As will be discussed later, the morphology of this margin is controlled by large relief faulted structures developed during margin breakup in the Middle and Late Jurassic. The Argo Abyssal Plain dips gently southeast from the lip of the Java Trench, attaining water depths greater than 5600 m adjacent to the continental margin east of the Exmouth Plateau.

The northwestern margin of the plateau has a gentler gradient into the Gascoyne Abyssal Plain. While the slope is occasionally rugged where volcanic rocks outcrop at the seabed, canyon development is generally limited. The floor of the Gascoyne Abyssal Plain is slightly shallower than the Argo Abyssal Plain and is somewhat more rugged, indicating the presence of volcanic buildups and seafloor expressions of faulting, particularly adjacent to the Exmouth Plateau.

The Argo and Gascoyne Abyssal Plains are separated by volcanic buildups of the NNW-trending, low-relief Platypus Spur, the rugged Joey Rise, which has relief of more than 2500 m above the adjacent abyssal plains, and the poorly-known ?volcanic Roo Rise to the far north.

The southwest margin of the Exmouth Plateau is strongly linear, steep, and convex upwards in profile, while the boundary traced along the Cuvier Abyssal Plain just to the southwest (water depths greater than 5000 m) is very sharp. The Gascoyne and Cuvier Abyssal Plains are separated by an area of seafloor dominated by north to north-northeast trending ridges (Sonja and Sonne Ridges) that emanate from the southwest corner of the Exmouth Plateau.

4.2 Plate Kinematics

A number of seminal papers have been published that deal with the plate kinematic development of the region and the breakup of eastern Gondwanaland; these papers are based mainly on the analysis of seafloor spreading magnetic lineations. The most recent work is that of Müller et al. (1998) and Mihut & Müller (1998), which make use of satellite gravity data (Sandwell & Smith, 1997), as well as magnetic data. While there are some details in these papers that are inconsistent with the seismic data available to this study, their work will be summarised in the remainder of this section, as it currently provides the most comprehensive and contemporary summary of the plate kinematics.

Prior to the work of Mihut & Müller (1998), the seafloor spreading anomalies in the Argo Abyssal Plain had been interpreted to trend approximately east-northeast, indicating a north-northwest azimuth of opening. This azimuth was very different to that interpreted from the anomaly trends in the Gascoyne, Cuvier and Perth Abyssal Plains, which indicate a west-northwest azimuth of opening (see, for example, AGSO North West Shelf Study Group, 1994, fig. 2). This difference led to the conclusion that the Argo spreading was a quite separate event to that which produced the other ocean basins of the western margin. A further consequence of this previous interpretation was that the northern margin of the Exmouth Plateau and the Argo margin of the Roebuck Basin were interpreted as largely comprising normal-rifted segments.

Mihut & Müller's (1998) revised interpretation, which incorporates interpretation of the satellite gravity data and the basement fabric mapped from seismic data (Rao et al., 1994), indicates that the magnetic anomalies trend northeast, similar to the trend of the magnetic anomalies in the abyssal plains to the southwest. There are two major implications of this revision. Firstly, the azimuth of opening is sub-parallel to the northern margin of the Exmouth Plateau, suggesting that this margin is a stepped transform margin, rather than being normally rifted. Secondly, the flowlines derived from this interpretation follow small circles about the same stage pole that describes the initial opening of the Perth Abyssal Plain. This similarity is interpreted to indicate that the formation of the Argo Abyssal occurred as the first stage of a southwards propagating rift between Australia and Greater India, as Argo Land and Burma were rifted away, with spreading commencing at about 156 Ma. At this time, Argo Land / Burma were separated from Greater India along a transform fault. The high average spreading rate of about 160 $mm.a^{-1}$ is suggested as being due to the presence of a hotspot associated with volcanism in the Joey Rise region.

Between M22A (the youngest magnetic anomaly identified in the Argo Abyssal Plain by Mihut & Müller, 1998) and the onset of spreading in the Gascoyne Abyssal Plain at about anomaly 12A time (Mihut & Müller, 1998), it is likely that transform motion between Argo land / Burma and the main part of Greater India ceased, and the two plates became attached. The subsequent separation of Greater India from Australia has long been an unresolved issue, with several different models being proposed. Again, we follow here the work of Müller at al. (1998) as we consider their work to combine a comprehensive analysis of magnetic anomalies, satellite gravity and global-scale tectonics.

Müller et al. (1998) interpret that the breakup of eastern Gondwanaland involves a large transform fault which could have formed in the early Valanginian, when seafloor spreading started west of Australia contemporaneously with slow rifting between India and Antarctica that culminated in the breakup of those continents in the Aptian at about 120 Ma. The rift-rift-transform triple junction between northern Greater India (NGI), southern Greater India (SGI) and Antarctica-Australia would have been located southwest of the Naturaliste Plateau. The presence of this triple junction may also account for the excess volcanism on the plateau in the Cretaceous. This model implies that the ocean floor west of the Naturaliste Plateau and southwest of the southernmost isochrons in the Perth Abyssal Plain would result from post-120 Ma spreading between Greater India and Antarctica which, as yet, have not been identified.

At about 99 Ma, a major change in spreading direction occurred, the relative transform movement between SGI and NGI ceased (with Greater India becoming a single plate), and Greater India began its rapid northward drift from Antarctica. This event possibly also triggered rifting between India and Madagascar.

Müller et al. (1998) also interpret a succession of ridge propagation events west of Australia that accreted large segments of the Indian Plate onto the Australian Plate. Two ridge propagators in the Cuvier Abyssal Plain increased the offset across the Wallaby-Zenith Fracture Zone to about 830 km.

With the onset of the rapid northward drift of India (which also shortly preceded the slow spreading between Australia and Antarctica), seafloor spreading adjacent to the western and northwestern margins effectively ceased. Subsequently, apart from far-field plate dynamic responses in the mid- to late Cretaceous and Palaeogene, the principal plate response impacting on the geology and evolution of northwest Australia has been the northwards-directed collision of the Australian and Eurasian Plates, commencing in the Oligocene.

5. STRATIGRAPHY

5.1 Introduction

The following discussion of the stratigraphy of the Exmouth Plateau region is drawn largely from Exon & Colwell (1994) and Exon & von Rad (1994). There has been no drilling on the outer Exmouth Plateau since the 1980s.

The seismic horizon and sequence nomenclatures are summarised in Plate 8, as are the horizon nomenclatures used by previous workers. Structures mapped from seismic data are shown in Plate 2, and the tectonic provinces are shown in Figure 9. The most recent published event history for the North West Region as a whole is given by Longley et al. (2002).

Our present understanding of the stratigraphy of the Exmouth Plateau comes from a number of sources:

- Petroleum exploration and Geoscience Australia surveys that provided high-quality seismic data sets tied to petroleum exploration wells, for structural and stratigraphic studies on the plateau. Valuable papers include Barber (1988), Stagg & Colwell (1994), AGSO North West Shelf Study Group (1994), Ross & Vail (1994), Symonds et al. (1998b), Bradshaw et al. (1998), and Longley et al. (2002). More detailed well information is available in company completion reports (for example, composite logs for key petroleum exploration wells in Plates 4 and 5).
- Figure 10 is a line drawing of a key transect across the plateau, to set the stratigraphic and structural scene (after AGSO North West Shelf Study Group, 1994). Figure 11 summarises the stratigraphy of the plateau. Figure 12 illustrates Triassic and Jurassic depositional environments as reconstructed from early company drilling. Figure 13 shows the stratigraphy of Delambre-1 well on the northern plateau, a well in which most of the main stratigraphic sequences were drilled.
- Papers dealing with the breakup history of the margin, based largely on marine magnetic lineations. Some key papers are those of Larson (1975), Heirtzler et al. (1978), Veevers et al. (1985a, b), Fullerton et al. (1989), Müller et al. (1998) and Mihut & Müller (1998).
- Papers dealing with the continental margins and adjacent abyssal plains, based largely on reflection seismic data and seabed sampling. Key papers include those of Symonds & Cameron (1977), Willcox & Exon (1976), Exon & Willcox (1978, 1980), von Stackelberg et al. (1980), Exon et al. (1982), von Rad & Exon (1983), Exon, Williamson et al. (1988), Mutter et al. (1989), Exon & Ramsay (1990), Colwell, Graham et al. (1990), von Rad et al. (1990), and a series of papers in Exon (1994a).
- Reports dealing with the drilling results of the Deep Sea Drilling Project and the continuously cored Ocean Drilling Program, which covered the Exmouth Plateau and the adjacent abyssal plains. Major references are Veevers, Heirtzler et al. (1974), Haq et al. (1990), von Rad, Haq et al. (1992) and Gradstein, Ludden et al. (1990, 1992). Key papers arising from the drilling are those of Williamson et al. (1989), Exon et al. (1991), von Rad et al. (1992a, b) and Exon & von Rad (1994).

Figures 14 & 15 show the sequences drilled on the Wombat Plateau, in the north of the area, which are particularly significant for what they reveal of the Triassic sequences. Figure 16 shows the thick sequences of Cainozoic and Cretaceous sediments drilled in the central plateau. Figure 17 shows the sequence drilled on the Argo Abyssal Plain at Site 765, and Figure 18 shows that drilled at Site 766, on volcanic crust off the southwest Exmouth Plateau.

Yeates et al. (1987) showed that Permian and thick Mesozoic sequences were laid down in the Westralian Superbasin northwest of what is now the North West Shelf, on the southern edge of the Tethyan Ocean and the northern shores of Gondwana, and the Exmouth Plateau is part of this scenario. Evidence of tilted fault blocks buried near the eastern margin of the Carnarvon Basin (Bentley, 1988) and deep-crustal seismic data from the Exmouth Plateau (Williamson et al., 1990) suggest that the continental crust was thinned in the Permo-Carboniferous. This period of stretching and thinning led to rapid and very widespread subsidence, leaving space for the deposition of several kilometres of assumed Permian, and documented Triassic, fluvio-deltaic sediments. Exmouth Plateau stratigraphy is similar to that of the rest of the Carnarvon Basin east of the plateau, and of the Rowley sub-basin of the Roebuck Basin beneath the Rowley Terrace. Figure 10 indicates that the Triassic sequences are thick everywhere, whereas the Jurassic, Cretaceous and Cainozoic sequences are highly variable in thickness. Figure 11 sets out the stratigraphy. The magnetic anomalies on the deep ocean floor and other evidence indicate that breakup occurred earlier north of the Exmouth Plateau (Oxfordian) than it did in the south and west (Valanginian). The Valanginian break-up appears to have triggered rapid subsidence of the plateau.

Reflection seismic data, dredging and drilling information for the Exmouth Plateau is summarised in Figure 11, which shows the stratigraphy of the Exmouth Plateau in general, and the rather different sequences present on the northern plateau.

5.2 Geological Development

The Exmouth Plateau area was part of the northern margin of Gondwana and the southern margin of the Tethyan Ocean until breakup in Late Jurassic to Early Cretaceous times, and lay within the largely shallow marine to paralic Westralian Superbasin in the Permian, Triassic and Jurassic (Yeates et al., 1987). Only after breakup did it take on its present configuration. The region is dominated by sedimentary strata, but volcanic rocks are common in some places and at some times (Crawford & von Rad, 1994; Symonds et al., 1998a).

5.2.1 Continental Basement Rocks

Continental basement rocks have not been recovered from the Exmouth Plateau, either by drilling or by dredging. However, magnetic, gravity and seismic reflection data suggest that most of the plateau is underlain at depth by continental basement rocks similar to those in the onshore Pilbara Block (e.g. Exon & Willcox, 1980; AGSO North West Shelf Study Group, 1994). Furthermore, deep crustal velocities from the Exmouth Plateau indicate the presence of thinned continental crust (Mutter et al., 1989). Symonds et al. (1998a) marshalled information (seaward dipping reflectors etc.) to suggest that basement beneath the plateau margins consists largely of volcanics, formed during rifting and early breakup. The ages of these volcanics include, at least, Late Triassic (rifting), Callovian (breakup) and Valanginian (breakup), as documented by dredging and seismic interpretation. Recent work by the

R/V *Ewing* over the Exmouth and Cuvier continental margins (Sugimoto et al., 2002; Tischer et al., 2002), combined with earlier Geoscience Australia OBS work (Fomin et al., 2000) may throw major new light on the deep-structure of the plateau.

5.2.2 Oceanic crust

Oceanic basalts of Late Jurassic age were drilled at the base of ODP Site 765 on the Argo Abyssal Plain, and tholeiitic basalt sills of assumed Early Cretaceous age and doubtful affinities were drilled at the base of Site 766 on the southwestern part of the plateau (Gradstein et al., 1990, 1992; Ludden, 1992).

Site 765 (Fig. 17) was drilled in the southeastern (oldest) part of the Argo Abyssal Plain, at a water depth of 5721 m and on magnetic anomaly M26, the oldest mapped on the plain (Plate 2). In this site a total of 280 m of volcanic basement was drilled. Twenty-two volcanic units could be distinguished by lithological and geochemical studies. The main lithologies are pillow basalt, massive basalt, diabase, autoclastic breccia, and tectonically brecciated pillow basalt. Two Ar/Ar ages on holocrystalline basalts were inexplicably very different at 111±2 Ma and 156±3 Ma (Ludden, 1992). However, a reliable K/Ar age of 155±3.4 Ma was obtained from a low-temperature alteration vein. An age of 155 Ma corresponds to the Oxfordian, so this is the most probable breakup age for this part of the Gondwana margin.

Site 766 (Fig. 18) was drilled on a westerly prolongation of the southwestern Exmouth Plateau toward the Gascoyne Abyssal Plain, in water 4534 m deep and on what was interpreted as magnetic anomaly M10. The site is below the main scarp of the Exmouth Plateau (Plates 2, 3), in a depression on a relatively rough surface. Seismic data indicate that the site is located on probable volcanic crust, with a thickness that is intermediate between oceanic and continental crust.

The volcanic rocks at the base of the hole consist of diabase sills that are interbedded with sediments (Fig. 18). Below undisturbed sediments are about 12 m of interbedded dipping sills and sediments; below that is a 60 m thick intrusion within which coring ended. An Ar/Ar age on a diabase sill is 155±18 Ma (Ludden, 1992); the large potential error was probably the result of extremely low amounts of K_20. The possible error in the dating overlaps the Valanginian age predicted from the magnetic anomalies and found in the overlying sediments.

5.2.3 Triassic mega-sequence

Extensive well and dredge information show that Triassic sedimentary rocks are present everywhere (e.g. Figs. 10, 13 & 15), except beneath the western margin, where volcanics replace and overlie them in places. No rocks older than Middle Triassic have yet been sampled. Seismic lines indicate that several kilometres of Triassic sedimentary rocks are present below the regional top-Triassic unconformity. Sampling shows that the entire Late Triassic is normally present (Rhaetian, Norian and Carnian), with Middle Triassic (Ladinian) penetrated in Jupiter-1 well. Fluviodeltaic siliciclastic sediments dominate (e.g. Fig. 13). However, ODP drilling (Haq et al., 1990) showed that Rhaetian reefs overlie Norian deltaic sediments on the Wombat Plateau, and the literature indicates that Triassic shelf carbonates are common elsewhere away from terrigenous sources (Barber, 1988). There are no proven seismic images of reefal buildups in the Triassic, except on the Wombat Plateau, where their seismic characteristics have been described by Williamson et al. (1989).

Dredging on a number of cruises has recovered Upper Triassic rocks from the northern Exmouth Plateau and the Rowley Terrace: fluviodeltaic sediments, shallow marine siliciclastics and shallow marine carbonates. Many of these are described by Colwell et al. (1994a). They contain palynomorphs, shelly macrofossils including corals, and conodonts (Burger, 1994; Grant-Mackie, 1994; Campbell, 1994; Stanley, 1994; Nicoll & Foster; 1994). The comparison of conodonts and marine microplankton from the same samples, from dredge hauls and petroleum exploration wells, led to a revision of the ages of the microplankton zones. Altogether, thirteen Late Triassic conodont zones are now recognised (Nicoll & Foster, 1998), allowing far better correlation of the microplankton zones with the tightly controlled international conodont zones. Some microplankton zones seem to be facies equivalents rather than time successive.

Seismic interpretation indicates the presence of unconformities within the Late Triassic, below the top-Triassic reflector; ODP drilling on the Wombat Plateau confirms that there are two unconformities within the Late Triassic sequence (von Rad, Haq et al., 1992). Most of the faulting affecting the Triassic sequence apparently occurred in the Jurassic. It is also clear that faulting was much more intense and widespread on the western half of the Exmouth Plateau than elsewhere on the North West Shelf. The large fault blocks involving Upper Triassic fluvio-deltaic sediments are commonly bounded by faults with throws of hundreds of metres.

The ODP results from the Wombat Plateau (Haq et al., 1990; von Rad, Haq et al., 1992; Dumont, 1992; Brenner et al., 1992; Exon & von Rad, 1994) show that the Carnian-Norian siliciclastic sequence (Mungaroo Formation) was laid down as part of a very large delta prograding northward, and can be separated into three upward shoaling third-order cycles. These represent a general change with time, from prodelta to lagoonal, to delta plain facies. The oldest cycle (> 200 m thick) consists largely of prodelta to delta plain mudstone and sandstone. The next cycle (100 m thick) consists largely of marginal marine to fluvio-deltaic mudstone, and its upper surface is a prominent unconformity. The upper cycle (350 m thick) consists largely of shallow marine deltaic mudstone, and non-marine delta plain mudstone, sandstone and coal. Shallow water limestone intercalations occur in all three cycles, but become more common up the section. Many of these appear to have been derived from carbonate shoals during storms. These sediments are probably typical of those laid down across much of the plateau.

The siliciclastic sediments in the ODP sites generally contain 1-3 % total organic carbon (TOC), with rare samples containing more than 10%. Rock-Eval pyrolysis indicates that the organic matter is dominantly from continental higher plants. Hydrogen indices are consistent with deltaic and lagoonal palaeoenvironments. Petrographic and geochemical methods prove that the organic matter is mainly detrital and of terrestrial higher plant origin. Average porosity values, measured on sandstone and limestone from Site 760, increase up the section from about 30 % to 40 %.

The Rhaetian shelf limestones (Brigadier Beds equivalent) cored on the Wombat Plateau include reefal buildups at Site 764, the first such carbonate buildups found anywhere on the North West Shelf. In 1990, high-resolution seismic reflection profiles were recorded on a detailed grid across the area of reefs on the Wombat Plateau by RV *Rig Seismic* (Exon & Ramsay, 1990). The profiles show that the buildups occur as patch reefs separated by lagoons.

A major transgression of Tethys southward across this area replaced the Norian delta-plain environment with a Rhaetian shallow marine shelfal environment; further south the delta plain persisted (Barber, 1988). Detailed microfacies studies of cores (Röhl, et al., 1992) have shown that the 300 m of Rhaetian carbonates at Sites 761 and 764 (Fig. 15) can be split into four major sedimentary cycles that represent four systems tracts covering 215-210 Ma. The lowest cycle is a transgressive systems tract, the second cycle is a highstand systems tract, the third cycle is another transgressive systems tract, and the upper cycle is a deepening-upward sequence of open-marine crinoidal grainstone and packstone, which unconformably overlies the underlying cycle, and is unconformably overlain by Cretaceous marine sediments.

The Rhaetian reefal sediments generally contain less than 0.2 percent TOC, whereas the lagoonal sediments typically have more than 0.5 percent TOC. In Site 761, in the more lagoonal sequence, the porosity measured in cores varies greatly, from 5-50 %. In Site 764, in the more reefal sequence, porosity is generally in the range 15-35 %.

5.2.4 Mesozoic rift volcanism

Dredging from the northern margin of the Wombat Plateau recovered rhyolite and undersaturated trachyte, three samples of which gave K/Ar ages of 213-192 Ma (von Stackelberg et al., 1980). These ages straddle the Triassic-Jurassic boundary, and the volcanics' composition suggests they are of early-rift character (von Rad & Exon, 1983).

From seismic reflection profiles, Exon & Buffler (1992) described a belt of generally reflector-free rock along the western and southwestern margins of the Exmouth Plateau that lay at the same level as Upper Triassic sediments and showed a lateral landward transition into them. They assumed that these were early-rift volcanics, like those on the Wombat Plateau. The seismic sequence was dredged, and vesicular andesite, microlitic lava, microgabbro and olivine dolerite were recovered (Crawford & von Rad, 1994). On the basis of their similarity to the Valanginian volcanics drilled at ODP Site 766 to the west, the latter authors assumed a Valanginian age for the dredged lavas, rather than an early rift age.

On the basis of the above results, the widespread undated, but similar, volcanics dredged along the margin, and the presence of typical features of volcanic buildups in the seismic profiles (Symonds et al., 1998a), it is apparent that rift and breakup volcanics are widespread along the outer margin of the plateau. Their ages probably include Late Triassic, Oxfordian/Callovian and Early Cretaceous.

5.2.5 Lower and Middle Jurassic mega-sequence

In much of the Carnarvon and Roebuck Basins, the Lower and Middle Jurassic sequence (Legendre/Dingo equivalent) is 1000-2000 m thick, but it is absent on much of the central Exmouth Plateau (e.g. Fig. 10). It is present on much of the northern plateau in sequences up to 2000 m thick (Fig. 13). However, on the unique high block of the Wombat Plateau, ODP drilling and dredging has not recovered any Jurassic rocks (Fig. 14). Dredge and well evidence suggests that thinning is caused by either non-deposition or erosion of the Jurassic sequence (e.g. Colwell et al., 1994a).

Dredge and seismic information indicates that there is a thick Lower Jurassic shelf carbonate sequence along the outer continental margin, beneath much of the northern Exmouth Plateau, overlain by a thick Middle Jurassic siliciclastic sequence (e.g.

Colwell et al., 1994a). Two seismic facies appear to correspond to these two lithofacies on the western end of BMR seismic line 95/12 (Ramsay & Exon, 1994). The lower, seismically relatively transparent facies is interpreted as consisting of homogeneous shelf carbonates and marls; and the upper, onlapping, seismically strongly reflective facies with internal normal faults, as consisting of detrital sediments and coal. On the central Exmouth Plateau, the Lower Jurassic shelf carbonates transgressed toward the continent with time (Fig. 12).

The dredged samples from the northern Exmouth Plateau and Rowley Terrace were examined in detail by Colwell et al. (1994a), Burger (1994), Shafik (1994) and Grant-Mackie (1994). They include a great variety of shelf carbonates; marine, paludal and fluvial siliciclastic detrital sediments; coal; and ferruginized detrital sediments that were exposed during the Middle to Late Jurassic pre-breakup thermal uplift of the margin. The foraminifers, ostracods and bivalves in the carbonates are similar to those of other Tethyan margins.

Exon et al. (1991) identified presumed large carbonate buildups on horsts on the northern Exmouth Plateau in the Lower and Middle Jurassic sequence, using older seismic data and early versions of BMR Survey 95 seismic data. Dredging of one of these buildups yielded Lower Jurassic limestone of carbonate bank facies (Colwell et al., 1994a). From the seismic data, it is uncertain whether reefal buildups formed on high blocks or, alternatively, whether limestone banks were widespread on a flat Triassic surface, and subsequently cut by faulting into horsts and graben (Ramsay & Exon, 1994).

The Lower and Middle Jurassic sequence, like the Triassic sequence, is strongly faulted on the Exmouth Plateau and on the northwestern margin of the Rowley Sub-basin.

5.2.6 Tectonism, volcanism and breakup: late Middle to early Late Jurassic

Seismic evidence from most of the southern North West Shelf shows that there was major tectonism in Callovian/Oxfordian time, represented most clearly by a major, frequently angular, unconformity (horizon ***call***). This unconformity has been dated palaeontologically as covering very variable time spans (commonly varying from a minimum of parts of the Callovian and Oxfordian, to as much as the entire Late Jurassic and Berriasian), and is related to thermal uplift preceding the breakup of Gondwana that formed the Argo Abyssal Plain.

The areas of most uplift, around the continental margin, were also extensively faulted. Weathering and erosion followed, and the relief across the faults was reduced. Weathered (ferruginized) Jurassic sedimentary rocks have been widely dredged along the margin (e.g. Colwell, et al., 1994a). Some areas were bevelled completely by wave action. Along the high blocks on the northernmost Exmouth Plateau, the bevelled area is about 50 km wide, lying landward of the steep continental slope (Ramsay & Exon, 1994).

Dredging shows that some areas along the continental margin contain abundant volcanic rocks of possible Jurassic age, while others contain none or very few (Colwell et al., 1994b). Ramsay & Exon (1994), using seismic characteristics, mapped a province where volcanic flows and volcaniclastics apparently underlie the Callovian unconformity on the northwestern edge of the Rowley Sub-basin. The position of the continent-ocean boundary (COB) is imprecise in most cases, since seismic quality is poor under the steeper and deeper parts of the margin, and volcanic provinces frequently separate continental and oceanic crust.

The oldest oceanic crust of the Argo Abyssal Plain has been dated as 155 Ma (Oxfordian) in ODP Site 765 (Ludden, 1992), where the oldest palaeontologically datable overlying sediments are Tithonian. Fullerton et al. (1989) identified the oldest magnetic anomaly as M26, in agreement with the drilling results. Thus the age of breakup on the abyssal plain corresponds to the age of the Callovian unconformity on the continental margin, indicating that the term 'breakup unconformity' is appropriate.

5.2.7 Late Jurassic to earliest Cretaceous megasequence

In this region, the Late Jurassic to mid-Valanginian sequence (earliest Cretaceous) varies from absent in some areas, to as much as 2000 m thick where the Barrow delta and its equivalents are present. The equivalent E-D seismic sequence occurs intermittently away from the main areas of deltaic deposition, preserved in structural lows where it onlaps the bounding highs, showing that its deposition was governed by the pre-existing structure. Well evidence (e.g. Exon, 1994b) indicates that the succession consists of deltaic and shallow marine detrital sediments, laid down as the margin started to subside following breakup. The thin Late Jurassic sequence (upper Dingo Claystone) has seldom been drilled on the Exmouth Plateau. Where it has, it is fine grained, and glauconitic in part.

ODP Sites 762 and 763 on the central Exmouth Plateau (water depths 1360 m and

stratigraphic control. The discussion below is drawn from Exon et al. (1992) and Exon & von Rad (1994). Site 763 lies in a relatively proximal, thick part of the earliest Cretaceous, northward-prograding Barrow Group delta, whereas Site 762 is above the thin distal part of the delta. About 380 m of Cretaceous sequence was cored at Site 762, and 790 m was cored at Site 763.

Figure 16 is a composite stratigraphic diagram. Haq et al. (1992) summarised the results for the central plateau. Key palaeontological papers are those of Bralower & Siesser (1992), Brenner (1992), Jones & Wonders (1992) and Wonders (1992). Organic geochemical and petrological information is drawn from Snowdon & Meyers (1992) and Rullkötter et al. (1992), and petrophysical information from O'Brien & Manghnani (1992).

The oldest sequence penetrated at both sites was the Barrow Group. Both seismic interpretation (Boyd et al., 1992) and benthic foraminiferal assemblages (Jones & Wonders, 1992) suggest deposition in water shallower than 400 m. At Site 763, 414 m of section was penetrated (depositional rate up to 30 m/m.y.), consisting of grey prodelta mudstones of Berriasian and early Valanginian age, in three lithological units. The very thick lowest unit consists of monotonous massive mudstone, with microplankton, pyrite, siderite and glauconite, along with red 'desert quartz' derived from a dry continental source. Some intervals contain abundant disseminated shell debris, and occasional belemnites, ammonites and bivalves.

The middle unit (24 m thick) consists of interbedded mudstone, carbonate-cemented graded quartz sandstone and a little limestone, and was probably formed from turbidites in a pro-delta fan. It contains dinoflagellates, nannofossils, pyrite and glauconite. The upper unit is a condensed section (14 m thick) of mudstone and lesser recrystallised limestone. It contains abundant belemnites, sand-sized glauconite pellets, siderite, disseminated pyrite, dinoflagellates, nannofossils and plant debris. The variations in lithology suggest that the middle unit was deposited in more reducing conditions than the other two, probably in deeper water. In Site 762 the group is thinner and finer grained, in accord with its distal position.

R. Helby and W. Brenner (pers. comm., 1990) have commented on extensive reworking of palynomorphs from pre-Cretaceous sediments into the Barrow Group, in ODP Sites 762 and 763, and the adjacent Eendracht-1 and Vinck-1 wells. In the ODP holes there is continuous reworking of Permian spores and pollen, and sporadic reworking of Triassic forms. Oxfordian, Kimmeridgian and Tithonian microplankton are also reworked from the upper Dingo Claystone. In Vinck-1 and Eendracht-1 wells, Triassic spores and pollen are reworked sporadically. Permian reworking is very common. Carboniferous reworking is common in the lowermost Barrow sequence in Eendracht well. The Permian and Carboniferous forms cannot have originated from local erosion and redeposition, but must have come from distant sources to the south or east.

TOC values are around 1 % in the Barrow Group, and Rock-Eval pyrolysis has shown that the kerogens are typical of organic matter from higher land plants. Hydrocarbon enrichment at some levels indicates that there is a limited potential to generate and expel both gaseous and liquid hydrocarbons, although the organic matter is immature to marginally mature. In the cores at Site 762, porosity is about 40-50 %.

5.2.8 Earliest Cretaceous (Valanginian) breakup and volcanism

Gondwana broke up along most of the western margin of Australia much later than it did north of the Exmouth Plateau: in the Valanginian, about 30 million years later than the Argo breakup. The Valanginian breakup unconformity is very widespread on the North West Shelf, even in areas where breakup occurred earlier, suggesting a tectonic coupling. It is marked by our horizon ***val***, which seldom shows much angularity, but does mark the onset of steadily increasing water depths in many areas, as the cooling continental margin and oceanic crust subsided together. Below the western Exmouth Plateau, the Late Triassic to earliest Jurassic volcanic sequence was planated during uplift of the margin, which was presumably caused by heating before breakup in the Early Neocomian (Exon & Buffler, 1992).

Breakup may have roughly coincided with the volcanism that formed the Wallaby Plateau (Colwell et al., 1994b). Furthermore, this was a period of basaltic volcanism on the Scott Plateau in the north, as evidenced by K/Ar ages of 128-130 Ma (von Stackelberg et al., 1980). This suggests that volcanism (probably related to Valanginian breakup) may have affected widespread areas of the outer western Australian margin, even those that had broken up 30 million years earlier. The volcanic sequence to the west of the Exmouth Plateau is almost certainly largely of this age (Symonds et al., 1998a).

5.2.9 Deposition on the plateau after breakup

Evidence from wells, for example the ODP sites on the Exmouth Plateau, indicates that a regional marine transgression started in the late Valanginian, immediately after breakup in the west (von Rad et al., 1992a, b). Burial of the Barrow Group followed, as the continental margin and the new oceanic crust in the west, and the old oceanic crust in the north, cooled and sank. Marine erosion appears to have formed the Valanginian unconformity, and the overlying sediments are wholly marine.

Shallow marine detrital sediments and marls of the Muderong-Haycock equivalents (seismic horizons ***val-tur***) were laid down over most of the region with a thickness of about 200-1000 m, with the exception of highly structured parts of the northern Exmouth Plateau, where they onlap highs and are absent in places. The conformable transition to carbonate sedimentation in the Late Cretaceous led first to the deposition of shelf carbonates. Bathyal carbonates were deposited thereafter in mega-sequences of Paleocene-Eocene, Oligocene, early to middle Miocene and late Miocene to Recent, often separated by a disconformity.

The Muderong Shale, overlying the Barrow Group, is 52 m thick at Site 763 and 10 m thick at Site 762. In Site 763 it spans four dinoflagellate zones and is probably of middle Hauterivian to early Aptian age. It unconformably overlies the Barrow Group with a time gap of at least 5 million years, the unconformity (D) corresponding to the Valanginian breakup of east Gondwana. The formation consists of a condensed sequence of grey mudstone and clayey sandy siltstone, with minor grey limestone beds and nodules. The sedimentation rate of about 10 m/m.y. was much lower than that prevailing during most of Barrow Group deposition at the same site. The formation is massive to parallel laminated and moderately bioturbated. It contains common quartz (often red 'desert quartz'), glauconite, shell and plant debris, nannofossils and dinoflagellates, and occasional pyrite, benthic foraminifers, radiolarians, spores and pollen, and echinoid fragments. The generally laminated and muddy character of the sediments, along with the presence of nannofossils, suggests outer shelf deposition, and the variations in grainsize suggest storm influence or eustatic sea level changes.

The overlying Gearle Siltstone is transitional in character between the Muderong Shale and the overlying Haycock Marl. It is 38 m thick at Site 763 and thinner at Site 762. At Site 763, the age of the sequence is probably early Albian, suggesting a disconformity of about 2 million years at its base. Depositional rates are low and hiatuses are probably present. The lower part of the formation consists largely of green-grey siltstone; the middle part of silty claystone; and the upper part of lighter coloured recrystallised limestone. The formation is heavily bioturbated and generally contains quartz, glauconite and nannofossils; radiolarians are present in the lower part, and foraminifers and dinoflagellates in the upper part. Overall, the biogenic content increases upward, and also seaward to Site 762 (dominantly white clayey nannofossil chalk). The pelagic influence, with both land-derived clay and calcareous nannofossils being important, meant that climatic cycles could affect the sediments, and they contain colour cycles tens of centimetres thick at Site 763.

The shelf sediments of the Haycock Marl are relatively homogeneous, and conformably overlie the Gearle Siltstone, and are well developed at Site 763 (161 m thick) and compressed at Site 762. At Site 763 the base of the unit is above the limestone at the top of the Gearle Siltstone, and its top below the limestones of the Toolonga Calcilutite. Sedimentation rates are 10-15 m/m.y. The lower part, of Albian age, consists of nannofossil marl, and contains glauconite, pyrite, bivalves, foraminifers and rare belemnites. The upper part, of late Albian to Turonian age, consists of clayey nannofossil chalk, and contains glauconite and intermittent pyrite and dinoflagellates. Black claystones, marking the worldwide anoxic event at the Cenomanian-Turonian boundary, deposited on the outer shelf, are within the upper part and are underlain by an hiatus. The sequence contains light and dark cycles, in couplets tens of centimetres thick, presumably Milankovitch climatic cycles. In Site

762 a change in oxidation state is evident, from dominantly green sediments in the Albian to dominantly red sediments later.

The Toolonga Calcilutite is a relatively dense sequence that is distinguished by a strong positive anomaly in resistivity logs. The contact with the underlying Haycock Marl and its equivalents generates the regional seismic horizon ***tur***. The formation is slightly thicker at Site 763 (25 m) than at Site 762. The age is approximately Turonian and Santonian, and the sequence was probably deposited in about 2 million years, so sedimentation rates were low at about 10 m/Ma. It consists of subtly colour-banded, bioturbated nannofossil chalk and clayey nannofossil chalk, with abundant foraminifers and some ostracods. The formation was deposited on the outer shelf, and again contains colour cycles tens of centimetres thick, and presumably caused by Milankovitch climatic cycles.

TOC values average about 0.5 percent in the Muderong Shale, 0.2 percent in the remainder of the Lower Cretaceous, and less than 0.1 percent in the Upper Cretaceous. Exceptions are the thin organic-rich black claystones at the Cenomanian-Turonian boundary which contain 10-15 percent TOC and marine organic matter. In the cores at Site 762, porosity is about 20-30 % in the Muderong to Toolonga sequence, and about 40 % in the remainder of the Cretaceous.

The Upper Cretaceous carbonate sequence in ODP Sites 262 and 263 conformably overlies the Toolonga Calcilutite, and consists of outer shelf and upper bathyal nannofossil chalk and marly chalk. As it is different from the carbonates known from the North West Shelf, established stratigraphic names have not been applied to it. At Site 762 the sequence consists of 325 m of continuous deposits of late Early Santonian to latest Maastrichtian age; the sedimentation rate is about 15 m/m.y. At Site 763 it is 99 m thick: a continuous sequence of late Santonian to late Campanian age.

Site 763 appears to have been subject to submarine erosion, which removed Maastrichtian, Paleocene and early Eocene sediments, or prevented their deposition. The uppermost Campanian sediments contain concentrations of quartz and glauconite, suggesting a period of winnowing. Wave or current erosion may have taken place in the Eocene, following arching related to the collision of Australia with the Sunda arc.

At both sites the chalky sequence contains colour cycles, involving white, greenish and reddish shades, which are related to variations in the proportion of clay and the oxidation state. Huang et al. (1992) identified two sets of cycles: 4-41 cm and 71-84 cm thick. They considered that the colour cycles formed in response to variations in continental insolation driven by Milankovitch climatic cycles. Wet, equable and warm periods led to more run-off and erosion, and deposition of dark clayey beds offshore. Dry, cooler periods led to less run-off and erosion, and deposition of light coloured, highly calcareous beds.

High headspace gas values of up to 100 000 ppm were found in the Upper Cretaceous to Eocene chalk above the Toolonga Calcilutite at Site 762, and in the upper Neocomian to Oligocene chalk, marl and siltstone at Site 763. The gas is dominantly methane, but does contain significant amounts of C2 to C6 hydrocarbons. The gas probably comes from the Triassic, and its concentration in the chalks and marls is related to reduced permeability caused by lithification (i.e. the gas escapes rapidly upward once it reaches the overlying unlithified oozes).

On the Wombat Plateau, the Cretaceous sequence is greatly reduced (Fig. 14). At Site 761, a 20 m thick, condensed, fining-upward transgressive Berriasian to Valanginian sequence rests on the Triassic (von Rad et al., 1992a, b). These 'juvenile ocean' sediments (von Rad & Bralower, 1992) consist of ferruginous arkosic sand and belemnite-rich sandy mudstone, overlain by calcisphere nannofossil chalks with six thick intercalations of bentonite formed by the alteration of ash turbidites (von Rad and Thurow, 1992). This explosive dacitic volcanism, related to the Valanginian breakup of Gondwana, may have come from volcanic vents on the northwestern Exmouth Plateau, and is also present in ODP Site 765 of the Argo Abyssal Plain.

The *Cainozoic section* (post-horizon ***cret***) is best developed at the central Exmouth Plateau sites. The summary stratigraphic diagram for the Wombat Plateau (Fig. 15) shows a maximum thickness of about 180 m of cored Cainozoic section containing four major unconformities. In contrast, the summary stratigraphic diagram for the central Exmouth Plateau (Fig. 18) shows about 560 m of Cainozoic section containing only one major unconformity between the early and middle Miocene. Little detailed work has been done on the sedimentology, but the palaeontology is well covered in various papers in von Rad, Haq et al. (1992), and especially by Siesser & Bralower (1992). The following description concentrates on the more complete central Exmouth Plateau section and is drawn from Haq et al. (1992) and Exon & von Rad (1994).

At Sites 762 and 763, the Cainozoic section consists of relatively homogeneous nannofossil and foraminiferal chalks and oozes. At Site 762, the Palaeogene section is well developed, and may be complete to the top of the lower Miocene. The overlying Neogene section is also almost complete. At Site 763, upper Campanian chalk is unconformably overlain by pelagic chalk of middle Eocene age, and an apparently complete upper Eocene through middle Miocene section is present. Above this section are a six million year hiatus and a relatively complete section of upper Miocene to Pleistocene ooze.

Of particular interest are the well-preserved radiolarian faunas on the Wombat Plateau that indicate that most of the Paleocene is present over 53 m at Site 761 (Blome, 1992). Many of the radiolarian taxa were previously unreported.

5.2.10 Deposition on the Argo Abyssal Plain

The oldest oceanic crust on the plain is Oxfordian in age, and the youngest crust is Berriasian, preserved south of the Java Trench. The oldest dated sediments are Tithonian in both ODP Site 765 and DSDP Site 261. Buffler (1994) correlated ODP Site 765 (Fig. 17) with DSDP Site 261on a high-resolution ODP seismic line. The thickness of sediments on the plain is generally 600-1000 m, and the bulk of it is calcareous turbidites and claystone. The thickest sequences are Lower Cretaceous and Middle Miocene to Pliocene.

Rao et al. (1994) used a seismic grid to show that the structural grain is generally NW to WNW, a trend that does not agree with the magnetic lineations mapped by earlier workers such as Fullerton et al. (1989), but does agree with satellite gravity maps and the magnetic lineations of Mihut & Müller (1998). Rao et al. also identified depressions, containing thicker sedimentary successions, in the oceanic crust along the Exmouth Plateau margin, and beside the eastern Joey Rise, formed because of down-bowing of the loaded crust. The early deposition was thickest near Australia, but Miocene and Plio-Pleistocene deposition was thickest in the middle of the plain.

At Site 765 (Fig. 17) on the Argo Abyssal Plain, 935 m of sediments were cored above oceanic crust, and the results are covered comprehensively by Gradstein, Ludden et al. (1990, 1992). Sedimentation was almost continuous from the Tithonian to the present day. There was an hiatus of about 10 million years (or highly condensed sedimentation) between basement emplacement and the oldest dated sediments (Tithonian) - only 1.5 m separates them from basement (Oxfordian). This lack of initial sedimentation may have been caused by eroded sediments being fed back inland from the uplifted and landward-tilted continental margin, as suggested by Ramsay & Exon (1994) for the Rowley Terrace area. The bulk of the sediments at Site 765 are calcareous turbidites (containing bathyal foraminifers from the continental margin) and claystone. The thickest sequences are Lower Cretaceous and middle Miocene to Pliocene.

Neocomian sedimentation was relatively uniform, consisting of about 310 m of pelagic claystone; much of it bentonite derived from ash falls (von Rad & Thurow, 1992). The Late Cretaceous to Eocene was a period of condensed sedimentation, with deposition of about 70 m of alternating claystone, calcareous turbidites and debris flows. Oligocene to middle Miocene sedimentation (about 160 m) was characterised by the deposition of carbonate turbidites, but pelagic claystones were still important. The late Miocene saw the deposition of about 200 m of carbonate turbidites. From the latest Miocene onward, clay content increased and carbonate debris flows were interbedded with carbonate turbidites; this sequence is 190 m thick.

In summary, oceanic crust was formed from the Oxfordian until at least the Berriasian, about a spreading axis oriented NE, with fracture zones trending NW. The abyssal plain contains an average of 500-1000 m of sediment that thins northwards. There was little sedimentation in the Late Jurassic, but relatively rapid deposition (especially in structural depressions in the south and west) in the Early Cretaceous. A mixture of pelagic clay and carbonate turbidites and debris flows were deposited on the steadily subsiding abyssal plain, with the turbidites and debris flows producing the highest sedimentation rates. Sedimentation rates from the middle Miocene onwards were relatively high, particularly on the central part of the plain. The onset of subduction in the Java Trench, possibly in the Early Miocene, led to a regional tilt to the south (Buffler, 1994), the fracturing of the northern area by northeast-trending faults and the concentration of sedimentation away from the fore-bulge of the trench.

5.2.11 Deposition on the western margin of the Exmouth Plateau (ODP Site 766)

At Site 766 (Fig. 18), 458 m of sediments were cored above volcanic basement in a water depth of 4535 m. Most sedimentation was in the Cretaceous, and it was fairly continuous from the latest Valanginian to the Campanian. All sedimentation was in bathyal or deeper water. The sediments are interbedded with poorly K/Ar dated diabase sills at the base of the hole (see section *Oceanic crust*). The following discussion is drawn largely from Buffler et al. (1992).

About 150 m of Hauterivian and Barremian glauconitic sandstone and siltstone were derived from shallow-water shelves and volcanic land masses to the east (when source and depositional areas were both high immediately after this part of Gondwana broke up) and possibly fed down canyon systems. Subsidence modelling suggests an initial depth of water of about 800 m at the site. The Barremian sequence consists of about 50 m of dark hemipelagic claystone, and was deposited while the source and depositional areas were subsiding rapidly as the crust cooled. The Aptian to Cenomanian sequence consists of about 110 m of open marine chalk deposited in deep water. The relatively thin (55 m) Upper Cretaceous sequence consists of clays and oozes deposited under sediment-starved open-marine conditions, with clay finally disappearing in the Campanian. The Cainozoic sequence of nannofossil ooze is only 95 m thick. Strong deep-sea currents swept through the area periodically throughout the Cretaceous and Cainozoic, as indicated by the condensed section and the numerous erosional unconformities visible on the seismic reflection profiles.

6. SEISMIC SEQUENCES AND FACIES

As the seismic stratigraphy of the sedimentary section on the Exmouth Plateau has been described in a number of reports, beginning with Exon & Willcox (1980), we will not describe it in detail here. Of more importance is a description of the characteristics of the many different volcanic units that are particularly found on the plateau margins and adjacent abyssal plains. In this section we will follow the approach of Frey (1998) and Planke et al. (2000), and modify and extend their volcanostratigraphy in light of the more extensive data set that is available to this study. All seismic units will be illustrated by detailed seismic sections. A full listing of the horizons and units that were mapped in the study is contained in Appendix 5.

6.1 Non-Volcanic Seismic Facies Units

Upper continental crust

The *upper crust* seismic facies units (i.e. horizons above horizon ***tran***; Fig. 19) are characterised by a well stratified sedimentary section that has been extensively cut by faulting to the Triassic-Jurassic level. Within this unit, we have interpreted a number of mega-sequence boundaries that coincide with the boundaries used by Stagg & Colwell (1994). These mega-sequence boundaries are at the following times:

- Oligocene (horizon ***olig***)
- Top Cretaceous (horizon ***cret*** = base Tertiary of Stagg & Colwell (1994))
- Turonian (base of carbonate section; horizon ***tur*** = Santonian of Stagg & Colwell (1994))
- Valanginian (horizon ***val***; Gascoyne/Cuvier 'breakup' unconformity)
- Oxfordian (horizon ***call***; Argo 'breakup' unconformity)
- Top Triassic (horizon ***tr***; top Mungaroo Formation)
- Near top Palaeozoic (horizon ***Pz***)

Some of the boundaries interpreted by Stagg & Colwell (1994; Aptian, top Jurassic, Ladinian) have not been used in this report as they cannot readily be identified over much of the Exmouth Plateau.

Mid continental crust

This unit is characterised by discontinuous, undulating, generally high-amplitude reflectors in an overall layered package (interval ***Pz-tran***; Fig. 20), and corresponds with the unit of the same name described by Frey (1998), who reports that it is associated with a constant P-wave velocity of 5 km/s; ESP stations E4, E6 and E7 show velocities in the range 4.9-5.2 km/s for this unit, while station E5 shows an anomalous velocity inversion from 4.8 back to 4.3 km/s. This unit is also the level at which much of the upper crust faulting dies out. We interpret the mid-crust to comprise pre-Westralian Super-basin sediments and meta-sediments that have also been strongly intruded by dykes and sills, particularly near the plateau margins.

Lower continental crust

The *lower crust* unit is characterised by generally low reflection amplitude and continuity (interval ***tran-tlcb***; Fig. 19), and again corresponds to the unit of the same name described by Frey (1998), who reports a P-wave velocity of 5.75 km/s. ESPs E4 to E7 show velocities in the range 5.9-6.2 km/s. Stagg & Colwell (1994) interpreted a correlative unit, as 'upper crystalline crust', which they suggested could correlate with the shallow greenstone belts and granitoid bodies of the upper part of the Pilbara Craton.

Shallow crystalline crust

This unit is only recognised beneath the inner flank of the Northern Carnarvon Basin, inboard of the major Jurassic troughs. This unit probably consists of Pilbara Craton equivalents (greenstone and granitoid bodies) and may correlate with the transparent *lower crust* described above.

Intruded lower continental crust

The *intruded lower crust* unit is characterised by low-frequency, relatively continuous, high-amplitude reflectors (interval ***tlcb-blcb***; Fig. 19), and corresponds to the 'top underplating' of Frey (1998). The unit is concentrated on the northwestern flank of the Exmouth Plateau. Seismic velocities greater than 7 km/s, and the differential subsidence that characterise all sequences on the outer Exmouth Plateau point to the unit being the result of intrusion of the lower crust by mantle melt.

Magmatic underplating

As will be noted later in this report, we distinguish between magmatic intrusion of the lower crust (which produces differential subsidence) and magmatic underplating of the crust (which produces differential uplift). A magmatic underplated unit is interpreted along the uplifted southwest margin of the Exmouth Plateau, where Lorenzo et al. (1991) reported a 10 km-thick body with a seismic velocity of 7.0 km/s. The seismic velocities reported for intruded lower crust and magmatic underplating are very similar, which means they must be distinguished by other criteria. The difficulty in recognising underplating beneath the Exmouth Plateau is highlighted by Fomin et al. (2000).

Mantle / Moho

Frey (1998) characterises the Moho as a single reflector or band of reflectors, and interprets it beneath the central and inner Exmouth Plateau at about the same level of Stagg & Colwell's (1994) reflector C2. We believe that the reflector C2 is too shallow high-amplitude, low frequency reflectors to a more finely-stratified, semi-transparent sequence, above which is interpreted to be equivalents of the marine Locker Shale. The thickness of the Permo-Carboniferous section is difficult to gauge, due to the poor definition of its base, but it is estimated to be 1-2 s TWT (*ca*, 2.5-5 km).

While this sequence comprises the first stage of the Westralian rift system, there is little evidence of crustal extension, leading Stagg & Colwell (1994) to refer to the sequence as 'Sag Phase 1', and to infer that lower crustal extension was the primary mechanism of basin formation.

Triassic

The distribution and geometry of the Triassic section is similar to that of the underlying Permo-Carboniferous. Beneath the inner margin of the basin it is incorporated into fault blocks which have generally undergone minor to moderate extension; beneath the Exmouth Plateau it is generally flat-lying and thick (2-3 s TWT; *ca*. 5-6 km; eg Plate 9, line 162/07-128/08-101R/09).

The seismic character of the Triassic section is very distinctive. The lower part of the section is characterised by generally low-amplitude reflections, and is a probable correlative of the transgressive Lower Triassic Locker Shale. The upper part of the Triassic section consists of the thick, regressive, fluvio-deltaic sediments of the Mungaroo Formation, and its equivalents to the northeast, the Keraudren Formation.

Faulting at the top of the Triassic section (in the Late Triassic or Early Jurassic) is one of the most distinctive aspects of the structural style on the Exmouth Plateau. The actual age(s) of faulting is difficult to determine since the Jurassic section is very thin or absent, except on the northern margin of the plateau, where the Lower and Middle Jurassic section is thick and faulting extends to the Oxfordian level.

While faulting of Triassic section is the most obvious structuring visible on the Exmouth Plateau, the style of faulting is variable. The particular faulting styles include:

- extensional, as typically observed beneath the inner flank of the Northern Carnarvon Basin and beneath the outer Exmouth Plateau (e.g. Plate 9, line 128/05-101R/10). On the Exmouth Plateau, these faults sole out oceanwards, either at the base of the Triassic section (probably within the Locker Shale), or within the Palaeozoic and deeper crust;
- transtensional, with negative 'flower' structures, as is common beneath the inner half of the Exmouth Plateau (Plate 10, line 162/01-110/15-101R/07). These faults, which may have expression as a mildly extensional fault zone at the top of the Triassic section, appear to be due to the reactivation of deep-seated, high-angle fault zones;
- transpressional, with compressional anticlines, as are interpreted beneath the oceanward flanks of the Exmouth Sub-basin and the southern Rankin Platform, but are less well-developed elsewhere on the Exmouth Plateau (Plate 10, line 162/04-135/01-110/12). As with the transtensional structures, these structures generally coalesce at depth into narrow fault zones.

The dominant trend of the Triassic faulting is N-S. As this is oblique to the trend of the interpreted continent-ocean boundary and not orthogonal to the trend of major transforms (for example, the Cape Range Transform), it is likely that the Triassic to be Moho and have not been able to identify Moho with any confidence beneath continental crust in this study. However, Moho is sometimes identified beneath oceanic or magmatic crust at depths of 10-10.5 s TWT (horizon ***moho***; Fig. 21). On the Cuvier and southeast Argo Abyssal Plains, it is a strong and continuous reflector, with some minor offsets due to reverse shearing, while on the Gascoyne Abyssal Plain it is less evident, being identified as a 'shadow zone' of discontinuous reflectors.

Modelling based on the single OBS transect across the Exmouth Plateau recorded by Geoscience Australia in 1995 indicates that relatively thick oceanic/volcanic margin crust lies beneath the lower continental slope and the inner part of the Gascoyne Abyssal Plain (Fomin et al., 2000) consistent with the volcanic nature of the margin.

6.2 Volcanic Seismic Facies Units

Sills in continental crust

Sills and related intrusions in continental crust are characterised by high-amplitude single reflectors or thin reflector bands (horizon ***sill***; Fig. 22). They tend to follow the stratigraphy, climbing up through the section along faults; elsewhere, they can cut directly across faults, indicating their post-depositional nature. Individual sills may have lateral extent ranging from a few kilometres up to about 70 km. While they are most commonly observed in the Palaeozoic and Triassic section, some of the most extensive sills are found in the lower transparent crust.

Intrusive pipes and dykes

Members of this unit are recognised particularly on the southwest corner of the Exmouth Plateau, near the junction of the Cuvier and Gascoyne Abyssal Plains. They are manifest as narrow, high-angle zones of chaotic reflection character, generally intruded along major faults (shaded area in Fig. 23).

Intruded continental crust

This unit is defined where the upper crust contains irregular, continuous, high-amplitude reflectors down to about 3 s TWT below the basement surface. The crust is interpreted to comprise Palaeozoic or Mesozoic sedimentary section, similar to that on the Exmouth Plateau, which has been heavily intruded by sills, dykes and laccoliths, and subsequently covered by lava flows. The type example comprises the most southeasterly portion of Platypus Spur horizon (interval below horizon ***icc***; Fig. 24).

Composite intact volcano – continental

This unit is interpreted as a large scale volcanic vent on continental crust, measuring up to tens of kilometres across and containing a layered sequence which dips towards a central vent (interval below horizon ***civc***; Fig. 25). The thickness of layered section may as much as 6-8 km. The upper surface of the unit is at about the same topographic level as the adjacent contemporary strata. The type example is located at the junction of the Platypus Spur and the northwest corner of the Exmouth Plateau.

Composite intact volcano – oceanic

This unit has similar internal form and external size to the *Composite Intact Volcano, Continental*, but is found as a high-relief feature on deep-seated magmatic crust (interval below horizon ***civo***; Fig. 26). The type example is the easternmost edifice of Joey Rise.

Debris flows

These units are situated on steep slopes, generally adjacent to volcanic units (interval below horizon ***tdeb***; Fig. 26). They are interpreted to have formed due to the rapid cooling and fracturing of steep-sided, subaqueous volcanic units.

Composite volcanic buildup

This unit is defined as a low- to moderate-relief, but areally extensive volcanic buildup, with little or no internal reflector character, extruded onto magmatic crust (interval below horizon ***cvb***; Fig. 27). The type example is the deeper, north-trending section of Platypus Spur, north of the segment of *Intruded Continental Crust*.

Landward flows

These units are interpreted to be lava flows that have been extruded landwards over the top of continental fault blocks, having the effect of smoothing out the underlying topography, while leaving the fault block edges visible (horizon ***flow***; Fig. 28). They also completely mask any stratigraphy in the underlying crust, leaving a seismically blank zone. The upper surface of the unit produces high-amplitude irregular reflections, while the base of the unit is not visible. The unit is commonly found on the outer Exmouth Plateau, adjacent to the lower slope volcanic province or to other volcanic units.

Slope volcanics

This unit underlies the continental slope below the Exmouth Plateau. The external form is typically mounded and there is no discernible internal reflection character (horizon ***slop***; Fig. 29). The unit is interpreted to have developed through intrusion and extrusion in proximity to the locus of continental breakup.

Seaward dipping reflector sequences (SDRS)

The SDRS has an external form of a wedge or, more probably, a fan, with convex upwards internal reflectors that dip seawards (interval below horizon ***tsdr***; Fig. 30). The flow length of individual SDRSs varies from about 50 km (proximal SDRS) to 10 km (distal SDRS), with the width (and flow length) probably reflecting the water depth at the time of extrusion. The maximum thickness of an individual SDRS is about 8 km. The oceanwards boundary of an SDRS often appears to be an extensional, landward-dipping fault, although an alternative interpretation is that the apparent fault is feeder dykes that have subsequently been rotated as the SDRS has subsided and tilted. The base of an SDRS is rarely observed.

Inter-SDRS buildups

Adjacent SDRSs are typically separated by volcanic buildups that may have relief ranging from a few tens of metres to several hundred metres (interval below horizon ***udif***; Fig. 31). No internal reflection character is evident. The origin of these buildups is unclear, and their possible genesis will be reviewed later in this report.

Buildups

These units are volcanic piles that have been extruded on to magmatic crust, but which are not related to SDRSs and do not lie beneath the lower slope (interval below horizon ***buil***; Fig. 32). The relief of individual units may vary from a few tens of metres to hundreds of metres. No internal reflection character is evident.

Transform volcanics

This unit is defined as volcanics that have been extruded along a transform, either between oceanic or continental crust or within oceanic crust (interval below horizon ***tiv***; Fig. 33). They are differentiated from the slope volcanics (see above) on the basis of their setting. They will also be younger than the slope volcanics. The unit is typically long, with respect to width, and may have vertical relief of several hundreds of metres.

Oceanic flows

These units are flows that have been subaqueously extruded on to magmatic crust or the overlying sediments. Flow lengths may be tens of kilometres and flow edges are often evident and mistaken for faults. This unit is generally only distinguished where they have been extruded over, or intruded through the sedimentary section, and the best examples are found on the margins of the Wallaby Plateau (Sayers et al., 2002). Where flows have been extruded directly onto magmatic basement they have been interpreted as the upper surface of that basement.

Volcanic margin/oceanic crust - smooth; rough; layered

This unit includes all volcanic crust that has been emplaced oceanward of the Exmouth Plateau and which has typically been referred to as oceanic crust or oceanic basement (Figs 21 & 34). We have used the term *volcanic margin crust* in reference to the Gascoyne Abyssal Plain adjacent to the Exmouth Plateau, where the crust is 50-100% thicker than 'normal' oceanic crust, and there is uncertainty about the nature of the underlying crust.

Laminated lower oceanic crust

This unit comprises the lower part of the magmatic crust in the Cuvier and southeast Argo Abyssal Plains (interval below horizon ***tlam***; Fig. 21), but is less well-developed on the Gascoyne Abyssal Plain. The top of the unit is marked by an envelope at about 8-9 s TWT, below which the reflectivity increases markedly.

7. STRUCTURE

7.1 Velocity Structure

7.1.1 Introduction

Information on the velocity structure of the Exmouth Plateau region derives from four principal sources, as follows:

1. *Refraction sonobuoys:*

Sonobuoy stations 57-59 (Appendix 6) of Francis & Raitt (1967) are located in the Gascoyne and Argo Abyssal Plains. While sonobuoys 58 and 59 are somewhat distant on the Argo Abyssal Plain, the dearth of oceanic velocity data makes them relevant to this study. The solution to sonobuoy 57 (Gascoyne) gave a fairly standard oceanic section, with layer 2 and layer 3 crustal thicknesses of 1.3 and 4.5 km, respectively, and Moho at a depth of 11.6 km. Sonobuoy 58 (Argo) gave a thicker than normal oceanic section, with layer 2 and layer 3 thicknesses of 2.4 and 6.1 km, and Moho at a depth of 14.7 km. Sonobuoy 59 (northeast Argo) also gave a thicker than normal oceanic section, with layer 2 and layer 3 thicknesses of 0.8 and 7.0 km, and Moho at a depth of 14.0 km.

2. *Two-ship Expanding Seismic Profiles (ESPs):*

These were recorded during a collaborative survey between the Bureau of Mineral Resources (now Geoscience Australia) and the Lamont-Doherty Geological Observatory (now the Lamont-Doherty Earth Observatory) in 1986 (Williamson & Falvey, 1988). Profiles were recorded across the northwestern (Gascoyne) and southwestern (Cuvier) margins of the Exmouth Plateau. Published data are contained in Appendix 6.

The Gascoyne margin ESPs (E4 to E7 have been published by Mutter et al., 1989, and Frey, 1998) show that the overall crustal thickness on the Exmouth Plateau is 21-23 km, commensurate with earlier estimates (eg Exon & Willcox, 1980). Within this crustal section, the sedimentary (and meta-sedimentary) section extends to depths of 10-15 km. Below this section, the crust comprises a 6-10 km-thick layer with velocities of 5.8-6.2 km/s, and, beneath the outer margin, a layer up to 3.5 km thick with velocities of 7.1-7.6 km/s.

The Cuvier margin ESPs (C1 to C4 have been published) show that this margin of the Exmouth Plateau has a markedly different velocity structure. Station C3 shows a sedimentary section that extends to a depth of about 10 km, underlain by 7 km of crystalline crust with a velocity of about 5.4 km/s. In turn, this crust is underlain by a 10 km layer with a velocity of 7.0 km/s, while Moho lies at a depth of about 27 km. Station C4, on the Cuvier Abyssal Plain, shows a slightly thicker than normal oceanic crust, with Moho at a depth of 13.6 km.

3. *Ocean Bottom Seismometer refraction/reflection data:*

Refraction / wide-angle reflection profiles were recorded by Geoscience Australia (Survey 168) in 1995-96 using Ocean Bottom Seismometers (OBSs) to record the seismic data. Profiles were recorded in the Bonaparte Basin, Vulcan Sub-basin, Browse Basin – Scott Plateau – Argo Abyssal Plain, Roebuck Basin – Argo Abyssal Plain, and Northern Carnarvon Basin – Gascoyne Abyssal Plain. A velocity model for the outboard segment of the Carnarvon-Gascoyne profile interpreted by Fomin et al. (2000) is shown in Figure 35, while the station locations are included in Appendix 6. This profile lies somewhat to the north of the ESP data referred to above.

The main characteristics of this model are as follows:

- Moho is at an average depth of 23 km beneath the Exmouth Plateau and 18 km beneath the inner flank of the Gascoyne Abyssal Plain;
- the main crustal layers have velocities of 5.7-6.4 km.s^{-1} beneath the Exmouth Plateau and 6.4-7.1 km.s^{-1} beneath the inner flank of the Gascoyne Abyssal Plain;
- beneath the outer margin of the Exmouth Plateau, the measured crustal velocities are 5.0-5.7 km.s^{-1}, which are somewhat unusual;
- the outer margin of the Exmouth Plateau is underlain by a body with a velocity of approximately 7.2 km.s^{-1} at 16-26 km depth; and
- assuming that the base of the sedimentary section on the Exmouth Plateau is at the velocity increase from 5.0-5.7 km.s^{-1}, the total sediment thickness beneath the outboard flank of the plateau is approximately 10 km.

A notable feature of the velocity model of Fomin et al. (2000) is the lack of correlation between velocity boundaries and prominent reflections in the seismic reflection data. In particular, the OBS-derived crustal thickness beneath the inner Gascoyne Abyssal Plain is considerably thicker than that derived from a stacking velocity depth conversion of the reflection Moho, and the prominent and areally-extensive reflectors at 14-18 km depth beneath the Exmouth Plateau do not correspond to any significant velocity discontinuity in the OBS data.

Kritski et al. (1998) analysed the abyssal plain and outer margin data from the Roebuck-Argo OBS transect and constrained their models with the high-quality reflection seismic data. In brief, they found an oceanic crustal thickness of 7.4 km and unusually high velocities of 7.3-7.4 km.s^{-1} for oceanic layer 3. These high velocities are not consistent with a gabbroic composition and might indicate serpentinite alternating with ultramafic material.

In November 2001, a research cruise by the R/V *Maurice Ewing* collected deep-seismic and OBS data over parts of the outer Exmouth Plateau. Initial results of this work were presented by Sugimoto et al. (2002) and Tischer et al. (2002).

Tischer et al. (2002) noted that modelling of seismic refraction data revealed a transitional zone about 200 km wide, flanked on the ocean side by crustal section of approximately 7 km thickness and on the continental side by normal continental crust with a crustal thickness of about 25 km. Whereas previous interpretations suggested the presence of an underplated layer on the continental side of the transition zone with p-wave velocities of 7.0-7.2 km/s, the high p-wave velocities and the oceanward thinning of this layer could also be interpreted as a highly thinned and magmatically intruded lower crustal.

4. Seismic processing:

Interval velocities have been computed from the processing of seismic data for Geoscience Australia surveys 128 and 162, and Shell *Petrel* line N211. These interval velocities are useful in providing velocity information about the sedimentary section and shallower parts of the crystalline crust, but are rather inaccurate in the deeper crust.

7.1.2 Published Velocity Interpretations

To date, the most detailed velocity analyses of the Exmouth Plateau crust have been published by Mutter et al. (1989) and Lorenzo et al. (1991), based on the ESP data referred to above. Hopper et al. (1992) presented a similar analysis for the southeast margin of the Cuvier Abyssal Plain.

Mutter et al. (1989) interpreted ESPs E5 to E7 on the outer Exmouth Plateau, adjacent to the Gascoyne margin, and integrated their interpretation with a wide-angle CDP reflection seismic line. They presented a three-stage, Jurassic to Early Cretaceous evolutionary model that incorporated both pure and simple shear mechanisms.

In the Early Jurassic, they proposed that the initial response to extensional stresses involved a non-magmatic simple shear mechanism, resulting in the development of a major detachment fault system. This detachment may have evolved near the sediment-basement contact that acted as a stress guide. Brittle deformation above the detachment in the east was interpreted to be balanced by distributed shear and thinning of the lower crust and lithosphere in the west. As extension continued into the Middle and Late Jurassic, the simple shear mechanism evolved into a complex deformational regime that included extensional duplexes. Lithospheric thinning released melt that led to plutonic underplating in the west, beneath the present-day outer plateau. Finally, in the Late Jurassic and Early Cretaceous, continental breakup occurred as pure shear deformation at the nascent continent-ocean boundary. Activity on the earlier detachment system had probably ceased and the basic morphology of the plateau had developed, except for the effects of post-breakup subsidence.

Lorenzo et al. (1991) interpreted ESPs C1 to C4 across the junction of the southwest Exmouth Plateau and the Cuvier Abyssal Plain, also integrating their interpretation with a wide-angle CDP reflection seismic line. They proposed a two-stage model to explain the principal tectonic and magmatic features observed in their data. During the first, rifting stage, detachment surfaces developed under conditions of extension at a high angle to the future Cape Range Fracture Zone, and were later sheared by right-lateral strike-slip faulting. Final transform rupture was attended by large block-fault rotation and mafic intrusions in conditions of pure shear. In the sea-floor spreading stage, as the Cuvier spreading ridge abutted the continent, the continental rim was underplated, resulting in the emplacement of a 10 km-thick, 7.3 km/s, 3 t/m^3 layer, and the permanent isostatic uplift of the crust and tilting of the Triassic to early Cretaceous sedimentary section.

7.2 Structure from Reflection Seismic

The following section will summarise the structure of the study area, primarily based on reflection seismic data sets. The key seismic lines and their interpretations are contained in Plates 9 and 10, while the structure and tectonic provinces are shown in Figure 9. This section is primarily descriptive, while an integrated interpretation of the tectonic-magmatic evolution will be contained in a subsequent section of this report.

7.2.1 Central & Southern Exmouth Plateau

The main part of the Exmouth Plateau is bound by the Rankin Fault System and Rankin Platform to the southeast, the Cape Range Fracture Zone and Cuvier Abyssal

Plain to the southwest, the Gascoyne margin to the northwest, and by an E-W trending crustal high in the north beyond which lies the northern plateau province and margin. Within the central and southern plateau we recognise, from southeast to northwest, the NE-trending crustal structures of the Kangaroo Syncline and Exmouth Plateau Arch, and a subsided outer flank, adjacent to the Gascoyne margin.

Crustal Structure

The crustal structure of the Exmouth Plateau and Northern Carnarvon Basin has been described by a number of authors, including Williamson et al. (1990), Mutter et al. (1989), Lorenzo et al. (1991), Stagg & Colwell (1994), Frey (1998), Stagg et al. (1999), and Driscoll & Karner (1998). In this report, we will expand on these earlier interpretations using the Geoscience Australia Survey 162 deep-seismic data.

As previously noted (eg Stagg & Colwell, 1994) the sedimentary and crustal structure of the Exmouth Plateau and the adjacent continental shelf is particularly characterised by a flat-lying, 'layer-cake' geology, with the crustal extension that produced sediment accommodation space not being readily identifiable (Plate 9, profile 162/07-128/08-101R09 & Plate 10, profile 162/04-135/01-110/12).

Stagg & Colwell (1994) noted the presence of flat-lying deep-crustal reflectors throughout much of the region (their reflectors C1 and C2). The deeper of these reflectors was described as normally being a single, strong event of high continuity corresponding to a boundary that partitioned upper- and lower-crustal extension. With access to a wider grid of deep-seismic data, particularly on the outer margin of the plateau, Frey (1998) correctly pointed out that this narrow interpretation of C2 by Stagg & Colwell (1994) was inaccurate, and that a diversity of deep crustal reflectors is present.

The reflector identified as C2 by Stagg & Colwell (1994) is only identified unequivocally beneath the inner half of the Exmouth Plateau, and seaward of the Rankin Fault System (Plate 9, line 162/07-128/08-101R/09). The event comprises either a single reflector or a narrow band of reflections and can be identified as deep as 10.5 s TWT (*ca*. 20-21 km) beneath the eastern flank of the Kangaroo Syncline, shallowing to about 6 s (*ca*. 12-13 km), where it terminates against the Rankin Fault System. The event also appears to lie at a relatively constant depth of about 9.5-10 s TWT beneath the southern part of the plateau, but shallows northeastward across the Beagle Sub-basin and onto the Bedout High. The shallowing of this event to the southeast and northeast effectively precludes it from being reflection Moho.

Beneath the western flank of the Kangaroo Syncline, deep crustal reflectors become indistinct and there is no definite correlation with deep reflectors on the Exmouth Plateau Arch and the Gascoyne margin. In this region, the deep crust is characterised by a band of strong reflectors below about 8 s TWT. This zone corresponds with the high-velocity (7.1-7.3 km/s) zone identified by Mutter et al. (1989), which they identified as plutonic underplating, and which Frey (1998) identified as underplating.

The northern boundary of this main Exmouth Plateau province is taken along a major E-W trending structural high in the deep crust at about 18^{o}S, parallel to, and approximately 90 km south of the continent-ocean boundary with the Argo Abyssal Plain. The deep crust beneath this structural high is also strongly laminated, in similar style to the intruded deep crust on the Gascoyne margin. As with the Gascoyne margin, there is a strong spatial relationship between the extent of the laminated deep crust and the intensity of Oxfordian faulting in the overlying sedimentary section.

The northern boundary also coincides with a major change in orientation of the Oxfordian faulting (Plate 3). The NNE trend of faulting on the plateau proper changes to an E-W trend over the boundary, and then back to a NE to ENE trend on the northern plateau margin. We interpret that the northern boundary of the main Exmouth Plateau province follows a fundamental underlying crustal boundary, which we believe is probably related to the early Palaeozoic Canning Basin.

Basin Fill

Stagg & Colwell (1994) divided the sedimentary section beneath the Exmouth Plateau into six mega-sequences, which they identified as pre-Westralian, Carboniferous-Permian, Triassic, Lower to Middle Jurassic, Upper Jurassic to Valanginian, and post-Valanginian. These mega-sequences reflected the following major tectonic events:

- initiation of the Westralian Super-basin (Yeates et al., 1987) in the Carboniferous;
- major episode of uplift, faulting and volcanism (the Bedout Movement) in the late Permian (we note here that the Bedout High, after which the Bedout Movement is named, has been re-interpreted as an impact structure [Becker et al., 2002]);
- regional structuring and compression (the Fitzroy Movement) in the latest Triassic or earliest Jurassic;
- breakup in the Argo Abyssal Plain in the Middle Jurassic; and
- breakup in the Gascoyne and Cuvier Abyssal Plains in the Valanginian.

Longley et al. (2002) place these events in a chronostratigraphic framework for the entire North West Shelf region.

<u>Pre-Westralian</u>

Carboniferous and older pre-Westralian Superbasin sediments are only known from the onshore Southern Carnarvon Basin and the nearshore flank of the Northern Carnarvon Basin (eg Bentley, 1988). As with Stagg & Colwell (1994), we believe that it is likely that sediments of this age are present deep beneath the Exmouth Plateau, occupying the deepest stratified section, immediately above the transparent mid-crust. By analogy with the onshore, the pre-Westralian section probably consists of lower Palaeozoic and Precambrian sediments and meta-sediments and crystalline basement.

<u>Carboniferous-Permian</u>

Permian rocks have only been drilled on the landward flank of the basin, southeast of the Rankin Fault System. These rocks are typically contained within fault blocks that exhibit moderate extension on southeast-verging faults. They constitute the first section that can be ascribed to the Westralian Superbasin, and thus may be as old as Carboniferous.

Beneath the Exmouth Plateau, no rocks older than Middle Triassic have been sampled by either drilling or dredging, and the presence of Permo-Carboniferous sediments has only been inferred on the basis of a marked upwards change in seismic character from faulting is largely controlled by a pre-existing structural grain. This grain is probably inherited from the N-S trending, Silurian to Permian Southern Carnarvon Basin, which is interpreted to underlie the Exmouth Plateau at depth.

Early-Middle Jurassic

The geometry and distribution of the Jurassic sediment package varies markedly throughout the basin. In the Exmouth, Barrow and Dampier sub-basins, rapid subsidence resulted in the deposition of thick, restricted marine shales of the Dingo Claystone that, in the Early to Middle Jurassic, attained a thickness of approximately 2 s TWT (~3-4 km; Plate 10, line 162/04-135/01-110/12). Subsidence was contemporaneous with deposition, leading to a pronounced thinning of the sediment package across the trough margins. Continuing deposition through the Middle and Late Jurassic eventually filled the troughs and spilled over the margins. On the Exmouth Plateau, Jurassic sedimentation was much more restricted. Most exploration wells on the plateau recorded a thin veneer of Jurassic sediments above the high-standing Triassic blocks, while pockets of Jurassic sediment up to a few hundred metres thick are interpreted to be deposited in minor half-grabens in the Triassic surface.

On the northern Exmouth Plateau, sedimentation in the early to Middle Jurassic appears to have continued in the same style as in the Triassic. Here the geology is typically layer-cake until the Oxfordian, at which time sea-floor spreading commenced in the Argo Abyssal Plain producing a marked unconformity.

Late Jurassic-Valanginian

The distribution of the uppermost Jurassic and Lower Neocomian section (Barrow Group and equivalents) is highly variable across the Exmouth Plateau, with the major accumulation being formed on the southern part of the plateau, where the Barrow Group delta prograded northwards prior to the separation of Australia from Greater India in the Cuvier Abyssal Plain (Plate 10, line 162/04-135/01-110/12). This sequence has undergone a later inversion such that there is now a large structural closure (at least on a 2-D profile) coinciding with the bathymetric culmination of the plateau. This inversion will be examined later in this report. The maximum thickness of the delta is about 2000 m in this area; elsewhere on the plateau sediments of this age are thin or absent. Stagg & Colwell (1994) referred to this sequence as being 'intra-breakup' as it could be considered to be post-breakup relative to the onset of seafloor spreading in the Argo Abyssal Plain, and pre-breakup relative to spreading in the Gascoyne and Cuvier Abyssal Plains.

Post-Valanginian

Since the separation of Greater India from Australia in the Valanginian, sedimentation on the Exmouth Plateau has taken place in an open marine environment that has progressively deepened. While the post-breakup history of the margin has been punctuated with a number of tectonic events, most notably the Tertiary collision with the Eurasian Plate, for these purposes the sedimentary section can be considered as a single megasequence. Throughout much of the region, the margin was relatively sediment-starved throughout the Late Cretaceous and Cainozoic, with no more than a few hundred metres of sediment being deposited.

Intra-sedimentary Volcanics

Symonds et al. (1998a, their fig. 2) have mapped the main volcanic provinces of northwest Australia at a regional scale. Their map shows an extensive area of 'intrusions in upper and middle crustal levels' beneath the southwestern half of the plateau. The most impressive of these intrusions are the strong, cross-cutting reflectors that are particularly common within the Triassic section, and described previously in this report (Plate 10, line 110/15, SP 600-1400, 4.5-6 s TWT). In this study, we also recognise an extensive intrusive volcanic field beneath the southwest corner of the Exmouth Plateau, which is of quite different character. These volcanics are manifest as narrow, near-vertical pipes or sheets that have generally been intruded along faults in the Triassic section (Fig. 23).

It is difficult to constrain the age of the southwest Exmouth Plateau volcanics, due to the thin post-Triassic section. However, Symonds et al. (1998a) point to a number of factors that indicate a latest Jurassic to earliest Cretaceous breakup-related origin, including:

- Hauterivian – late Valanginian sediments overlying a diabase sill at ODP Site 766, in the southwest corner of the plateau (Exon & Buffler, 1992);
- sills intruding Oxfordian-Kimmeridgian sediments at Yardie East-1 on North West Cape;
- Berriasian-Valanginian bentonites (ash falls) sampled in Barrow Group sediments at ODP sites on the Exmouth Plateau (von Rad & Thurow, 1992; Thurow & von Rad, 1992); and
- anomalous reflections within Barrow Group sediments overlying intrusive complexes, which may represent extrusives, intrusives or diagenetic features related to fluid release associated with intrusions.

7.2.2 Exmouth Plateau Margins

The margins of the Exmouth Plateau are geologically very distinctive, reflecting their differing origins, from north to south, in mixed rifted / transform, rifted, and transform settings, respectively. The following section will describe the structures of these margins, which are readily divided into the northern (Argo), northwest (Gascoyne), and southwest (Cuvier) segments.

The northern margin of the plateau is structurally complex, probably reflecting its interpreted origin in a mixed rift/transform setting (Müller et al., 1998), as well as the influence of underlying early Palaeozoic structures related to the Canning Basin.

The most striking structures of the northern margin are the high-standing planated blocks of the Wombat Plateau (Plate 9, line 128/05-101R/10) and Emu and Echidna Spurs. These blocks, which are common on the margins of the Argo Abyssal Plain (*cf.* Wilson Spur of the northwest Scott Plateau; Stagg & Exon, 1981, fig. 16), are characterised by seabed relief of up to 2000 m compared to adjacent areas, and relief of as much as 4000 m at the Triassic level in the case of the Wombat Plateau. All the blocks have been subjected to strong wave-base erosion, with the tops of the blocks currently lying at depths of 2500-3500 m below sea level.

The Wombat Plateau was extensively drilled during ODP Leg 122 (Sites 759-761 and 764; Plate 3; von Rad et al., 1992a, b). This drilling showed that the pre-rift, dipping sedimentary section within the blocks was of Late Triassic age, and that the thin capping sediments were of Cretaceous and Cainozoic age (Fig. 14). The composite Upper Triassic section consists of several shallowing-upward cycles of fluviodeltaic siliciclastics with carbonate intercalations, overlain by Rhaetian carbonate platform of lagoonal and reefal facies (Fig. 15). During the Jurassic, the plateau underwent volcanism and a major block-faulting episode (coinciding with the onset of Argo spreading), resulting in uplift, rift flank tilting and subaerial erosion of the horst. Subsequent to spreading onset, the plateau subsided rapidly. It is reasonable to assume that the other planated blocks of the Argo margin underwent a similar history. An important question that will be addressed later in this report is: what are the underlying structural controls that gave rise to the unique tectonic development of these blocks?

The crust beneath the Argo Abyssal Plain is quite variable. On most lines, the crust shows negligible internal reflectivity and reflection Moho is only occasionally visible as an indistinct band of reflections. However, in the southeast of the plain (east of this study area), where the crust is oldest, it appears to be very similar to the crust of the Cuvier Abyssal Plain, albeit at greater depth due to its greater age (*ca*. 155 Ma *vs ca*. 130 Ma). The crust comprises an upper, seismically transparent layer from basement to about 9.3 s TWT. Occasional strong, cross-cutting reflectors in this layer are interpreted to be planar shear zones that have probably been intruded with upper mantle material. The lower crust is highly reflective, overlying a strong reflection Moho at about 10.5 s.

The northwest (Gascoyne) margin is characterised by a rugged slope that is generally concave in profile and has a relatively gentle gradient (eg Plate 9, line 162/07-128/08-101R/09). Volcanic intrusions and extrusions dominate the margin, strongly influencing the margin physiography and masking the sedimentary section. From southeast to northwest, this margin is characterised by four distinct provinces, as follows:

Northern Carnarvon Basin margin – 'flows' province: The oceanward extent of the thick Palaeozoic-Mesozoic section of the main part of the Exmouth Plateau is not readily determined due to interpreted lava flows at the Triassic-Jurassic level. These flows, which are probably only several metres to tens of metres thick, effectively obliterate the seismic response of any underlying sediments. However, the topography of the flows indicated that they have been extruded over the tops of Triassic fault blocks. The distribution of the lava flows indicates that they have flowed landward and that the outer margin of the plateau was therefore high-standing at the time of eruption. On one line (162/01; Fig. 36a), where the lava flows are less well-developed, it appears that thick Triassic section underlies the continental slope and that the section is terminated by a major, oceanward-dipping crustal fault.

Continental slope – 'slope volcanics' province: In places the continental slope appears to be buttressed by volcanic intrusions/extrusions (e.g. Fig. 29). The degree of development of this province varies widely along the margin, being extensive and broad in some areas, and narrow and weakly developed in others.

Continental slope – 'volcanic margin' province: This province, which is up to 250km wide, consists of complex amalgam of volcanic features, including SDRSs, flows and build-ups (e.g. Figs 30 & 31). The crustal thickness of 3.5-4 s TWT (*ca*. 11-13 km) is up to twice the thickness of 'normal' oceanic crust. This agrees with unpublished gravity modelling of the combined lines 101R/07-110/15 and with the OBS velocity profile along line 128/8, which indicate Moho at depths of 15-20 km, and a magmatic crust density of about 2.7 t/m^3, which is considerably less than normal oceanic crust. On at least one line (162/01; Fig. 36a), it is possible that the inboard edge of this province could be underlain by highly-thinned continental crust. This province lies inboard of unequivocal oceanic crust.

The nature of the crust in this province is complicated by identification by Müller et al. (1998) of magnetic lineations with amplitudes of up to 500 nT and wavelengths of 20-50 km which they interpret as M-series Cretaceous seafloor–spreading anomalies. However, this interpretation is open to doubt as it was not fully integrated with seismic data. Also, Schreckenberger & Roesser (1994) report that magnetic anomalies that had previously been interpreted in the context of normal sea-floor spreading have actually been generated in volcanic margin SDRS provinces. Thus the occurrence in the volcanic margin province of magnetic lineations unrelated to seafloor spreading is not surprising.

The volcanic margin province is particularly characterised by the presence of SDRSs (e.g. Figs 30, 31). While these are most strongly developed in the southwest, on the northern flank of the Cape Range Fracture Zone (Plate 10, line 162/04-135/01-110/12), they are also present elsewhere over the full width of this province. Characteristics of the SDRSs were summarised earlier in the section *Volcanic seismic facies units*.

A notable feature of the southern margin of the magmatic crust province is the system of ridges that splays northwards from the southwest corner of the Exmouth Plateau. We suggest that the ridges were developed as the hot spreading centre in the Cuvier Abyssal Plain passed the southwest corner of the Exmouth Plateau, reheating and stressing the young crust of the volcanic margin province.

The sediment cover in the volcanic margin province is generally very thin, only being thicker than 500 m where it has been dammed behind volcanic outcrops. Morphologically the province has a low gradient, but without the thick wedge of sediments characteristic of continental rise. It is therefore correctly classified as a low-gradient, lower continental slope. The base of the continental slope lies along the oceanward (western) edge of the province.

Abyssal plain – 'oceanic crust' province: At the very outermost end of some seismic lines (eg Plate 10, line 162/03), the crustal thickness is less than 2.5 s TWT (*ca.* 8 km), which is only slightly thicker than normal oceanic crust. SDRS are no longer evident, and it is likely that the crust formed under a conventional sea-floor spreading regime. The sediment thickness on the Gascoyne Abyssal Plain is generally much less than 500 m; this is of the order of half the sediment thickness on the Argo and Cuvier Abyssal Plains, presumably reflecting greater sediment input to those abyssal plains via turbidites derived from the adjacent continental margin.

Gascoyne oceanic crust is characterised by the weak development of internal reflectors (Plate 10, line 162/03). In general, from basement at about 8 s TWT to a depth of about 9 s the crust is seismically transparent. Below these depths, the reflectivity increases, but not to the same degree as for the Cuvier and southeast Argo Abyssal Plains. A weakly reflective Moho is observed at about 10.5 s.

A notable feature of the northeast sector of the Gascoyne Abyssal Plain, adjacent to the Platypus Spur, is the development of large reverse faults that nucleate in the lower crust near Moho depth, and offset the seabed by up to 400 m (e.g. Plate 9, NW end of line 162/11 and W end of line 162/12). In the tectonic evolution section of this report, this faulting is ascribed to the present-day stress field resulting from the collision along the northern margin of the Australian Plate.

The southwest (Cuvier) flank of the plateau is strongly linear, reflecting its genesis as a transform margin between the oceanic crust of the Cuvier Abyssal Plain and the continental crust of the Exmouth Plateau. In contrast to the Gascoyne margin, this margin is convex upwards in profile. The abrupt termination of the sedimentary section of the plateau against this margin (Plate 10, line 135/11) indicates that the Northern Carnarvon Basin continued into Greater India prior to continental breakup in the Valanginian.

The southwest margin has undergone major uplift and erosion of the sedimentary section (*ca*. 2 km), with the uplift distributed across a zone some 100 km in width. This uplift accounts for the unusual convex-upwards profile. The uplift has been accompanied by extensive volcanism, manifest as high-amplitude sills, particularly in the ?Permian and Triassic section, and by masking of the sedimentary section at the plateau margin, presumably by shallow lava flows. The ESP-based velocity interpretation of Lorenzo et al. (1991) indicated that this margin of the plateau was underlain by a 10 km-thick, 7.3 km/s, 3.04 t/m^3 layer, to a depth of ~27 km, which was emplaced as the Cuvier spreading ridge abutted the continent.

As did Lorenzo et al. (1991), beneath the edge of the Cuvier Abyssal Plain we observe a pair of reflections that bifurcate from reflection Moho at 10.25 s TWT northeastward beneath the Exmouth Plateau (Plate 10, line 135/11). The upper of these reflections (M1 of Lorenzo et al., 1991) shallows to about 9 s beneath the edge of the abyssal plain, while the lower event (M2) deepens to about 11.3 s at the same point. ESP station C4 was recorded across the wedge defined by these reflections (Appendix 6). M1 coincides with the base of a unit of average velocity of 6.8 km/s, which is typical of oceanic crust layer 3. The velocity then increases to a typical mantle velocity of 8.3 km/s at about 10 s TWT, within the wedge. Gravity modelling by Lorenzo et al. (1991) gave a density of 2.95 t/m^3 for the wedge, slightly less than the computed density for the underplating beneath the Exmouth Plateau margin, and most adequately described by densities appropriate for ultramafic rocks. They concluded that the M1-M2 interval represents an expanded crust-mantle transition layer which appears to map the region of oceanic crust that was affected by the increased melt flux associated with the formation of the underplated layer beneath the transform margin.

The seismic data (Plate 10, line 135/11) show that an acoustically semi-transparent, probably Lower Jurassic section, which is thin in oil exploration wells on the southwest plateau (eg at Eendracht-1, Sirius-1, Vinck-1 and Investigator-1), thickens towards the margin, where it is at least 0.5 s TWT (>700 m) thick, before being removed by erosion at the seabed. The seismic character of this sequence (and the faulting style that affects it and the underlying Triassic section) is very similar to the equivalent sequences below the northern margin of the plateau.

As with the Argo Abyssal Plain, Cuvier Abyssal Plain oceanic crust is overlain by about 1 km of Lower Cretaceous and Cainozoic sediments and the crust is characterised by strong vertical stratification (Plate 10, line 135/11). From basement to a depth of about 9.3 s TWT, the crust is effectively seismically transparent, with the exception of some strong dipping events that are extensions of structuring in the lower crust. Below this transparent layer, a highly reflective lower crust overlies strongly reflective Moho at about 10.3 s.

7.2.3 Platypus Spur and Joey Rise

The complex area between the Gascoyne and Argo margins is occupied by the Platypus Spur and adjacent Joey Rise. Cook et al. (1978) have reported the results of seismic and sampling work carried out by Woods Hole Oceanographic Institution in 1976. On the basis of hyaloclastites recovered in cores, they concluded that the Joey Rise was a volcanic feature underlain by basaltic rocks. Since Cook et al.'s work, the Joey Rise and Platypus Spur have received little further attention due to the paucity of good-quality seismic data in this remote area. However, the Survey 162 deep-seismic data available to this study do allow us to make a tentative interpretation of their origins.

The Platypus Spur is a northwest- and north-extending low-relief extension of the northernmost corner of the Exmouth Plateau. The southeast segment of the spur is interpreted to be a small fragment of probable continental crust that has been isolated by a transform fault along its southwest margin with the Gascoyne Abyssal Plain and short transform/rift segments along its northern margin with the Argo Abyssal Plain. The seismic character suggests that the crust has been strongly overprinted by volcanics, destroying much of the pre-existing sedimentary fabric.

The boundary of the spur with the Exmouth Plateau proper is marked by an interpreted major volcanic vent (Plate 9, lines 162/10 and 162/11), elliptical in outline and measuring some 70 x 50 km. The vent (caldera) appears to have progressively collapsed, and the seismic data indicate that its centre comprises lava flows and volcaniclastics that are as much as 7-8 km thick. Similar volcanic features are present on the Joey Rise and the Wallaby Plateau. It is possible this vent is a source of the lava flows that blanket much of the Triassic and Jurassic section on the northwestern Exmouth Plateau and also of the Berriasian-Valanginian bentonite / smectite layers that were cored at ODP Site 761 on the Wombat Plateau (Shipboard Scientific Party, 1990). Minor volcanic vents, with tops that have apparently passed through wave-base, are also observed on the spur.

In contrast with the southeast part of the spur, the more northerly-trending extension (north of about 16^{o}S; Plate 9, line 162/11) is totally devoid of seismic reflections within basement, and we interpret the feature as being a low-relief volcanic buildup within the volcanic margin.

The Joey Rise is a large edifice some 100 km northeast of the Platypus Spur, with some 3000 m of relief above the adjacent abyssal plains (Plate 9 lines 162/09 & 162/13). Its origins are enigmatic, although it is likely that it was emplaced contemporaneously with the volcanics on the spur (i.e. Berriasian-Valanginian). Satellite-predicted bathymetry and ship-track data show the Joey Rise as being connected to the northern extension of the Platypus Spur (see Plate 1) . Seismic data indicate that the small embayment of ?Argo-aged abyssal plain between the Joey Rise and the northern Exmouth Plateau (the 'Kivi Graben' of Rao et al., 1994; here called the Kivi Basin) has trapped a much greater thickness of sediment (~500 m) than has the Argo Abyssal Plain to the east, suggesting that the Joey Rise and the northern Exmouth Plateau are linked by a volcanic ridge (see predicted bathymetry in Plate 1).

The two seismic lines that extend on to the Joey Rise (Plate 9, lines 162/9 & 162/13), are supportive of a volcanic origin for the feature. In particular, line 162/9 terminated on an apparent volcanic vent that is similar in appearance to interpreted vents on the Platypus Spur (see above) and on the Wallaby Plateau.

7.3 Heat-flow and Relationship to Structure

7.3.1 Introduction

Swift (1990) compiled all the available present-day heat-flow data for the Exmouth Plateau and adjacent ocean basins in an interpretive study of the heat-flow regime on the Exmouth Plateau. These data are included here as Appendix 4 and illustrated in Figure 37. Most values are derived from measurements made in the shallowest 2-5 m of the surficial sediments. Most of the data were acquired on AGSO Survey 53 (Choi, Stagg et al., 1987) and on a 1987 research cruise of the RV *Franklin* (Swift, 1990). Approximately 80% of the available data are concentrated on the Exmouth Plateau; therefore, the detail in Figure 37 is strongly biased towards this area.

Computation of heat-flow requires measurement of both the geothermal gradient and the thermal conductivity of the rocks or sediments in which the gradient is measured. While other effects also contribute to the measured heat-flow, these effects are either very small (internal heat production) or cannot be measured directly, and must be computed from modelling (pore fluid velocity). The heat-flow data used in this study have been derived from two sources:

- Direct measurement of the thermal gradient in a few metres below the seabed and measurement of the thermal conductivity on short sediment cores collected nearby. This technique is generally restricted to water depths of more than about 700 m because of temporal variations due to the varying seawater and shallow sedimentary pore fluid temperature at shallower depths and consequent fluid convection within the sediments.
- Measurement of the temperature gradient in oil exploration wells by using the bottom hole temperature and using representative values of thermal conductivity of the drilled section based on a compaction model.

Both these techniques are subject to multiple sources of error and caution must be exercised in over-interpreting the results.

Caution should also be taken in interpreting the heat-flow data in terms of regional tectonics, as heat-flow perturbations due to Mesozoic tectonism will generally have decayed to a negligible level by the present. It is more likely that most of the variation in the heat-flow data is due to pore fluid convection, together with conduction (Swift, 1990). In the case of the Exmouth Plateau, Swift interpreted a major convection cell beneath the plateau that operated to a depth of about 10 km over a lateral distance of more than 200 km. However, while interpretation of the heat-flow data might add little to our understanding of the tectonic evolution of the region, it has the potential to provide information on the present-day thermal maturity of hydrocarbon sources, and some understanding of the pattern of convection in sedimentary pore fluids and their influence on hydrocarbon migration pathways.

Figure 37 shows that the heat-flow varies at a regional scale (variations over 300-1000 km) and at a sub-regional scale (variations over 30-80 km). The regional anomalies are likely to be due to crustal variations (eg oceanic versus continental crust; rifted basin boundaries with short-wavelength lateral crustal heterogeneities versus areally extensive thick sedimentary basins). The sub-regional anomalies are more likely to be due to the convection cell effects described by Swift (1990); these will not be described further here, as their analysis is highly specialised.

While accepting that the distribution of heat-flow measurements is irregular (Fig. 37), we can make the following general interpretation of the heat-flow pattern:

7.3.2 Exmouth Plateau

The average heat-flow on the Exmouth Plateau is about 56 mW/m^2, close to the generally accepted world-wide marine average of about 60 mW/m^2. The Exmouth Plateau average is based on 89 values, of which all but two are on the central and southern plateau. The range of values from 19 to >100 mW/m^2 is far greater than on the adjacent abyssal plains, and is ascribed to pore fluid convection within the sedimentary section, particularly on the central plateau (Swift, 1990). In general, it appears that the heat-flow is higher on the margins of the plateau than it is in the centre, although there is insufficient data to draw any serious conclusions about the heat-flow distribution on the northern margin. It is also unclear as to whether the higher heat-flow on the northwestern and western margins is due to residual tectonic effects or to focussing of convection cells or conduction at the steep margins.

7.3.3 Abyssal Plains

The average heat-flow on the abyssal plains ranges from 44 mW/m^2 in the Argo and Cuvier to about 49 mW/m^2 in the Gascoyne, approximately 20-25% below the world-wide marine average, but in general agreement with results reported for oceanic crust. The low heat-flow in oceanic crust is ascribed to the lower proportion of radioactive elements in oceanic crust compared to continental crust. While there are only 17 available stations for this study, the range of values is only from 35-62 mW/m^2, suggesting that local effects due to pore fluid convection are very limited, compared to the Exmouth Plateau.

7.3.4 Continental Shelf

Heat-flow values on the continental shelf southeast of the study area have been derived from oil exploration wells. While there is some doubt as to their compatibility with deep-water heat-flow measurements acquired in shallow sediments, there is little doubt that the elevated average heat-flow of 82 mW/m^2 (~40% higher than on the Exmouth Plateau) is real. It is likely that the high heat-flow is related to the greater thickness of crystalline crust underlying the sedimentary section, but it is unclear as to whether residual tectonic effects also contribute.

8. DISCUSSION OF KEY SCIENTIFIC ISSUES

8.1 Introduction

This study has been fortunate in having access to a wide range of geophysical and geological data in an area which has been previously used to define some of the key components of volcanic passive margins. In particular, the availability of high-resolution and deep-penetration seismic data is a unique aid to interpretation in a geological environment that has a major volcanic component.

In spite of this, a large number of unresolved questions remain regarding the geology and evolution of the outer Exmouth Plateau. Some of these questions are listed in Appendix 7. Unfortunately, time constraints in the present study prevented investigation of many of the issues raised by these questions.

8.2 Volcanic Issues

Menzies et al. (2002) noted that breakup-related magmatism is a common attribute of many rifted margins across the globe, with 75% of the margins of the Atlantic and 90% of all rifted margins being volcanic to some degree. The classic case of a volcanic rifted margin with voluminous magmatism has usually been taken as the conjugate margins formed of Greenland and the combined Voring and Rockall plateaux in the North Atlantic. Together with the non-volcanic rifted Iberian margin (e.g. papers in Wilson et al., 2001), these have been considered to represent end members of the spectrum of rifted continental margin styles (Eldholm et al., 1995; Symonds et al., 2000).

The widespread influence of magmatism and volcanism has been addressed in a number of papers since the late 1980s. White and McKenzie (1989) presented both a broad global overview of volcanic continental margins and flood basalt provinces, as well as some ideas on their relationship to underlying large-scale mantle plumes. Eldholm et al. (1995) extended these descriptive ideas of margin development by attempting to inter-relate the individual volcanic features as a system. Planke et al. (2000) focus more on the defining elements of a volcanic margin and present this as a new nomenclature for seismic stratigraphy in a volcanic setting. Both Frey (1998) and Symonds et al. (1998a) extend this nomenclature to the Gascoyne margin of the Exmouth Plateau and to the more extensive West Australian margin setting, respectively. Frey also presents an evolutionary model for the tectono-magmatic setting of the Exmouth Plateau, while Symonds et al. extend this concept to cover some implications for basin development and hydrocarbon potential.

A volcanic rifted margin has usually been defined on the basis of the presence of seaward-dipping reflector sequences (SDRS) near the continent-ocean boundary or transition, and high P-wave velocities ($V_p > 7$ km/s) in the lower crust (Symonds et al., 1998a). Other volcanic-related features are usually also present, but these two elements suffice to show that pre- and post-breakup transient magmatism and volcanism altered the standard configuration of deep continental and thin basaltic oceanic crust abutting a thicker wedge of continental crust. The theories of the genesis of this volcanic margin vary widely, but at a broad level can be taken to represent the igneous manifestation of a thermal anomaly in the underlying mantle (White & McKenzie, 1989). In the case of the volcanic margin off Western Australia, plume (e.g. White & McKenzie, 1989; Mihut & Muller, 1998), non-plume (e.g. Mutter et al., 1988; Hopper et al., 1992; Planke et al., 1996) and hybrid models (e.g. Colwell et al., 1994b) have been proposed to explain the arrangement of volcanic features. Symonds & Planke (1997) and Symonds et al. (1998a) suggested that any model for the region needed to incorporate a broad and long-lasting zone of elevated asthenosphere temperatures (which may or may not be plume related), with the timing and distribution of magmatism being controlled by dynamic processes associated with rift, breakup and transform tectonism.

Planke et al. (2000) recognised six main volcanic seismic facies units on a volcanic margin:

- Inner SDRS;
- Landward flows;
- Lava delta;
- Inner flows;
- Outer volcanic high; and
- Outer SDRS

With the high-quality deep-seismic data available on the Exmouth Plateau, these seismic facies can be augmented with the recognition of a seismically transparent lower crust and associated laminated deep crust underlying the outboard edge of the margin. Other intrusive volcanic features such as sills and dykes are identified by their crosscutting relationships with the sedimentary section.

The Gascoyne margin is strongly altered by magmatism and volcanism that have spread out over several hundred kilometres from the seaward limit of visible Triassic section to abyssal depths on the Gascoyne oceanic crust. This broad zone of volcanism overprints the ‘transition zone’ from unequivocal continental crust (e.g. as shown by Triassic fault blocks) to unequivocal oceanic crust. Where a continent-ocean boundary (COB) is located in such a setting is contentious. We favour placing the COB at the inner edge of unequivocal oceanic crust i.e. at the outer (oceanward) edge of the volcanic margin.

The features of interest on the Gascoyne margin can be summarised as follows:

- the arcuate nature of a massive magmatic/volcanic high along the southwestern and western edge of the plateau;
- a parallel and en echelon arrangement of at least four SDRS units separated by large-scale volcanic highs;
- seaward termination, and occasional internal disruptions, of the SDRSs by major landward-dipping reflection events, possibly faulting with contemporaneous dyke injection;
- indication on bathymetry and satellite-gravity of the northward progression of the SDRS-buildup assemblage from the northern edge of the CRFZ near the southwestern corner of the plateau; and
- the anomalously thick nature of the Gascoyne crust.

In contrast to the Gascoyne margin, the Cuvier margin along the southern flank of the Exmouth Plateau is a continent-ocean transform boundary (i.e. Cape Range Fracture Zone) with igneous intrusions, some volcanics and widespread uplift (Lorenzo et al., 1991). The nature of the movement along the transform, particularly in its relation to the Cuvier seafloor spreading azimuth, and the possible development of subsidiary fracturing within the plateau remain to be resolved.

The Argo margin along the northern boundary of the Exmouth Plateau represents a complex interplay of shear-motion tectonics and volcanism. This complexity is shown by the complicated bathymetry and the composite nature of many of features along this margin.

8.3 Igneous Underplating and Lower Crustal Intrusion

It is possible that there is some confusion in the over misleading use of the term ‘underplating’. This term has generally been used to describe all cases in which a high-velocity layer (>7 km/s) has been interpreted intermediate to the lower continental crust and upper mantle, particularly on continental margins near the COB.

The term ‘underplating’ should be used in those cases where upper mantle melt has ponded immediately beneath continental crust, but has not significantly intruded that crust. The effect of this underplating is to replace high-density mantle with lower density mantle melt. This produces an overall buoyant force that in turn leads to differential uplift of the underplated crust and, frequently, erosion of the shallow sedimentary section. In this case, the chemical change corresponding to Moho can be considered to underlie the continental crust and overlie the underplated layer with velocities in the range 7-7.6 km/s.

In contrast to the case of underplating, if the upper mantle melt intrudes the lower continental crust, the effect is to replace some low-density crust with higher density melt. This results in an increase in average crustal density and consequent negative buoyancy, leading to differential subsidence. In this case, the chemical change corresponding to the pre-intrusion Moho lies beneath the crust and beneath the high-velocity layer. In the extreme case of lower crustal intrusion, where the entire lower crust may have been altered or replaced by mantle melt, any concept of Moho as a chemical boundary becomes meaningless.

The three margins of the Exmouth Plateau, southwest, northwest and northern, all exhibit major amounts of deep crustal alteration, but of very different styles.

The southwest margin is characterised by a 10 km-thick layer with a velocity of 7.3 km/s (Lorenzo et al., 1991). The overlying crust shows differential uplift of up to 2 km, as measured by the amount of erosion of the Cretaceous and Lower to Middle Jurassic section, and hence we interpret the high-velocity layer to be true underplating. The uplift is also localised over a zone some 50 km wide. The chemical Moho boundary therefore occurs at a depth of about 17 km, according to ESP station C3 (Appendix 6). There is also a question about the cause and timing of this underplating – that is, is it a function of pre-breakup extension and thinning of the crust, or was it produced by heat generated from the Cuvier spreading ridge as it moved past on the abutting oceanic crust? The geometry of the Barrow Group (i.e. pre-breakup) sediments at this margin – uniform thickness, with major erosion at the plateau edge

(Plate 10, line 135/11) – shows that uplift post-dates the Barrow Group and that it was therefore likely caused by the adjacent Cuvier spreading ridge.

In contrast, the high-velocity layer beneath the northwest (Gascoyne) margin shows differential subsidence, relative to the Exmouth Plateau arch, indicating that the laminated lower crust is the result of widespread intrusion of sills and dykes into the lower crust. The chemical Moho boundary therefore occurs beneath the laminated lower crust at a depth of about 22 km. Compared to the southwest margin, the zone of laminated lower crust is considerably wider, at about 150 km. This suggests that the heating and uplift of the Cuvier margin was due to a sharp pulse of anomalous heating which decayed quickly, thus localising its effect, whereas intrusion of the Gascoyne margin occurred over a much longer period.

The nature of the deep crustal alteration beneath the northern margin is more difficult to define as is the relative importance of this alteration compared to the influence of the underlying structural grain. Strongly laminated and elevated lower crust is present over a zone about 100 km in width. However, as this zone lies some 150+ km inboard of the continent-ocean boundary, the relationship between the distribution of the altered crust and breakup magmatic processes is not straightforward, and we conclude that the underlying structural grain (see later) has had a major influence on the configuration of the margin. The Lower-Middle Jurassic section has undergone major faulting and some considerable erosion, probably at Callovian-Oxfordian Argo breakup time, suggesting that the margin may have been underplated at this time. This conclusion may need to be revised if an alternative interpretation (AGSO Geoscience Australia, 2001), in which the Triassic and Callovian unconformities are interpreted at a shallower level beneath the Montebello Canyon, is correct.

8.4 Crustal Thinning and Formation of the Exmouth Plateau:

Since the late Palaeozoic, the Exmouth Plateau component of the Northern Carnarvon Basin has accumulated 10-15 km of clastic sediments in environments ranging from fluvial to deep marine. Creation of this accommodation space requires substantial crustal extension and subsidence. However, it has long been recognised that the mechanism by which this extension occurred was not apparent, since most of the visible faulting in the basin is high-angle, with very small amounts of extension.

As summarised earlier, on the basis of wide-angle reflection and expanding seismic profiling, Mutter et al. (1989) proposed an extensional model in which initial deformation of the region was dominated by a simple shear detachment system along low-angle fault planes. This passed laterally and temporally into a region of pure shear deformation characterised by high-angle normal faults and magmatism in the area that was subsequently the locus of final breakup.

In an interpretation of the structural foundations of the Northern Carnarvon Basin, based on the early Geoscience Australia deep-seismic data sets, Stagg & Colwell (1994) favoured a model which involved a major episode of deep crustal thinning, commencing in the early Palaeozoic, with almost the entire crust removed below a mid-crustal discontinuity by a mechanism that largely involved pure shear. They further suggested that their crustal reflector ‘C2’ (mapped here as ‘red2’) could represent the boundary between upper and lower crustal extension beneath the Exmouth Plateau. In the tectonic model shown in Figure 38, the C2/red2 reflector has been correlated with a crustal discontinuity reported in the Pilbara Block (Drummond, 1981). As commensurate upper crustal extension is not evident, they proposed that this extension was accommodated in the conjugate passive margin.

More recently, Driscoll & Karner (1998) have integrated sequence stratigraphy with kinematic and isostatic models of basin development to derive a four-stage model for the evolution of the Northern Carnarvon Basin, as follows:

- Development of a 500 km-wide Permian basin represents the late stages of intra-cratonic basin formation across the region. The distribution and thickness of thick Triassic section is explained by a broadly distributed Permian, depth-independent extension event, with the amount of extension increasing westwards.
- Renewed depth-independent extension in the Late Triassic generated an extensive along-strike network of basins (eg the Barrow, Exmouth and Dampier Sub-basins) that was limited to a narrow portion of the margin, adjacent to the southeast boundary.
- In the Callovian, extension reactivated the border fault systems that delineated the Exmouth and southern Barrow Sub-basins with only minor accompanying deformation across the Exmouth Plateau. As with the Late Triassic event, extension was depth-independent and was spatially restricted to the basin margin troughs.
- In the Tithonian-Valanginian, extension was of very different style to the earlier extension events. Only minor amounts of brittle upper crustal extension are evident at this time, and they are entirely inadequate to account for the amount of post-Valanginian subsidence that is observed throughout the basin. Matching the distribution and amount of post-Valanginian subsidence requires significant lower crustal and mantle extension across the basin. According to Driscoll & Karner (1998), the distribution of extension implies the existence of an east-dipping, ramp-flat-ramp detachment. The western ramp of the detachment breached the surface west of the Exmouth Plateau. The flat lies at about 15 km depth beneath the Exmouth Plateau, and then ramps down again to Moho depth beneath the Barrow-Dampier Sub-basins.

However, we believe that there are significant problems with the Early Cretaceous stage of this model, as follows:

- There is no indication of a detachment breaching the surface beneath the outer margin of the Exmouth Plateau. Indeed, this area appears to be faulted to the northwest (eg line 162-1, Fig. 36a).
- If the detachment shoals beneath the outer margin of the plateau (as shown in Driscoll & Karner's figure 5a), we would expect that the major Triassic faults would terminate at relatively shallow depth. However, Plate 10, line 162/01 shows these faults extending to >7.5 s TWT (*ca*. 10-12 km) depth immediately adjacent to the continental slope.
- The model also proposes that the ramp deepens beneath the inboard rift basins to Moho level at about 30 km. Again, there is no reflection seismic expression of this ramp. In fact, the velocity correlations of Stagg & Colwell (1994) suggest that the major crustal discontinuity actually shallows from about 20 km to 10 km in the same area.

We therefore believe that, while the timing of the different extensional episodes and the magnitudes of extension are now reasonably well constrained, the extensional mechanisms for the Palaeozoic and widespread Valanginian episodes are still inadequately understood.

8.5 Influence of Palaeozoic Structural Grain

Many of the characteristic structural trends of the Exmouth Plateau show little obvious correlation with the extension and spreading azimuths of the adjacent Mesozoic seafloor spreading. We believe it is likely that underlying Palaeozoic trends have been overprinted by the Mesozoic extension to produce many of the present-day structures of the plateau. This is particularly pronounced in two areas.

Firstly, on the central and southern Exmouth Plateau, the major Triassic fault block trends, which are oblique to the azimuth of extension and breakup, are coincident in trend with the major structures of the mainly onshore, Silurian to Permian Southern Carnarvon Basin. We therefore believe that is likely that this part of the Exmouth Plateau is underlain by an extension of the Southern Carnarvon Basin.

Secondly, as previously noted in this report, the northern margin of the Exmouth Plateau is dominated by belts of prominent structures which comprise, from north to south:

- high-standing, planated blocks of Triassic sedimentary rocks (Wombat Plateau, Emu and Echidna Spurs), with relief of up to 2000 m at the seabed and 4000 m at the top Triassic;
- generally E-W to ENE-WSW trending, *en echelon* troughs and canyons; and
- a major E-W trending deep crustal high along the northern margin of the Exmouth Plateau proper (e.g. Plate 9, line 128/05, SP 2000-4000, 6-10 s TWT), which also coincides with marked changes in Triassic-Jurassic fault trends (Plate 2, at approximately 18^{o}S).

We also note that the high-standing, planated blocks are common along the margins of the Argo Abyssal Plain, being found on the northern Scott Plateau (eg Wilson Spur) and at the junction of the southern Scott Plateau and Rowley Terrace (Stagg & Exon, 1981, figs 16 & 22).

Inspection of the tectonic elements map of the North West Shelf (eg AGSO North West Shelf Study Group, 1994, fig. 2) shows that there is a strong correlation between the WNW-ESE trending Palaeozoic structures of the onshore Canning Basin and the northern margin of the Exmouth Plateau. In particular,

- the southern flank of the Fitzroy Trough appears to lie on the same trend as the continent-ocean boundary along the northern Exmouth Plateau;
- the shallow basement of the Broome Platform lies on trend with the Wombat, Emu and Echidna structures; and
- the Willara Sub-basin south of the Broome Platform is collinear with the trough/canyon trend and the crustal high underlying the northern margin of the Exmouth Plateau proper.

This coincidence of structures and trends suggests that the northern margin of the plateau is largely controlled by underlying Palaeozoic trends of the Canning Basin, with breakup occurring along the early Palaeozoic Fitzroy Trough rift, as was suggested by Exon & Willcox (1980).

Daim & Lennox (1998, figs 3 & 5) have proposed that the northern margin of the Exmouth Plateau is controlled by an extension of a continental-scale WNW-ENE trending lineament (transcurrent fault), which forms the southern boundary of the Canning Basin. This lineament is broadly similar to the structural alignment proposed here. Daim & Lennox further suggest that extension at releasing bends triggers melting in the lower crust, leading to mantle plume upwelling, and that upwelling produced in this way could account for the volcanic rocks of the Bedout High (reinterpreted as an impact breccia by Becker et al., 2002). If this model is valid, then a similar process might account for the high-standing Wombat, Emu and Echidna blocks.

9. TECTONIC-STRATIGRAPHIC-MAGMATIC EVOLUTION

The following discussion of the tectonic, stratigraphic and magmatic evolution of the Exmouth Plateau draws extensively on a number of papers and incorporates the results of this study. These papers include:

Gondwanan Context: Ogg et al. (1992)

Regional Tectonics: AGSO North West Shelf Study Group (1994); Müller et al. (1998); Longley et al. (2002)

Stratigraphy: Exon et al. (1992); Exon & von Rad (1994); Longley et al. (2002)

Magmatism: Frey (1998); Symonds et al. (1998a); Planke et al. (2000)

The basins of the North West Shelf are the end-product of a multi-phase geological history that commenced in the Proterozoic. The evolution of the region has produced a series of stacked, overlapping and adjacent basins whose structural styles cover the full range of settings from intra-cratonic, through passive margin to collisional and foreland basin. Throughout this evolution, the basin system has been characterised by the influence of older structures and structural grains on subsequent basin phases, resulting in a region of considerable geological complexity.

Broadly, the geological evolution of northwest Australia can be described in terms of three major phases of basin development:

- Proterozoic ?intra-cratonic basins (eg Kimberley, Hammersley and Ashburton Basins), which will not be considered further here;
- early to middle Palaeozoic basins (Southern Carnarvon, Roebuck and Southern Bonaparte Basins) largely of intra-cratonic origin; and
- Late Palaeozoic to Cainozoic intra-cratonic to passive margin basins (collectively referred to as the Westralian Superbasin).

In the Late Devonian to Early Carboniferous, extension on an approximate northeast azimuth between the Darwin, Kimberley and Pilbara Blocks and, presumably, an un-named block to the southwest (probably part of Greater India), resulted in the formation of the N- to WNW-trending intra-cratonic Southern Carnarvon, Canning and Southern Bonaparte Basins (Fig. 39; AGSO North West Shelf Study Group, 1994).

These basins were bound by accommodation structures which, in the southeast, utilised the Fitzmaurice and Halls Creek Mobile zones (segments of the postulated Lasseter Shear Zone of Braun et al., 1991), which are known to have been reactivated at this time (Veevers & Roberts, 1968), and, in the northwest, possibly by another complex accommodation feature (referred to as the North West Shelf Megashear by AGSO North West Shelf Study Group, 1994). These structures formed a system of predominantly extensional basins linked by regional-scale accommodation zones.

As noted previously, fault trends on the Exmouth Plateau suggest that the N-trending Southern Carnarvon Basin extended into the area now occupied by the Exmouth Plateau. It was also noted that structural trends on the northern margin of the Exmouth Plateau indicated that this margin was largely controlled by an E-W trending extension of the Canning Basin. If this interpretation is correct, then it is likely that the two basins intersected beneath the present-day northern Exmouth Plateau in the area occupied by the Wombat Plateau and Platypus Spur. Such a setting may have been a rift triple-junction, with the third arm of the rift being subsequently caught up in the subsequent rifting away of the Sibumasu Block (see below), or the Jurassic-Cretaceous breakup of the Argo Land / Burma and northern Greater India plates. In this scenario, it is possible that the anomalous structures of the Wombat Plateau and its environs are the Mesozoic-Cainozoic expression of a major Palaeozoic triple-junction, while the complexities of the boundary between the Argo and Gascoyne Abyssal Plains (i.e. northern Platypus Spur, Joey Rise, Roo Rise) are inherited from the since-departed third arm of the rift.

In the mid-Carboniferous to Early Permian, a major episode of crustal thinning commenced, giving rise to the elements of the Westralian Superbasin (Yeates et al., 1987). These elements comprise, from southwest to northeast, the Northern Carnarvon, Roebuck (formerly Offshore Canning), Browse and Northern Bonaparte Basins. This thinning event was most pronounced in the lower crust and was concentrated beneath the present-day continental margin. The azimuth of extension has been generally assumed to be northwest.

In the Late Carboniferous, the Sibumasu Block separated and drifted away from northwest Australia (summarised in Longley et al., 2002). An implication of this breakup event is that the Permian section throughout the region should be considered as a sag phase section, rather than a rift section, as has commonly been the case. As the Carboniferous-Permian extension was concentrated in the deep crust/upper mantle, it is likely that the boundaries between extensional compartments will be reflected only as subtle reactivation features through the upper crust and in the basin fill.

In the Late Permian or earliest Triassic, a major episode of uplift, faulting, and volcanism (the Bedout Movement) affected most of the North West Shelf, from the Northern Carnarvon to the Browse Basin. This movement is particularly well-developed in the Roebuck Basin and on the landward flank of the Browse Basin. Late Permian volcanics have been drilled at Bedout-1 on the Bedout High, at the junction of the Canning and Northern Carnarvon Basins, and have also been drilled at Perindi-1 and interpreted from seismic data in the Canning Basin (Reeckmann & Mebberson, 1984). While volcanics of this age have not been sampled in the Northern Carnarvon Basin, their presence would not be unexpected. At present, there is no widely accepted explanation for this event on the North West Shelf, although it is documented in the basins of eastern Australia (Elliott, 1993), and appears to be of plate-wide significance.

In recent studies, the previously-interpreted volcanics on the Bedout High have been interpreted as an impact breccia and the structure has been interpreted as a massive impact structure that may be associated with the global Permian/Triassic extinction event (Becker et al., 2002). If this interpretation is correct, then the impact would have significantly modified the crustal structure in the region. In late 2003, a pre-proposal for a National Science Foundation grant was prepared to investigate the crustal structure of the Bedout High, including multi-channel seismic, OBS and aeromagnetic surveys, and drilling of basement rocks.

The sequence stratigraphic, kinematic and isostatic modelling carried out by Driscoll & Karner (1998) interprets a broadly distributed episode of Late Permian extension that generates accommodation space for the thick Triassic section (Locker Shale and Mungaroo Formation) that was subsequently deposited in the Northern Carnarvon Basin. While they make no mention of the timing of this extension event relative to the Bedout Movement, it is likely that it post-dates that movement.

By the Triassic a single continental mass (Pangaea) was surrounded by a single ocean (Panthalassa), with the Northern Carnarvon Basin (and Exmouth Plateau) occupying a continental margin setting. In the Jurassic, Pangaea was split by the giant equatorial Tethys Sea into two super-continents, Laurasia in the north and Gondwana in the south. During the Late Jurassic, Gondwana was split into west Gondwana (South America and Africa) and east Gondwana (including Australia), with a proto-oceanic rift between. During earliest Cretaceous times, the eastern Gondwana super-continent started to break up, and Greater India separated from the still continuous Australian-Antarctica continent. Other east Gondwanan continental fragments also broke away and were carried northward away from the Australian-Antarctic continent by spreading oceans, and subsequently collided with and accreted to the Asian continent (see Ogg & von Rad, 1994).

The first documented breakup in the Australian region occurred in the north, during Late Jurassic times (155 Ma) and formed the Argo Abyssal Plain between the northern Exmouth Plateau and the Argo land / Burma plate that was presumably later subsumed in Asia (Görür & Sengör, 1992). The breakup between the Exmouth Plateau and Greater India to the west started at least 20 million years later than breakup in the north, during mid-Neocomian times (*ca*. 134 Ma), and led to the formation of the Gascoyne and Cuvier Abyssal Plains. On the southwest Australian margin, sea-floor spreading started to form the Perth Abyssal Plain at much the same time.

Thus, during Triassic and Jurassic times, the Exmouth Plateau was located along the southern Tethyan margin, connected with west Gondwana near the future northeast rim of Greater India, and connected with the future southeast Asia to the northeast. Using then existing data, Exon et al. (1992) compiled the series of palaeogeographic maps for the Carnian to Albian shown in Figure 40. Longley et al. (2002) have since published a more detailed set of palaeogeographic maps for the North West Shelf region for the period from Sinemurian to the Barremian (Early Jurassic to Early Cretaceous) and the reader is referred to that paper for a detailed discussion of that time interval.

In the Carnian-Norian (Fig. 40A) the area lay in cool temperate waters (50-55°S), and fluvio-deltaic siliciclastic sediments of the Mungaroo Formation built northward across the plateau; the Tethyan Ocean already existed in the north. The shoreline was approximately in its present position, and fast-building deltas were supplied from highlands to the south and east. Late Triassic rifting between Australia and Greater India, along the axis of later breakup on the northwestern margin of the Exmouth Plateau, led to intrusion and extrusion of a suite of rift volcanics that formed subaerially (Exon & Buffler, 1992; Crawford & von Rad, 1994; Symonds et al., 1998a). Contemporaneous volcanism is indicated by volcanic clasts in carbonates on the Wombat Plateau (Röhl et al., 1992) and by Triassic volcanics interpreted in seismic data on the Wombat Plateau (Plate 9, line 128/05) and in the Roebuck Basin.

The Rhaetian (Fig. 40B) was tectonically quiet, but the area had moved rapidly northward into subtropical waters (25-30°S). The shoreline had scarcely moved since the Carnian and Norian, but deltaic input now was confined to the south. The central plateau was covered in marl, and shelf carbonates (including reefal and lagoonal facies) were deposited on the northern plateau.

In the Hettangian to Sinemurian (Fig. 40C), the palaeolatitude was unchanged and carbonate deposition continued. Deltaic and shallow marine sedimentation was concentrated near the shoreline, and there was slow and intermittent deposition of shelf marl elsewhere. A resurgence of volcanism along the rift zone in the north is documented by rift volcanics dredged on the Wombat Plateau.

The next key tectonic event that affected the structuring of the Northern Carnarvon Basin occurred in the latest Triassic or Early Jurassic, and has been referred to as the 'Fitzroy Movement'. In early North West Shelf literature, this event was often referred to as 'rift onset'. However, while the effects of this event are widespread (including the major faulting episode that dominates the Exmouth Plateau), the cause is less clear.

In a regional analysis of the Fitzroy Movement, Etheridge & O'Brien (1994) suggested that the Late Triassic-Early Jurassic structures developed in response to largely compressional to transpressional deformation, with accompanying by uplift and widespread erosion. The compression was directed N-S or NNW-SSE along the entire margin and may also have been responsible for the development of the inboard Jurassic troughs (e.g. the Lewis Trough and the Barrow Sub-basin) through the creation of crustal-scale synclines and anticlines. In contrast to this model, Driscoll & Karner (1998) interpret Late Triassic extension as forming the Jurassic troughs, with the extension being localised in the crust beneath those troughs. While the Jurassic section on most of the Exmouth Plateau is thin or absent, the ubiquitous Exmouth Plateau fault block are also interpreted to have formed at this time.

By the Bathonian to Callovian (Fig. 40D), the area had moved southward (35-40°S), and carbonate deposition is no longer evident. The major troughs to the southeast of the Exmouth Plateau (Lewis Trough, Barrow and Exmouth Sub-basins) were rapidly filled with marine to paralic siliciclastic sediments up to 2000 m thick. These troughs were sediment traps during much of the Jurassic, leaving the central Exmouth Plateau largely sediment-starved. However, sedimentation continued through the Early to Middle Jurassic on the northern margin of the plateau, where the inboard troughs are less well-developed, with up to about 1500 m of mainly inner shelf clastics being deposited, possibly with some shelf limestone (Quilty, 1990). Sediments of similar Early to Middle Jurassic age were also deposited at the southwest margin of the Exmouth Plateau (Plate 10, line 135/11), and probably continued onto the formerly contiguous Greater India plate. This sequence probably indicates that sediment-trapping Jurassic troughs were not developed southwest of the Exmouth Sub-basin.

The next major tectonic phase was the uplift, erosion and faulting that accompanied breakup in the Argo Abyssal Plain in the Callovian-Oxfordian. In our interpretation, this faulting is most intense beneath the northern margin of the plateau (Plate 9, line 128/05) and adjacent to the future Cape Range Fracture Zone (Plate 10, line 135/11), where it has reactivated the underlying Triassic fault blocks. We note that the interpretation of line 128/05 presented in AGSO Geoscience Australia (2001) differs from the interpretation here in that the faulted Callovian surface is picked at a shallower depth beneath the Montebello Canyon. Faulting of this age probably also took place beneath the central Exmouth Plateau; however, the thin Jurassic sedimentation makes it difficult to assess its intensity.

In the late Oxfordian to Kimmeridgian (Fig. 40E), the palaeolatitude was little changed; indeed, there was little palaeolatitude change through into the Albian. This period came immediately after the formation of the Callovian-Oxfordian breakup unconformity, that is present everywhere in the Carnarvon Basin. There had been widespread uplift along the trend of the Rankin Platform, and much of the northern area was dry land. The Roebuck Basin margin, to the east of the Argo Abyssal Plain, was uplifted and subjected to rift volcanism (Ramsay & Exon, 1994). Marine clay was deposited southeast of the Rankin Platform, and a condensed shelfal series of clay, marl and carbonate mud was laid down in the southwest and northeast.

Major changes in depositional patterns took place in the Berriasian to early Valanginian (Fig. 40F), a period which post-dated breakup in the north, and immediately pre-dated breakup in the west and south. The Exmouth Plateau lay a little further north than previously (33-38°S). There was major uplift along the Cape Range Fracture Zone in the south, the shear zone along which the southern margin later broke up, and also in the southeast. Deltaic sediments of the Barrow Group were derived from uplifted areas, and deposited to the north and northwest. Local volcanic highs were being eroded in the south. The formation of the Argo Abyssal Plain during the Late Jurassic to Berriasian produced rapid subsidence of the northern margin of the plateau. A condensed, transgressive, juvenile ocean sequence was deposited on the Wombat Plateau. Between the northern Exmouth Plateau and the Barrow delta was an area of non-deposition, and further south thin, shallow marine to bathyal sediments were deposited.

The period around breakup in the Gascoyne and Cuvier Abyssal Plains is the most important in terms of volcanic activity. The relative timing of individual volcanic events is difficult to determine, given that volcanic activity encompassed a wide range of styles, over a wide area. Frey (1998) and Planke et al. (2000) have interpreted the sequence of volcanic events at this time, and we build on their interpretations with the additional data now available.

Volcanism probably peaked immediately prior to breakup, with an initial explosive phase in an aquatic or wet environment. This was then followed by extensive effusive volcanism that filled in the topographic lows in the rapidly subsiding axial rift valley along the incipient breakup axis, before spilling out landwards and creating the landward flows unit. Possibly contemporaneously with this activity, a major volcano centre was active on the northwest corner of the plateau, adjacent to Platypus Spur. This feature occupies an area measuring approximately 70 x 50 km, and the interpreted flows at its core are about 8 km thick. It is likely that this volcano, and perhaps others like it, produced the bentonites that were cored on the Argo Abyssal Plain (DSDP 261 and ODP 765), Wombat Plateau (ODP 761), Exmouth Plateau (ODP 763) and Gascoyne Abyssal Plain (ODP 766; von Rad & Thurow, 1992).

The volcanic edifice of Joey Rise has similar physical characteristics to the Exmouth-Platypus volcanic centre and may well have been active at the same time. It is likely that the massive and widespread volcanism associated with Gascoyne breakup also impacted on the 20 Ma old crust in the adjacent Argo Abyssal Plain.

Continued subsidence and volcanism in the central rift then led to the deposition of the first SDRS units (Frey's 'inner SDRS'), probably very close to breakup time. SDRS were deposited in probable fault-bounded half-grabens in both wedge and fan configurations, with overlap and stacking of adjacent units.

SDRS are best-developed adjacent to the southwest corner of the Exmouth Plateau, becoming progressively more indistinct to the north. This may indicate that the southwest part of the Gascoyne rift valley was below sea level, permitting the formation of SDRS, while to the northeast, less subsidence had occurred and extrusion took place subaerially. This interpretation finds some support in the areal distribution of low-angle extensional faulting in the upper crust, which is more concentrated in the southwest.

Frey (1998) and Planke et al. (2000) interpreted 'outer highs' as having formed by explosive volcanism with magma-water interaction, and an 'outer SDRS' province beyond the outer high. The outer SDRS province was interpreted to have formed subsequent to breakup, with the shorter flow lengths, and less well-developed seismic character being the result of extrusion in deeper waters. Further, their model implies that there is strong linearity of these features along-strike. However, we see little evidence for the simple categorisation of inner and outer SDRS separated by an outer high, although there is a definite change in SDRS character with distance from the margin, which is likely due to increasing water depth.

The final large-scale magma event on the margin occurred approximately 10 m.y. after breakup in the Gascoyne-Cuvier Abyssal Plains, as the Cuvier spreading ridge passed the southwest corner of the Exmouth Plateau to abut the oldest Gascoyne crust. This event is marked by the emplacement of the splayed, generally north-trending volcanic ridges which are overprinted on the older SDRS.

Following late Valanginian breakup in the west and south, the Exmouth Plateau became a separate entity as Greater India moved away westward. In the Aptian, the region lay again at 35-40°S, and was bounded southward by the Cuvier Abyssal Plain and westward by the Gascoyne Abyssal Plain (Fig. 40G). The main source of terrigenous sediment to the plateau had vanished, but a marine transgression resulted in the shallow marine Muderong Shale being laid down very widely. Around the margins of the plateau, bathyal clay and chalk were deposited.

In the Albian (Fig. 40H), the plateau still lay at the same palaeolatitude. It was subsiding along with the neighbouring abyssal plains. Detrital shallow marine sediments were laid down near the coastline in the southeast, with shelf marl beyond them. Hemipelagic clay and eupelagic calcareous ooze were deposited over most of the plateau, and clays on the abyssal plains.

In the Campanian, a major inversion event occurred, possibly in response to changes in plate motions (Bradshaw et al., 1998). This produced the structural closure of the crest of the Exmouth Plateau (including the Scarborough gas field structure) and may explain the lack of oil migration to the central part of the plateau.

Throughout the remainder of the Cretaceous, the plateau continued to subside, outpacing the slow rain of pelagic carbonate. Late Cretaceous deposition on the plateau and much of the adjacent North West Shelf comprised marl, chalk and carbonate mud. On the plateau, such conditions continued throughout the Cainozoic. However, from the early Miocene, when the region had drifted northward into tropical waters, North West Shelf deposition was characterised by northwesterly prograding wedges of shelf carbonates. From then on, the plateau was clearly distinguished from the North West Shelf by pelagic rather than shelf carbonate deposition.

During the Tertiary, the major event affecting the geology of northwest Australia has been the collision of the Australian and Eurasian Plates, particularly from the Middle to Late Miocene onwards. The reactivation effects from this collision are concentrated in the Timor Sea and the Browse Basin, but are less obvious in the Northern Carnarvon Basin. In this latter area, the collision is reflected in two ways. Firstly, Müller et al. (1998) have interpreted accelerated subsidence from well data at least since 10 Ma (Late Miocene), and perhaps as early as 20 Ma (Early Miocene). Secondly, in the Gascoyne Abyssal Plain, west of Platypus Spur, major, N-trending reverse faults have been developed which extend to the seabed (Plate 9, lines 162/11 & 162/12). The stress field map illustrated by Hillis (1998) shows that the maximum present-day horizontal stress in the Northern Carnarvon Basin is oriented at 090-100^{o}, an orientation that accounts for this observed fault trend.

10. RESOURCE POTENTIAL

10.1 Hydrocarbons

10.1.1 Discoveries and shows

The close proximity of the Exmouth Plateau to the hydrocarbon discoveries on the Rankin Platform and at Barrow Island in the Northern Carnarvon Basin led to a high level of exploration interest in the mid 1970s to early 1980s. This culminated with the drilling of a number of exploration wells in 1979-80. Renewed exploration interest in the early- to mid-1990s led to the drilling of several further deep-water exploration wells, including the Scarborough-2 appraisal well. A production test on Scarborough-2 in January 1997 flowed gas at a rate of 32 MMCf/d (WA Dept of Mineral and Petroleum Resources, 2002). Various options are currently being considered by the joint venture partners to commercialise this substantial gas resource.

The original Rankin Platform discoveries were characterised by gas condensates and light oils, interpreted to have been sourced from the mature Upper Triassic Mungaroo Formation. The interpretation of a faulted thick Triassic section across much of the Exmouth Plateau increased speculation of the potential for major accumulations in deep water. This interpretation was encouraged by the identification of seismic anomalies possibly indicating the presence of gas. The drilling program of 1979-80 led to the discovery of several non-commercial gas accumulations, including the major Scarborough gas field. The lack of liquid hydrocarbons, however, saw most exploration effort subsequently withdrawn and concentrated inboard in the Barrow-Dampier-Exmouth Sub-basins and adjacent Rankin Platform. Over last several years significant new oil discoveries have been made in the Exmouth Sub-basin (e.g. Vincent, Enfield and Laverda oil fields), as well as substantial additional gas discoveries in the Greater Gorgon and Greater Goodwyn areas along the eastern edge of the Exmouth Plateau.

Table 1 summarises the basic data for the original wells drilled in the Exmouth Plateau. The data are based on Barber (1988) and Spencer et al. (1995). Note that all wells reached total depth (TD) in the Triassic Mungaroo Formation except for Scarborough-1, which reached TD in the Lower Cretaceous Barrow Group.

Table 1. Summary of wells drilled in the Exmouth Plateau

Well	TD (mKB)	Primary Target	Status	Discovery Formation	Comment
Altair-1	3793		dry		no shows
Eendracht-1	3410	seismic anomaly in Triassic fault block	gas	multiple gas sands in Mungaroo marine equivalent	very dry gas
Investigator-1	3745	domal high in Barrow Group	gas	multiple gas sands in Brigadier Beds or upper Mungaroo sands	no shows in Barrow Group
Jupiter-1	4946	DHI in Triassic fault block	gas	thin sands of Brigadier Beds	very thin Jurassic

Leyden-1B	4300	NE-SW trending eroded Triassic horst block	dry	gas shows in basal Barrow Group	leakage via faults
Mercury-1	3812	tilted Triassic fault fault block	dry	gas shows in Upper Triassic	thin Jurassic
Resolution-1	3884	Triassic fault block flanked by shales	gas	sands of Mungaroo Formation	
Saturn-1	4000	Triassic fault block flanked by shales	gas	thin sands in Brigadier Beds	Jurassic absent
Scarborough-1	2713	domal high in Barrow with DHI	major gas	thick sand sequence in Barrow	suspended gas producer
Scarborough-2	2068	test extension of sand fans in Scarborough-1	major gas	thick sand sequence in Barrow	suspended gas producer
Sirius-1	3490	domal high in Barrow Group	gas	sands in Mungaroo Formation or Brigadier Beds	some condensate
Vinck-1	4600	domal high in Cretaceous section	gas	gas and gas-condensates in fluvio-deltaic sands of Mungaroo Formation	deeper sands tight
Zeepard-1	4215	Triassic fault block flanked by shales	gas	thin sands in Brigadier Beds	Jurassic absent
Zeewulf-1	3500	Triassic fault block flanked by shales	gas	thin sands in Brigadier Beds	

According to Longley et al. (2002), the Exmouth Plateau is estimated to contain (based on Woodside's definition of the boundaries of the plateau), scope reserves of 32 Tcf of gas, 81mmbbls of condensate and no oil. The Scarborough field is estimated to contain 4 Tcf of extremely dry and low CO_2 gas in a large Campanian inversion structure which is still at the bathymetric crest of the plateau (Longley et al., 2002; Bradshaw et al., 1998).

10.1.2 Source and Maturity

Barber (1988) postulated two distinct geochemical domains on the Exmouth Plateau, based on organic matter type and maturation, above and below the Oxfordian unconformity. Above the unconformity, the Barrow Group shales indicate high levels of soluble organic matter derived from marine or hydrogen-rich kerogen (Resolution-1, Saturn-1, Scarborough-1 and Zeepard-1). These are considered good oil and gas sources (Barber, 1982).

Below the unconformity, sediments of the Mungaroo Formation have high aromatic/saturate ratios suggesting derivation from terrestial or hydrogen-poor kerogens. These are considered currently mature for generation of gas and gas-condensates. Cook et al. (1985), however, demonstrated the potential for generation of light oils in the Mungaroo Formation based on, amongst other indicators, the presence of high molecular weight n-alkanes. Furthermore, oil generative potential improves in the marine Mungaroo equivalents (Eendracht-1 and Vinck-1).

Much interest has focused on the Late Jurassic sequences on the North West Shelf, particularly in the inboard parts of the rift system. For example, Resolution-1 on the southeast Exmouth Plateau shows that the Upper Dingo Claystone has reached full generative potential for gas-condensate and some oil. This is due to the prevalence of anoxic conditions in the Barrow Trough rift system, which is favourable for preservation of sapropelic organic matter (Volkman et al., 1983; Kopsen & McGann, 1985). However, these conditions were absent further westwards as the plateau was more exposed to marine circulation and breakup-related uplift meant that much of the plateau was sediment-starved or eroded. According to Longley et al. (2002), the principal effective oil source rocks in the Barrow, Dampier and Exmouth Sub-basins are Oxfordian-Kimmeridgian anoxic marine shales which are currently within the oil window on the basin margins and within the gas window in basinal areas.

Vitrinite reflectance studies (Barber, 1988) indicate that peak hydrocarbon generation occurs at depths of 3800-4000 m on the central Exmouth Plateau and at least at 5000 m on the western flank of the plateau near Eendracht-1. Vitrinite reflectance values are generally low in the Upper Triassic, although higher values at Resolution-1 and Zeepard-1 probably reflect an elevated thermal regime due to deep igneous intrusions.

10.1.3 Reservoir

Drilling on the Exmouth Plateau has delineated four major hydrocarbon-bearing reservoir units (Barber, 1988): the Upper Triassic Mungaroo Formation, the uppermost Triassic Brigadier Beds, unnamed Tithonian sands and the Lower Cretaceous Barrow Group.

Vos & McHattie (1981) show the Mungaroo Formation to be laid down in a meandering and braided stream depositional environment. Marine equivalents are probable along the western margin of the plateau as suggested by intervals in Eendracht-1 (Barber, 1988). Where drilled on the plateau, the non-marine facies have porosities in the range of 15-28% and permeabilities up to 1000 md. These decrease with increasing depth, to levels of 15% and 30 md, respectively, below about 3700 m. Carbonate cementation can also reduce the porosity and permeability, as at Eendracht-1.

The Brigadier Beds comprise transgressive shallow marine deposits of interbedded calcareous sands, siltstones and minor limestone. In shoreward locations, these interfinger with barrier bar sands and facies of a back lagoonal complex. The Tithonian sands are generally thin but have porosities averaging 15% to 25%. The sands can be thin units of conglomeratic greensand (Saturn-1) overlying the Oxfordian unconformity, and are generally sourced from structural highs on the Rankin Platform (Barber, 1982). Saturn-1 showed poor permeability, but porosities of 27% to 30% in this unit. The thickness of these sands is highly variable along the Rankin Platform, and they are unlikely to be present on the more distal parts of the Exmouth Plateau.

The Barrow Group is dominated by interbedded shale and distal submarine-fan to proximal-fan sand facies. Correlation of wells and regional seismic data indicate that the formation is extensive on the southern Exmouth Plateau and in the Barrow and Exmouth Sub-basins. The interfingering of sand and shale pulses makes the barrow

Group an ideal reservoir facies. The Flag Sand member has the best characteristics, with porosities averaging 23% in mass-flow sandy facies (Scarborough-1). It probably blankets the plateau out to the Gascoyne margin, but is thinner and likely to be more shale-prone.

10.1.4 Seals and Play Types

Shale facies within the Barrow Group have potential to seal underlying sand lenses in stratigraphic updip pinchouts, as well as structural closures (Scarborough-1). These stratigraphic plays are particularly attractive along the Cuvier and Gascoyne margins, where transform faulting and deep-seated igneous intrusions, respectively, have produced major uplifting of the Barrow Group.

Siltstones and claystones of the widespread Lower Cretaceous Muderong Shale act as a more regional seal for structural-style closures in the Barrow Group. This unit is an excellent seal throughout the Northern Carnarvon Basin, but thins over the outer Exmouth Plateau due to planation by the Aptian/Albian and Turonian unconformities. Furthermore, extensive shallow faulting towards the margins is likely to compromise the sealing integrity.

The Triassic Mungaroo Formation reservoirs within north-northeast trending fault blocks are generally sealed by the overlying Lower Dingo Claystone (Resolution-1, Saturn-1, Zeepard-1, Zeewulf-1). These structural plays extend across the plateau (the Lower Dingo Claystone is fairly widespread) and the bounding faults act as migration pathways from deeper source rocks (Locker Shale).

All play types must take into account the style of faulting and potential reactivation that has acted to seriously compromise the integrity of sealing facies. On the other hand, consideration should also be taken for the same faulting providing hydrocarbon migration and fractionation pathways from deeper accumulations.

Recently, in a study of the deep-water Northern Carnarvon Basin (inc the Exmouth Plateau) in comparison to other deep-water petroleum exploration areas in the world (Gulf of Mexico and Mauritania), Bussell et al. (2001) concluded that the deep-water Northern Carnarvon Basin lacks a world-class, widespread, oil-generating source rock; parts of the Exmouth Plateau have insufficient thickness of sediment to form an effective seal; and that factors such as long-term gas markets, development costs and condensate-gas ratio will continue to adversely effect exploration in the region.

10.2 Non-hydrocarbon Minerals

Exploration and exploitation of non-hydrocarbon minerals in the marine environment is both in its infancy and relatively small in economic terms. The principal minerals that are of interest and immediate or long-term economic value are construction materials (sand and aggregate), alluvial diamonds, and manganese nodules and crusts (which contain nickel, copper and cobalt). Of these, exploration and exploitation of construction materials and diamonds are confined to shallow waters and hence are unlikely ever to be relevant to the Continental Shelf beyond the 200 nautical mile EEZ. However, manganese nodules and crusts are known to be present at a number of deepwater locations around Australia and its island territories (Exon et al., 1990), including the environs of the Exmouth Plateau. Von Stackelberg et al. (1980) found that thin manganese crusts (but not nodules) were common on the plateau margins. Average metal concentrations for the Exmouth and Wallaby Plateau crusts are 0.16%

cobalt, 0.28% nickel and 0.09% copper, in deposits with 12.7% iron and 12.2% manganese. Such values are of no current economic interest.

De Carlo & Exon (1992) have described in detail the mineralogy of ferromanganese crusts and nodules and ferromanganese-rich sediments that have been recovered by dredging and ODP drilling on the Wombat Plateau on the northern margin of the Exmouth Plateau. Their analyses probably apply in general to the nodules and crusts that have been recovered by other sampling programs in the region during the past 20-30 years from water depths of 2000-4600 m.

Both the nodules and crusts described by De Carlo & Exon (1992) are primarily vernadite (δMnO_2) and are chemically and mineralogically similar; they are also not dissimilar from ferromanganese deposits found elsewhere on Australian and other marginal plateaus, but are markedly different from most deep-sea deposits. Metals of potential economic interest are generally only present in low concentrations compared to those from vernadite-rich seamount crusts and nodules and from abyssal nodules from areas of high resource potential in the Pacific Ocean. The maximum metal concentrations measured were 0.55% cobalt, 0.58% nickel and 0.20% copper, in deposits containing 4.8-30.9% iron and 4.4-21.1% manganese.

In summary, the deep-sea mineral deposits of the Exmouth Plateau region are unlikely to have any economic value, in at least the short- to medium-term.

ACKNOWLEDGEMENTS

The authors are grateful to Jim Colwell, Damien Ryan and John Kennard for reviewing this manuscript. The figures and plates were drafted by Angie Jaensch and Neville Montgomerie.

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APPENDIX 1: 1982 UNITED NATIONS CONVENTION ON THE LAW OF THE SEA (UNCLOS)

Article 76 : Definition of the continental shelf

1. 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 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 SEISMIC SURVEYS

Survey	17
Contractor	CGG / BMR
Vessel	Lady Christine
Year	1972
Streamer length (m)	1000
Seismic channels	6
Sample rate / rec. length (ms)	analogue / continuous
Group length/interval (m)	50 / 200
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	sparker / 120 kJ
Nominal vessel speed (kn)	7-9
Primary navigation	Transit Satnav + Marquardt sonar doppler
Secondary navigation	Transit Satnav + Chernikeef paddle log
Tertiary navigation	Transit Satnav + pressure log
Primary echo-sounder	Elac
Secondary echo-sounder	seismic
Magnetic data	yes
Gravity data	yes

Survey	18
Contractor	CGG / BMR
Vessel	Lady Christine
Year	1972-73
Streamer length (m)	1000
Seismic channels	6
Sample rate / rec. length (ms)	analogue / continuous
Group length/interval (m)	50 / 200
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	sparker / 120 kJ
Nominal vessel speed (kn)	7-9
Primary navigation	Transit Satnav + Marquardt sonar doppler
Secondary navigation	Transit Satnav + Chernikeef paddle log
Tertiary navigation	Transit Satnav + pressure log
Primary echo-sounder	Elac
Secondary echo-sounder	seismic
Magnetic data	yes
Gravity data	yes

Survey	Roving reconnaissance seismic (N)
Contractor	Shell Internationale Petroleum Maatschappij N.V.
Vessel	Petrel
Year	1971
Streamer length (m)	2400
Seismic channels	24
Sample rate / rec. length (ms)	4 / 6000
Group length/interval (m)	50 / 100
Shot interval (m)	50
Cable depth (m)	15
Source type / power or volume	airgun array / 6.4 litres
Nominal vessel speed (kn)	6
Primary navigation	Transit Satnav + Marquardt sonar doppler
Primary echo-sounder	Not known
Magnetic data	yes; analogue only
Gravity data	yes; analogue only

Survey	55
Contractor	AGSO
Vessel	Rig Seismic
Year	1986
Streamer length (m)	2400
Seismic channels	48
Sample rate / rec. length (ms)	2 / 7500
Group length/interval (m)	50 / 50
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	2 x Bolt airguns / 16.4 litres
Nominal vessel speed (kn)	5.5
Primary navigation	Transit Satnav + Magnavox sonar doppler
Secondary navigation	Transit Satnav + Raytheon sonar doppler
Tertiary navigation	HiFix radio-navigation
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	no

Survey	56
Contractor	AGSO
Vessel	Rig Seismic
Year	1986
Streamer length (m)	2400
Seismic channels	48
Sample rate / rec. length (ms)	2 / 7500
Group length/interval (m)	50 / 50
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	2 x Bolt airguns / 16.4 litres
Nominal vessel speed (kn)	5.5
Primary navigation	Transit Satnav + Magnavox sonar doppler
Secondary navigation	Transit Satnav + Raytheon sonar doppler
Tertiary navigation	HiFix radio-navigation
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	no

Survey	90
Contractor	AGSO
Vessel	Rig Seismic
Year	1990
Streamer length (m)	2400
Seismic channels	96
Sample rate / rec. length (ms)	2 / 6000
Group length/interval (m)	25 / 25
Shot interval (m)	37.5
Cable depth (m)	10
Source type / power or volume	10 x sleeve airguns / 24.6 litres
Nominal vessel speed (kn)	5.5
Primary navigation	Transit Satnav + Magnavox sonar doppler
Secondary navigation	Transit Satnav + Raytheon sonar doppler
Tertiary navigation	GPS
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	101
Contractor	AGSO
Vessel	Rig Seismic
Year	1991
Streamer length (m)	4800
Seismic channels	192
Sample rate / rec. length (ms)	4 / 16000
Group length/interval (m)	25 / 25
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Transit Satnav + Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	110
Contractor	AGSO
Vessel	Rig Seismic
Year	1992
Streamer length (m)	4800
Seismic channels	192
Sample rate / rec. length (ms)	2 / 16000
Group length/interval (m)	25 / 25
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Transit Satnav + Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	128
Contractor	AGSO
Vessel	Rig Seismic
Year	1994
Streamer length (m)	4800
Seismic channels	192
Sample rate / rec. length (ms)	2 / 16000
Group length/interval (m)	25 / 25
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	135
Contractor	AGSO
Vessel	Rig Seismic
Year	1994
Streamer length (m)	4800
Seismic channels	192
Sample rate / rec. length (ms)	2 / 16000
Group length/interval (m)	25 / 25
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	162
Contractor	AGSO
Vessel	Rig Seismic
Year	1995
Streamer length (m)	3000
Seismic channels	240
Sample rate / rec. length (ms)	2 / 12000
Group length/interval (m)	12.5 / 12.5
Shot interval (m)	37.5
Cable depth (m)	6
Source type / power or volume	12 GI airguns in harmonic mode / 41.3 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	168 (OBS refraction survey
Contractor	AGSO
Vessel	Rig Seismic
Year	1995-96
Streamer length (m)	na
Seismic channels	na
Sample rate / rec. length (ms)	na / na
Group length/interval (m)	na / na
Shot interval (m)	100
Cable depth (m)	na
Source type / power or volume	32 sleeve airguns / 78.7 litres
Nominal vessel speed (kn)	5
Primary navigation	differential GPS
Secondary navigation	differential GPS
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

APPENDIX 3: DETAILS OF GEOLOGICAL SAMPLE STATIONS IN WATER DEPTHS GREATER THAN 200 M

Site	Alias	Latitude	Longitude	Dep	th 1-2	Survey	Reference	Oldest Age	Description of Oldest components	Uno
096DR030	C1 Echidna Plateau	-17.6275	115.6902	2300	2000	RS A96	A1990/85	N/A	Limestone	S6900040
096DR031	G1 Platypus Spur	-16.9045	114.3737	2510	2310	RS A96	A1990/85	Pleistocene	Ooze	S6900040
096DR032	G2 Platypus Spur	-16.9045	114.2757	3100	2560	RS A96	A1990/85	M. Miocene	Chalk + volcanics	S6900040
096DR033	G2 Platypus Spur	-16.9017	114.2800	3050	2470	RS A96	A1990/85	E.-M. Miocene	Chalk + ?basalt	S6900040
096DR034	H1 Exmouth Plateau	-19.9378	110.5678	3950	3410	RS A96	A1990/85	N/A	Amygdaloidal basalt/andesite	S6900040
096DR035	H2 Exmouth Plateau	-20.1812	109.9142	5025	4050	RS A96	A1990/85	N/A	Fault breccia + siliceous mudstone + basalt/gabbro	S6900040
096DR029	C1 Echidna Plateau	-17.6230	115.6917	2280	1995	RS A96	A1990/85	E. Miocene	Clay	S6900040
096DR006	B1 Exmouth Sub-basin	-21.8683	112.7300	4100	3340	RS A96	A1990/85	Quaternary	Mud/ooze	S6900040
096DR007	B0 Exmouth Sub-basin	-21.8777	112.7185	3700	3150	RS A96	A1990/85	L. Paleocene	Chalk + sandstone	S6900040
096DR008	B2 Exmouth Sub-basin	-21.8488	112.7615	3550	3180	RS A96	A1990/85	L. Oligocene (nanno) or E. Miocene (foram)	Chalk + sandstone	S6900040
096DR009	B3 Exmouth Sub-basin	-21.9290	113.0220	2650	2200	RS A96	A1990/85	L. Cretaceous (nanno) or L. Paleocene (foram)	Mudstone	S6900040
096DR010	B4 Exmouth Sub-basin	-21.9381	113.1612	2410	2100	RS A96	A1990/85	L. Eocene	Mudstone	S6900040
096DR004	B0 Exmouth Sub-basin	-21.8843	112.7490	4200	3540	RS A96	A1990/85	Quaternary	Sandstone + ooze	S6900040
096DR005	B0 Exmouth Sub-basin	-21.8687	112.7292	4200	3150	RS A96	A1990/85	Quaternary	Sandstone	S6900040
107GC003		-12.2758	107.8615	2939			(?)			S0910002
095GC003		-16.9198	115.5407	1970		RS A95	A1990/57	M. Pleistocene	Foram and nanno ooze	S6900039
056GC003		-16.9750	115.5583	2400		RS A56	A1988/30	L. Miocene	Nanno chalk	S6860023
056GC004		-16.9750	115.5550	2160		RS A56	A1988/30	Quaternary	Nanno ooze	S6860023
056DR010	Echidna Spur (E)	-16.8567	116.7700	3790	3710	RS A56	A1988/30	? Jurassic ? E. Cretaceous	Coal measures/claystone	S6860023
056DR011	Echidna Spur (E)	-16.8500	116.7700	3230	2840	RS A56	A1988/30	? E. Cretaceous; L. Oligocene & L. Miocene	Tectonized silty slate/siltstone - sst, chalk	S6860023
056DR012	Wombat Plateau	-16.5133	115.2933	4600	3500	RS A56	A1988/30	? Triassic	Volcanics, tuff breccia	S6860023
056DR013	Wombat Plateau	-16.5667	115.2600	3380	2800	RS A56	A1988/30	? Triassic	Volcanics, basalt, tuff, volcaniclastic sst, mudstone, carbonates	S6860023
056DR014	Wombat Plateau	-16.5217	115.4417	3440	2690	RS A56	A1988/30	L. Triassic	Limestone, chalk, Mn crusts, nodules	S6860023

056DR015	Wombat Plateau	-16.9917	115.5617	2720	2030	RS A56	A1988/30	? Triassic redbeds	Silty mudstone, ?Jurassic coal mesrs, lst, chalk, clay	S6860023
056DR016	Wombat Plateau	-16.9833	115.5667	2570	2040	RS A56	A1988/30	L. Triassic	L. Triassic limestone, ?E. Cretaceous sst	S6860023
053PC009	53-EP-PC01	-19.8932	114.9705	1177		RS A53	BMR 274	N/A	Silt-mud	M0860001
053GC007	53-EP-GC01	-19.8933	114.5900	1279		RS A53	BMR 274		Silt-mud	M0860001
053GC008	53-EP-GC02	-19.7112	114.3351	1352		RS A53	BMR 274		Silt-mud	M0860001
053GC009	53-EP-GC03	-19.5354	113.8829	1141		RS A53	BMR 274		Silt-mud	
053GC010	53-EP-GC04	-19.5852	113.5342	956		RS A53	BMR 274		Sand	M0860001
053GC011	53-EP-GC05	-19.3253	113.1066	1279		RS A53	BMR 274		Silt-mud	M0860001
053GC012	53-EP-GC06	-19.0528	112.7523	1979		RS A53	BMR 274		Silt-mud	M0860001
053GC013	53-EP-GC07	-18.8923	112.6315	2256		RS A53	BMR 274		Silt-mud	M0860001
053GC014	53-EP-GC08	-19.5224	113.2247	936		RS A53	BMR 274		Silt-mud	M0860001
053GC015	53-EP-GC09	-20.0042	112.9313	962		RS A53	BMR 274		Silt-mud	M0860001
053GC016	53-EP-GC10	-20.4983	112.5859	947		RS A53	BMR 274		Silt-mud	M0860001
053GC017	53-EP-GC11	-20.8948	112.3336	1432		RS A53	BMR 274		Silt-mud	
139GR620	620	-18.8500	116.7833	366		Espi.Sant	A1970/27		Lime mud	O6680100
139GR629	629	-19.1167	116.4500	274		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR637	637	-19.0000	116.1167	357		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR655	655	-19.2667	115.9167	293		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR661	661	-19.5333	115.4833	274		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR671	671	-19.8833	115.2333	247		Espi.Sant	A1970/27		Calcarenite	O6680100
139GR687	687	-19.9667	115.1333	219		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR691	691	-19.7833	115.3333	201		Espi.Sant	A1970/27		Oolite	O6680100
139GR735	735	-19.1000	116.3167	293		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
139GR737	737	-19.2167	116.1000	271		Espi.Sant	A1970/27		Globigerina Calcarenite	O6680100
054KL059	SO8-KL59	-16.9000	115.5733	2105		Sonne B8	A1979/26			
054BC013	SO8-KA60	-16.9433	115.1850	1610		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC014	SO8-KA80	-18.6200	113.7467	1470		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC015	SO8-BL81	-18.6200	113.7467	1486		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC016	SO8-BL82	-18.6050	113.7450	1473		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC017	SO8-BL83	-18.6150	113.7383	1485		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC018	SO8-BL84	-18.6167	113.7367	1486		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC019	SO8-BL85	-18.6817	113.7583	1469		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC022	SO8-BL88	-18.6900	113.7717	1461		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC023	SO8-BL89	-18.6917	113.7750	1454		Sonne B8	A1979/26	Quaternary	Ooze	S6790026

054BC024	SO8-BL90	-18.6933	113.7817	1458	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC027	SO8-KA93	-20.3467	112.9383	820	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC028	SO8-KA95	-20.2817	112.9500	820	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC029	SO8-KA96	-20.2333	112.9600	820	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC030	SO8-KA97	-19.9983	113.8383	1120	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC031	SO8-BL98	-20.0000	113.8167	1130	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC032	SO8-BL99	-20.0000	113.8383	1120	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC033	SO8-BL100	-20.0000	113.8433	1120	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC034	SO8-BL101	-20.0000	113.8533	1120	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC036	SO8-KA104	-20.7450	114.0417	1027	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC037	SO8-KA107	-20.9500	114.3500	493	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BL112	SO8-BL112	-21.0001	113.6167	1198	Sonne B8	A1979/26			
054BC041	SO8-BL113	-21.1117	113.6150	1198	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC042	SO8-BL114	-21.1083	113.6117	1198	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC043	SO8-BL115	-21.1050	113.6083	1202	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC044	SO8-BL116	-21.1017	113.6067	1203	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC045	SO8-BL117	-21.0967	113.6033	1205	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC046	SO8-KA118	-21.1333	112.7767	1502	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC047	SO8-BL125	-20.9733	111.9200	1455	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC048	SO8-BL126	-20.9767	111.9233	1466	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC049	SO8-BL127	-20.9800	111.9267	1489	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC050	SO8-BL128	-20.9833	111.9300	1515	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054KL132	SO8-KL132	-20.1433	112.30000	1715	Sonne B8	A1979/26			
054BC053	SO8-KA133	-21.9517	111.7700	5040	Sonne B8	A1979/26	Quaternary	Clay	S6790026
054BC056	SO8-KA141	-21.4733	112.5167	2918	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054BC057	SO8-KA145	-21.3300	110.4817	5060	Sonne B8	A1979/26	Quaternary	Clay	S6790026
054GC007	SO8-SL45	-17.2133	115.3267	3210	Sonne B8	A1979/26	Quaternary	Mud	S6790026
054GC008	SO8-SL94	-20.3083	112.9433	815	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054GC009	SO8-SL103	-20.2600	114.5367	1075	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054GC011	SO8-SL108	-20.9333	114.3333	498	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054GC013	SO8-SL119	-21.1233	112.7733	1493	Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054GC016	SO8-SL138	-21.6183	112.5317	4017	Sonne B8	A1979/26	Quaternary + ? Mesozoic	Ooze + mudstone	S6790026
054GC017	SO8-SL142	-21.4600	112.5083	2798	Sonne B8	A1979/26	Quaternary + M. Oligocene	Ooze + Oligo. chalk	S6790026
054GC018	SO8-SL144	-21.3633	112.5583	2330	Sonne B8	A1979/26	M. Miocene	Chalk	S6790026
054GC019	SO8-SL146	-21.2583	110.5017	5060	Sonne B8	A1979/26	Quaternary	Clay	S6790026

054TC002	SO8-KAL67	-16.9350	115.1917	1600		Sonne B8	A1979/26	Quaternary	Globigerina ooze	S6790026
054TC003	SO8-KAL106	-20.7583	114.0400	1027		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC003	SO8-KL52	-17.0517	115.3800	1795		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC004	SO8-KL55	-17.0667	115.3817	1860		Sonne B8	A1979/26	Quaternary	Foram ooze	S6790026
054PC005	SO8-KL59	-16.9500	115.5733	2105		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC006	SO8-KL64	-16.6033	115.2333	2600		Sonne B8	A1979/26	E. Miocene – Eocene to Oligocene, Quaternary	Quart. sand + Oligo. – Mio. chalk	S6790026
054PC007	SO8-KL70	-18.5383	112.3367	3190		Sonne B8	A1979/26	Quaternary	Sand	S6790026
054PC008	SO8-KL74	-18.3450	112.4567	2840		Sonne B8	A1979/26	Quaternary	Sand	S6790026
054PC009	SO8-KL76	-18.4333	112.4300	3100		Sonne B8	A1979/26	M. Miocene	Ooze	S6790026
054PC010	SO8-KL78	-18.3250	112.4333	3860		Sonne B8	A1979/26	E. Miocene	Ooze	S6790026
054PC011	SO8-KL79	-18.4450	112.4267	3070		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC012	SO8-KL122	-20.9367	111.7050	2065		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC013	SO8-KL124	-21.0550	111.8383	2170		Sonne B8	A1979/26	Quaternary	Ooze	S6790026
054PC014	SO8-KL132	-21.1433	112.3000	1715		Sonne B8	A1979/26	M. Miocene	Sand	S6790026
054PC016	SO8-KL156	-21.8883	109.2350	4780		Sonne B8	A1979/26	E. Paleocene/Eocene	Clay	S6790026
054PC017	SO8-KL158	-21.8833	109.2367	4845		Sonne B8	A1979/26	? Quaternary	Clay	S6790026
054DR014	SO8-KD43	-17.1100	115.2133	2600	1800	Sonne B8	A1979/26	? Jurassic	Quartz calcarenite	S6790026
054DR015	SO8-KD46	-17.1167	115.3167	3140	2710	Sonne B8	A1979/26	? Jurassic	Siltstone	S6790026
054DR017	SO8-KD48	-17.1083	115.3200	2710	1850	Sonne B8	A1979/26	? Jurassic	Siltstone	S6790026
054DR018	SO8-KD49	-17.1233	115.3617	3280	2520	Sonne B8	A1979/26	? Jurassic	Biosparite	S6790026
054DR020	SO8-KD51	-17.0967	115.3883	2190	1910	Sonne B8	A1979/26	? Cretaceous	Mudstone	S6790026
054DR024	SO8-KD57	-17.0867	115.5100	3200	2800	Sonne B8	A1979/26	? Jurassic	Shale	S6790026
054DR026	SO8-KD61	-16.4783	115.2400	4800	4260	Sonne B8	A1979/26	E. Jurassic (Sinemurian)	Sandstone	S6790026
054DR027	SO8-KD62	-16.5700	115.2367	3110	2580	Sonne B8	A1979/26	E. Jurassic	Biocalcarenite	S6790026
054DR028	SO8-KD63	-16.5867	115.2567	2960	2620	Sonne B8	A1979/26	? Jurassic	Volcanics – amygdaloidal basalt, andesite, breccia	S6790026
054DR029	SO8-KD65	-16.5567	115.2383	3510	3040	Sonne B8	A1979/26	? Jurassic + ? Cretaceous	Basalt + limestone	S6790026
054DR030	SO8-KD66	-16.5700	115.1717	3120	2490	Sonne B8	A1979/26	? Jurassic	Volcanics	S6790026
054DR034	SO8-KD72	-18.4233	112.3633	3920	3450	Sonne B8	A1979/26	Albian	Chalk	S6790026
054DR035	SO8-KD73	-18.4383	112.4267	3050	2690	Sonne B8	A1979/26	? Cretaceous	Carbonate	S6790026
054DR041	SO8-KD131	-21.3400	111.8667	4415	3770	Sonne B8	A1979/26	? Triassic or Jurassic	Sandstone	S6790026
054DR045	SO8-KD147	-21.2100	110.5150	5060	5060	Sonne B8	A1979/26	Tertiary/Quaternary	Marl	S6790026
054DR046	SO8-KD148	-20.9733	110.5583	4875	4540	Sonne B8	A1979/26	? E. Cretaceous	Volcanics + clst. + Quart. Mn nodules	S6790026
054DR047	SO8-KD149	-21.4150	110.3083	4930	4920	Sonne B8	A1979/26	? E. Cretaceous	Volcaniclastic breccia	S6790026

054DR051	SO8-KD155	-21.8667	109.2700	5060	4830	Sonne B8	A1979/26	? E. Cretaceous	? Basalt + volcaniclastic breccia	S6790026
054KD159	SO8-KD159	-21.3917	109.7183	4470	4130	Sonne B8	A1979/26		Volcanics	

References:

Ship, Agency, survey	Report, ref.	Author	Title
Rig Seismic AGSO 96	AGSO 1990/85	Colwell, J.B., Graham, T.L. et al,	Stratigraphy of Australia's NW Continental Margin. Post-cruise Report...
Rig Seismic AGSO 95	AGSO 1990/57	Exon, N.F., and Ramsay, D.C.,	Postcruise Report. Triassic and Jurassic sequences of the northern ...
Rig Seismic AGSO 56	BMR 1988/30	Exon, N.F., Williamson, P.E.	Preliminary Postcruise Report, Rig Seismic Research Cruises 7 & 8.
Espirito Santo AGSO	AGSO 1970/27	Jones, H.A.	The Sediments, Structure, and Morphology of the Northwest Australian...
Sonne BGR 8	AGSO1979/26	Exon, N.	Preliminary Deep Sea Sampling Results, R.V. Sonne geological cruises...

APPENDIX 4: HEAT-FLOW DATA

The data in this table have been extracted from Swift (1990). Stations shown in italics are considered to be dubious.

Station	***Latitude***	***Longitude***	***Water depth*** *(m)*	***Temp. grad.*** *(°C/km)*	***Heat-flow*** *(mW/m²)*	***Bottom temp.*** *°C*
53HF-1	-19.906630	114.969080	1162	0.095	67.8	4.314
53HF-2	-20.055960	114.834810	1149	0.091	65.0	4.453
53HF-3	-20.006450	114.760200	1236	0.093	65.3	4.225
53HF-4	-19.887330	114.570130	1276	0.079	55.6	4.066
53HF-5	-19.808050	114.482500	1328	0.111	78.5	3.876
53HF-6	-19.712610	114.326360	1353	0.090	72.2	3.891
53HF-7	-19.689130	114.179900	1255	0.131	66.6	3.995
53HF-8	-19.682210	114.007730	1251	0.081	64.5	4.208
53HF-9	-19.553830	113.886060	1139	0.050	39.2	4.529
53HF-10	-19.557810	113.782880	1175	0.043	33.1	4.400
53HF-11	-19.642680	113.673330	1098	0.037	30.9	4.600
53HF-12	-19.587960	113.513000	947	0.038	31.8	5.234
53HF-13	-19.498230	113.354800	922	0.035	29.2	5.269
53HF-14	-19.410650	113.231600	980	0.025	20.6	4.971
53HF-15	-19.331800	113.107380	1266	0.071	56.9	4.078
53HF-16	-19.241960	112.986780	1490	0.083	68.3	3.394
53HF-17	-19.128600	112.854430	1671	0.062	46.2	0.062
53HF-18	-19.066880	112.740710	2000	0.060	45.2	2.377
53HF-19	-18.888830	112.625950	2257	0.041	33.2	2.214
53HF-19BT	-18.887860	112.616250	2223	0.055	44.0	2.211
53HF-20	-18.885800	112.534050	2220			2.137
53HF-21	-18.876210	112.465030	2218			2.115
53HF-22	-19.534660	113.212150	935	0.038	30.9	5.189
53HF-23	-19.633580	113.154960	940	0.070	56.4	5.111
53HF-24	-19.733130	113.092050	952	0.062	51.4	5.048
53HF-25	-19.832900	113.034560	947	0.075	60.7	5.109
53HF-26	-19.988880	112.935150	943	0.123	102.7	4.909
53HF-27	-20.088880	112.868030	909	0.121	98.0	5.200
53HF-28	*-20.199830*	*112.797510*	*848*	*0.222*	*183.7*	*5.160*
53HF-29	-20.289660	112.735860	852	0.048	40.2	5.200
53HF-30	-20.398560	112.666130	875			5.302
53HF-31	-20.498110	112.577450	953	0.081	65.1	5.088
53HF-32	-20.590130	112.525250	1103	0.079	66.7	4.619
53HF-33	-20.706210	112.448510	1264	0.061	50.7	4.016
53HF-34	-20.800660	112.397610	1426	0.051	42.3	3.489

Station	*Latitude*	*Longitude*	*Water depth (m)*	*Temp. grad. (^{o}C/km)*	*Heat-flow (mW/m^2)*	*Bottom temp. ^{o}C*
53HF-35	-20.887480	112.337710	1427	0.066	54.1	3.408
53HF-36	-21.020100	112.263010	1541	0.115	94.4	2.999
53HF-37	-20.993860	112.074360	1270			3.850
53HF-38	-21.089330	112.008100	1780			2.736
53HF-39	-21.670780	111.645180	5053	0.053	44.0	1.240
56HF-1	-19.591660	113.536660	1100	0.023	19.2	5.150
FRHF-1	-19.806500	115.050660	1186	0.108	77.5	4.922
FRHF-2	-19.907660	114.969500	1165	0.099	70.7	4.963
FRHF-3	-19.521830	114.702660	1458	0.068	54.7	4.208
FRHF-4	-19.121500	114.147160	1312	0.091	66.2	4.583
FRHF-5	-18.967660	113.883160	1386	0.099	72.9	4.242
FRHF-6	-18.844500	113.676160	1425	0.063	48.8	4.207
FRHF-7	-18.709500	113.464330	1348	0.077	59.4	4.363
FRHF-8	-19.033660	113.353830	1152	0.058	45.8	5.168
FRHF-9	-19.121830	113.487330	1048	0.042	33.5	5.406
FRHF-10	-19.285660	113.710660	1283	0.073	59.3	4.862
FRHF-11	-19.467000	113.972830	1153	0.037	28.7	5.068
FRHF-12	-19.606500	114.181000	1315	0.076	60.7	4.889
FRHF-13	-19.548500	113.887000	1144	0.051	40.3	5.127
FRHF-14	-19.787330	113.807500	1173	0.087	69.0	4.958
FRHF-15	-20.138000	114.310330	1260	0.104	72.6	4.720
FRHF-16	-20.372500	114.657330	972	0.110	81.3	5.000
FRHF-17	-20.524330	114.521330	861	0.115	82.9	6.224
FRHF-18	-20.736000	114.421330	748	0.126	91.9	6.651
FRHF-19	-20.400660	114.058500	1144	0.100	73.9	4.409
FRHF-20	-20.132000	113.639000	1094	0.042	34.9	4.577
FRHF-21	-19.937500	113.364330	963	0.039	32.6	5.028
FRHF-22	-19.881500	113.143160	910	0.062	51.9	5.048
FRHF-23	-19.830660	113.034660	940	0.070	58.5	5.743
FRHF-24	-19.633660	112.933500	1150	0.040	33.4	5.211
FRHF-25	-19.521810	112.763810	1430			4.379
FRHF-25BT	-19.531500	112.787830	1448	0.071	52.4	3.676
FRHF-26	-19.668830	112.338000	1510	0.026	21.3	3.424
FRHF-27	-19.780330	112.510660	1358	0.076	63.3	4.474
FRHF-28	-19.896330	112.680330	1186	0.070	59.3	5.036
FRHF-29	-20.091500	112.866000	926	0.045	37.3	5.158
FRHF-30	-20.254660	113.189830	909	0.046	38.2	5.329
FRHF-31	-20.461830	113.479160	1043	0.074	61.4	4.788
FRHF-31BT	-20.599660	113.688330	1136	0.062	46.7	4.467

Station	***Latitude***	***Longitude***	***Water depth (m)***	***Temp. grad. (°C/km)***	***Heat-flow (mW/m²)***	***Bottom temp. °C***
FRHF-32	-20.685160	113.884830	1100	0.073	56.0	4.591
FRHF-33	-20.939660	114.184800	646	0.084	63.9	6.168
FRHF-34	-21.230000	113.965660	716	0.078	59.4	6.160
FRHF-35	-21.121000	113.613830	1198	0.102	79.1	4.922
FRHF-36	-20.784660	113.308330	1100	0.051	39.9	5.231
FRHF-37	-20.580330	113.007830	955	0.047	65.5	5.117
FRHF-38	-20.349660	112.965830	980	0.102	78.4	5.056
FRHF-39	-20.287160	112.736330	855	0.070	51.8	6.143
FRHF-40	-20.185000	112.444500	1003	0.078	65.3	5.567
FRHF-41	-20.042660	112.238500	1275	0.108	83.7	4.034
FRHF-42	-19.897500	112.230330	1425	0.088	71.5	5.902
FRHF-43	-20.312660	111.971500	1482	0.064	48.7	4.125
FRHF-44	-20.474160	112.209500	1357	0.050	38.8	3.863
FRHF-45	-20.570160	112.186660	1378	0.055	41.4	4.391
FRHF-46	-20.688160	112.448660	1265	0.041	34.8	4.135
FRHF-47	-20.871660	112.700330	1136	0.062	49.1	4.552
FRHF-48	-20.902500	112.837500	1103	0.054	41.7	5.708
FRHF-49	-21.110830	113.141160	1257	0.070	55.3	4.885
FRHF-50	-21.331500	113.474330	1300	0.069	53.2	4.623
FRHF-51	-21.279330	113.686000	1115	0.101	77.8	5.699
FRHF-52	-21.510830	113.737830	976	0.117	90.1	5.753
FRHF-53	-21.804330	113.503830	1230	0.098	69.2	4.877
FRHF-54	-21.440000	112.969000	1602			3.878
FRHF-55	*-21.442330*	*112.656330*	*1882*	*0.001*	*0.8*	*3.441*
FRHF-56	*-21.011660*	*112.259000*	*1538*	*0.016*	*13.1*	*4.068*
FRHF-57	-20.758160	111.975000	1446			4.375
MSN-17	-12.800000	115.400000	5400	0.064	44.0	
MSN-20	-13.316600	109.566600	4630	0.080	62.0	
LSDA-37	-14.933300	108.150000	5580	0.068	48.2	
LSDA-38	-13.766600	115.533300	5680	0.069	47.7	
LSDH-44	-14.933300	107.266600	5805	0.079	57.4	
LSDH-45	-14.966600	109.200000	5630	0.065	47.3	
LSDH-46	-14.216600	114.900000	5670	0.063	42.7	
LSDH-47	-13.150000	116.483300	5670	0.069	46.5	
LSDH-48	-13.683300	117.383300	5715	0.580	39.4	
V20-145	-14.600000	116.316600	5680	0.052	38.9	
V20-146	-15.100000	114.383300	5660	0.046	34.8	
V20-147	-16.183300	110.283300	5670	0.061	45.6	
V24/155	-13.483300	110.433300	5354	0.067	51.1	1.390

Station	***Latitude***	***Longitude***	***Water depth** (m)*	***Temp. grad.** (°C/km)*	***Heat-flow** (mW/m²)*	***Bottom temp.** °C*
V24/156	-16.033300	108.133300	5376	0.063	52.3	1.400
CC-1	-17.616600	115.200000			45.2	
CC-2	-15.766600	114.716600			54.8	
CC-3	-16.100000	110.466600			54.8	
CC-4	-18.300000	109.250000			38.5	
CC-5	-19.066600	112.750000			61.1	
CC-6	-19.166600	110.000000			50.2	
CC-7	-18.066600	112.916600			72.0	
CC-8	-16.500000	116.750000			96.3	
CC-9	-15.716600	112.400000			41.5	
CC-10	-21.666600	115.083300			121.1	
CC-11	-21.716600	114.750000			118.3	
CC-12	-21.650000	114.350000			112.8	
CC-13	-22.450000	113.583300			81.4	
CC-14	-21.600000	114.500000			77.2	
CC-15	-20.816600	115.333300			72.6	
CC-16	-20.816600	115.366600			69.0	
CC-18	-21.833300	115.066600			63.5	
CC-19	-21.716600	114.533300			56.5	
CC-20	-21.583300	114.216600			77.2	
CC-21	-21.533300	114.420000			74.0	

APPENDIX 5: INTERPRETED SEISMIC HORIZONS

Seismic Horizon	***Description***
olig	Oligocene
cret	top Cretaceous
tur	Turonian; base carbonate section
val	Valanginian; Cuvier-Gascoyne breakup
call	Callovian; Argo breakup
tr	top Triassic
pz	near top Permian
xtal	crystalline continental basement
tran	top transparent continental crust
tlcb	top laminated deep continental crust
blcb	base laminated deep continental crust
c2	deep crustal reflector beneath Exmouth Plateau
intr	intrusions in continental crust (sub-vertical)
sill	sills in continental crust (sub-horizontal)
icc	strongly intruded ?continental crust
civc	composite intact volcano; ?continental crust
cvvm	composite volcanics on ?oceanic and volcanic margin crust
cvb	areally extensive, low-relief volcanic buildup
tdeb	top debris flows
slop	slope volcanics
tsdr	top Seaward Dipping Reflector Sequence (SDRS)
bsdr	base Seaward Dipping Reflector Sequence (SDRS)
flow	volcanic flows overlying sediments on continental crust
udif	inter-SDRS volcanic buildup
buil	volcanic buildups; oceanic setting; no associated SDRS
tobs	top smooth ?oceanic and volcanic margin basement
tobl	top layered ?oceanic and volcanic margin basement
tobr	top rough ?oceanic and volcanic margin basement
oflo	flows/sills above oceanic basement

tlam	top reflective oceanic crust
tiv	volcanics extruded along transform faults
moho	Moho

APPENDIX 6: VELOCITY ANALYSES

Locations

Sonobuoys

Station	*Latitude*	*Longitude*
57	-14.950000	108.150000
58	-13.783333	115.550000
59	-13.516667	118.433333

Expanding-Seismic Profiles (ESP)

Station	*Latitude*	*Longitude*	*Nearest reflection seismic line*
C1	-20.336667	112.667500	135/11, SP 15400, offset 7 km
C2	-20.558333	112.283333	135/11, SP 14500, offset 5 km
C2A	-20.675000	112.041667	135/11, SP 13950
C3	-20.791667	111.783333	135/11, SP 13350, offset 5 km
C4	-21.258333	111.304167	135/11, SP 11900
E1	-19.916667	116.125000	101R/9, SP 2950, offset 12 km
E2	-19.793333	115.560833	101R/8, SP 2080, offset 4 km
E3	-19.610833	114.580000	110/9, SP 2050, offset 8 km
E4	-19.387500	114.006667	110/9, SP 650, offset 3 km
E5	-19.512500	113.336667	110/15, SP 850, offset 5 km
E6	-19.536667	112.526667	110/15, SP 2400, offset 50 km
E7	-19.195000	112.058333	162/2, SP 9250, offset 4 km
E8	-18.798333	111.596667	162/2, SP 7600, offset 12 km
E9	-18.355833	111.083333	162/1, SP 4400, offset 20 km
			110/15, SP 6200, offset 20 km
E9A	-18.166667	111.450000	162/1, SP 3600, offset 12 km
			110/15, SP 5800, offset 20 km

Ocean-Bottom Seismometers

Station	*Latitude*	*Longitude*	*Reflection seismic line*
168/1	-17.221500	112.000000	128/8, SP 1000
168/2	-17.402600	112.326400	128/8, SP 1800
168/3	-17.545100	112.583000	128/8, SP 2430
168/4	-17.719500	112.897400	128/8, SP 3200
168/5	-17.843400	113.124200	128/8, SP 3755
168/6	-17.894700	113.215100	128/8, SP 3980
168/7	-17.945200	113.306100	128/8, SP 4200
168/8	-18.125500	113.633100	128/8, SP 5000
168/9	-18.307900	113.960600	128/8, SP 5800
168/10	-18.488500	114.288600	128/8, SP 6600
168/11	-18.669300	114.617100	128/8, SP 7400
168/12	-18.853200	114.945600	128/8, SP 8205

Station	*Latitude*	*Longitude*	*Reflection seismic line*
168/13	-18.570700	115.638900	N211, SP 60725
168/14	-18.774900	115.827400	N211, SP 60140
168/15	-18.976200	116.025200	101R/10, SP 3550
168/16	-19.130200	116.169300	101R/10, SP 3100
168/17	-19.334100	116.369500	101R/10, SP 2500
168/18	-19.528700	116.570900	101R/10, SP 1900
168/19	-19.623400	116.676500	101R/10, SP 1590
168/20	-19.711000	116.777400	101R/10, SP 1300
168/21	-19.889200	116.989100	101R/10, SP 700
168/22	-20.071700	117.199100	101R/10, SP 103

Velocity Analyses

Sonobuoy 57

Vel. (km.s^{-1})	*Depth (km)*
1.5	0
1.5	-5.59
2.15*	-5.59
2.15*	-5.86
5.38	-5.86
5.38	-7.16
6.51	-7.16
6.51	-11.66
8.28	-11.66

* assumed velocity

Sonobuoy 58

Vel. (km.s^{-1})	*Depth (km)*
1.5	0
1.5	-5.68
2.15*	-5.68
2.15*	-6.13
5.18	-6.13
5.18	-8.53
7.0	-8.53
7.0	-14.63
8.23	-14.63

* assumed velocity

Sonobuoy 59

Vel. (km.s^{-1})	*Depth (km)*
1.5	0
1.5	-5.67
2.15*	-5.67
2.15*	-6.23
4.89*	-6.23
4.89*	-7.03
6.61	-7.03
6.61	-14.03
8.09	-14.03

* assumed velocity

C1

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-0.9	1.2
3.6	-2.7	2.61
3.8	-3.0	2.77
4.1	-3.2	2.87
4.1	-4.2	3.36
4.5	-4.5	3.5
4.8	-5.7	4.02

C2

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-1.2	1.6
3.5	-3.0	3.04
3.9	-3.7	3.42
4.2	-4.2	3.67
4.2	-7.5	5.24
4.8	-7.5	5.24

C2A

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-1.3	1.73
1.8	-1.7	2.21
2.0	-1.9	2.42
2.3	-2.4	2.89
2.9	-2.7	3.12
3.4	-3.3	3.5
3.5	-3.6	3.67
3.8	-3.7	3.72
4.2	-4.3	4.02
4.5	-4.7	4.2

C3

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-1.5	2.0
2.0	-1.5	2.0
2.7	-2.3	2.68
3.1	-3.1	3.23
3.7	-3.3	3.35
4.1	-3.8	3.61
4.4	-4.5	3.94
4.8	-5.1	4.20
5.0	-9.8	6.12
5.4	-9.8	6.12
5.4	-16.8	8.71
7.0	-16.8	8.71
7.0	-26.8	11.57
8.0	-26.8	11.57

E4

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-1.2	1.6
2.4	-1.2	1.6
2.4	-1.92	2.2
3.0	-1.92	2.2
3.0	-2.82	2.8
3.5	-2.82	2.8
4.8	-5.1	3.9
4.8	-5.58	4.1
5.2	-5.58	4.1
5.2	-15.2	7.8
6.1	-15.2	7.8
6.1	-21.0	9.7
7.1	-21.0	9.7

C4

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-5.0	6.67
2.0	-5.6	7.27
3.2	-5.6	7.27
4.9	-6.3	7.62
5.0	-6.9	7.86
5.2	-7.1	7.94
5.3	-8.1	8.32
6.1	-8.7	8.53
6.7	-10.0	8.94
6.8	-12.2	9.59
8.3	-13.6	9.96

E5

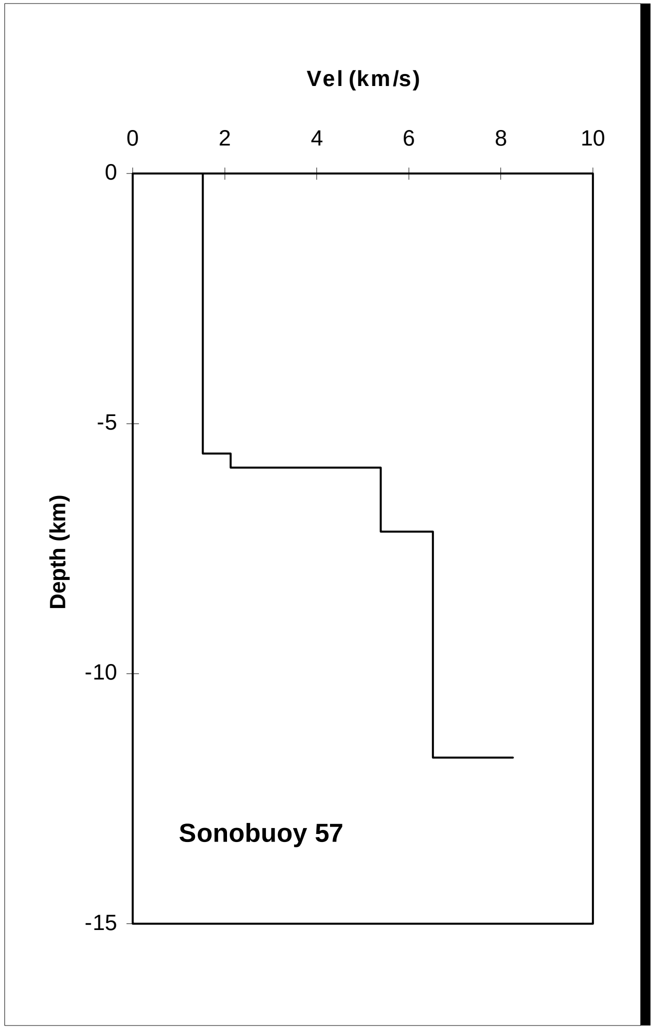
Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-0.98	1.3
2.2	-0.98	1.3
2.2	-1.64	1.9
2.6	-1.64	1.9
2.6	-2.29	2.4
3.0	-2.29	2.4
4.6	-4.57	3.6
4.9	-7.18	4.7
4.6	-7.18	4.7
4.6	-7.87	5.0
4.8	-7.87	5.0
4.8	-8.59	5.3
4.3	-8.59	5.3
4.3	-9.88	5.9
6.2	-9.88	5.9
6.2	-20.42	9.3
6.8	-20.42	9.3
6.8	-22.12	9.8
8.1	-22.12	9.8

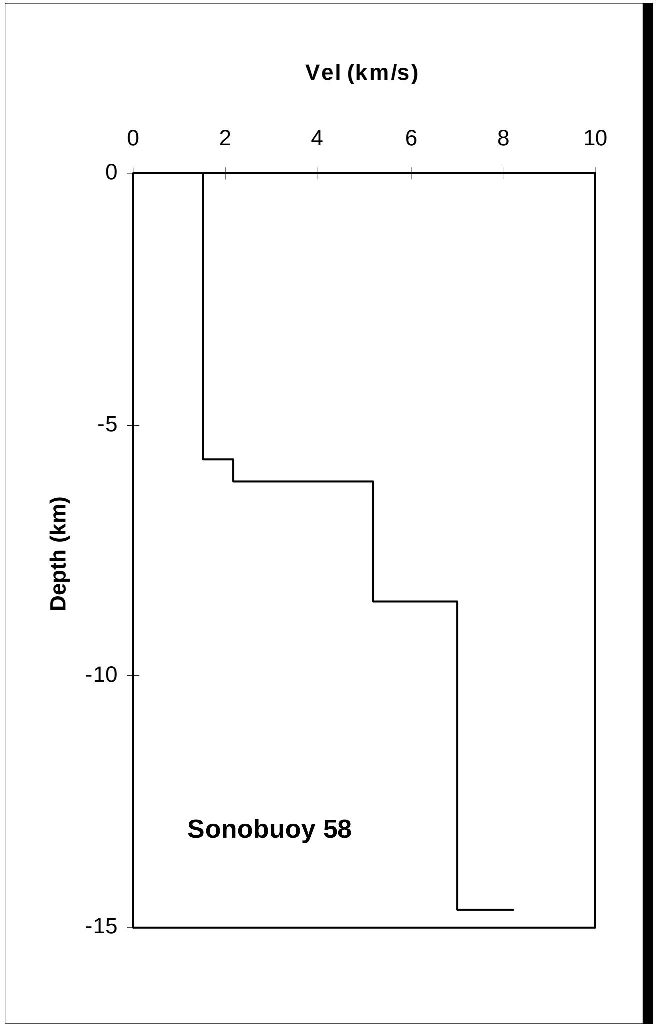
E6

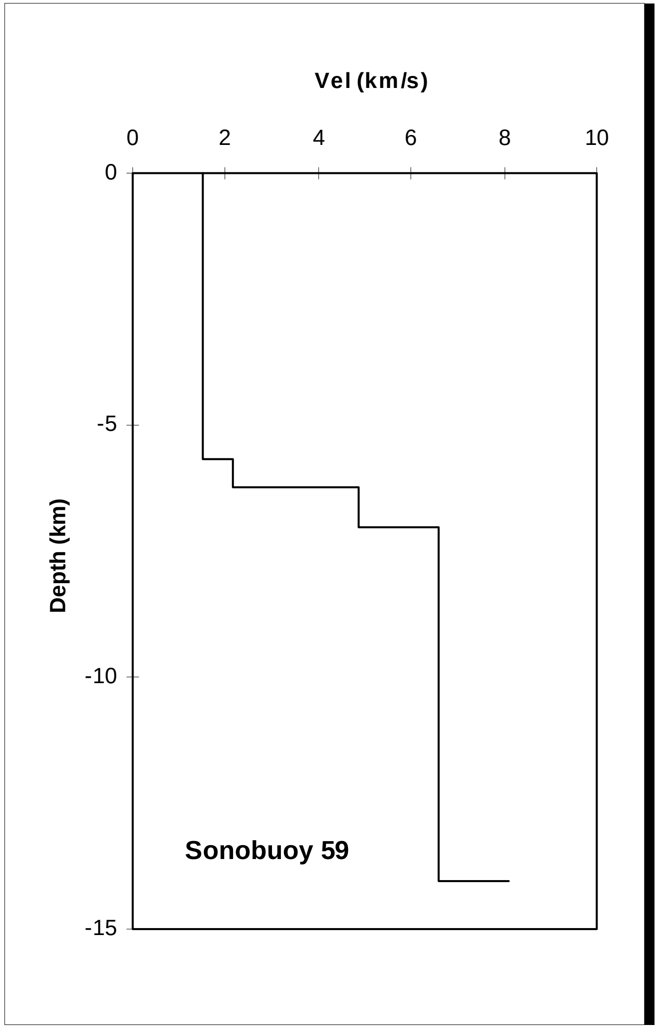
Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-1.54	2.05
1.6	-1.54	2.05
1.6	-1.58	2.1
2.1	-1.67	2.2
2.1	-1.99	2.5
2.4	-1.99	2.5
2.4	-2.35	2.8
2.5	-2.35	2.8
2.5	-2.73	3.1
2.8	-2.73	3.1
4.5	-4.74	4.2
4.9	-4.74	4.2
4.9	-11.6	7.0
5.9	-11.6	7.0
5.9	-19.57	9.7
7.1	-19.57	9.7
7.6	-21.41	10.2
8.1	-21.41	10.2

E7

Vel. (km.s^{-1})	*Depth (km)*	*TWT (s)*
1.5	0	0
1.5	-2.4	3.2
1.6	-2.48	3.3
1.9	-2.48	3.3
1.9	-2.67	3.5
2.4	-2.67	3.5
2.4	-3.03	3.8
2.5	-3.03	3.8
2.5	-3.41	4.1
3.7	-4.34	4.7
4.1	-4.34	4.7
4.6	-5.65	5.3
5.0	-5.89	5.4
5.0	-11.89	7.8
5.8	-11.89	7.8
5.8	-17.69	9.8
6.2	-17.69	9.8
6.2	-19.24	10.3
7.3	-19.24	10.3
7.3	-22.89	11.3
8.2	-22.89	11.3


Vel (km/s)
0
2
4
6
8
10
0
-5
-10
-15
Depth (km)
Sonobuoy 57


Vel (km/s)
0
2
4
6
8
10
0
-5
-10
-15
Depth (km)
Sonobuoy 58


Vel (km/s)
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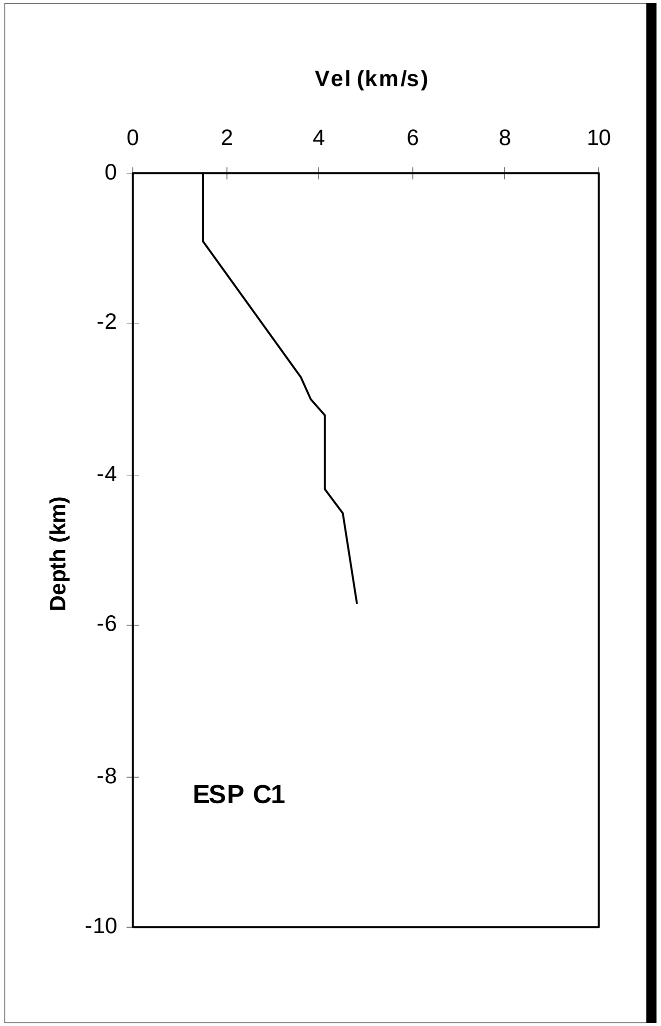
2
4
6
8
10
0
-5
-10
-15
Depth (km)
Sonobuoy 59


Vel (km/s)
0
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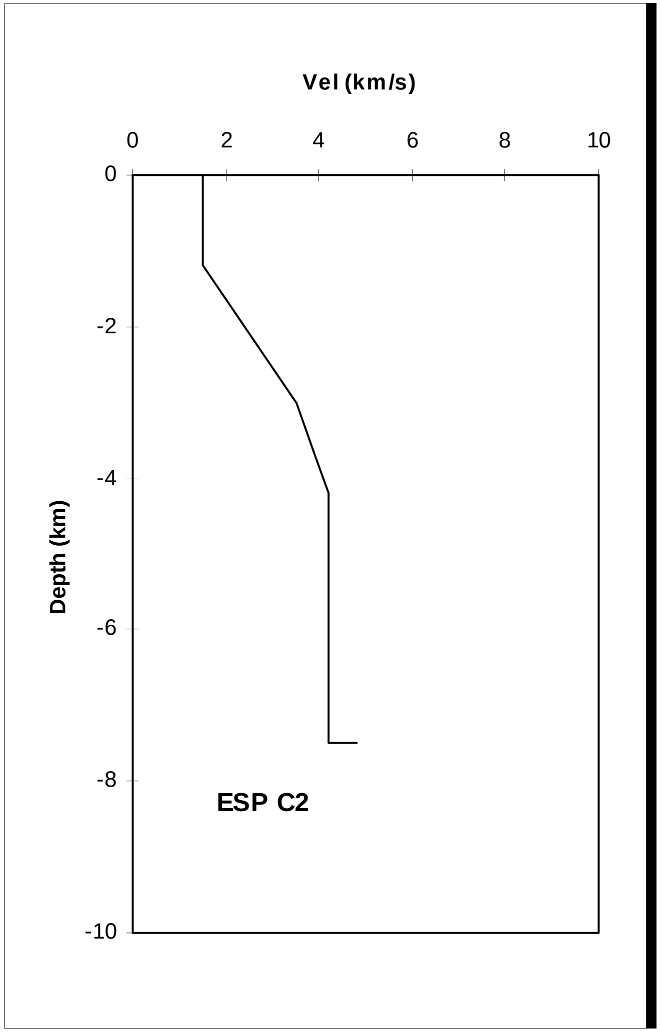
4
6
8
10
0
-2
-4
-6
-8
-10
Depth (km)
ESP C1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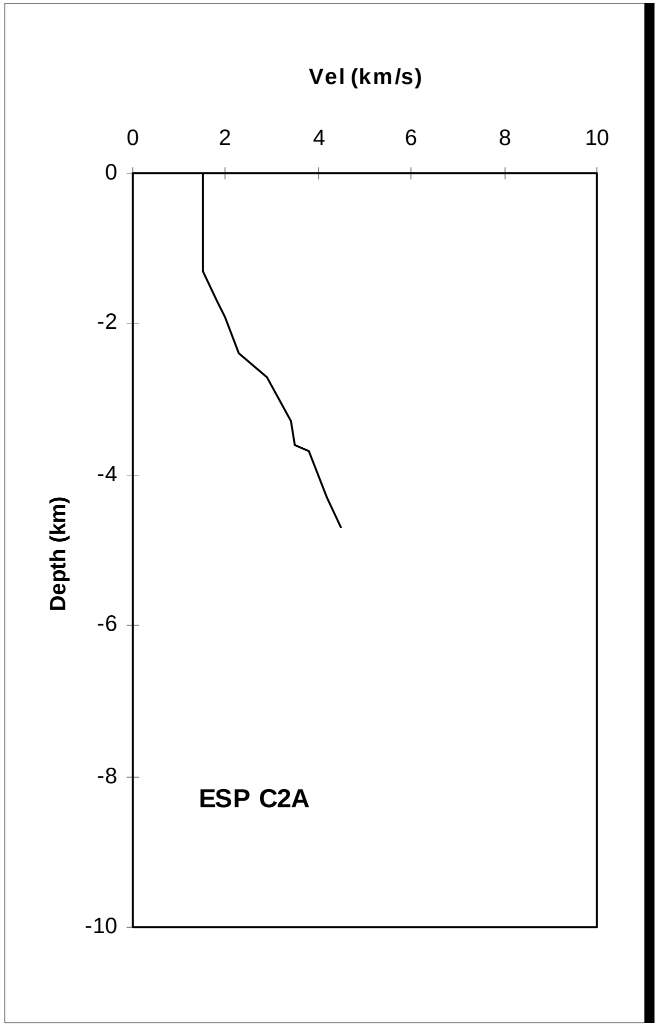
-2
-4
-6
-8
-10
Depth (km)
ESP C2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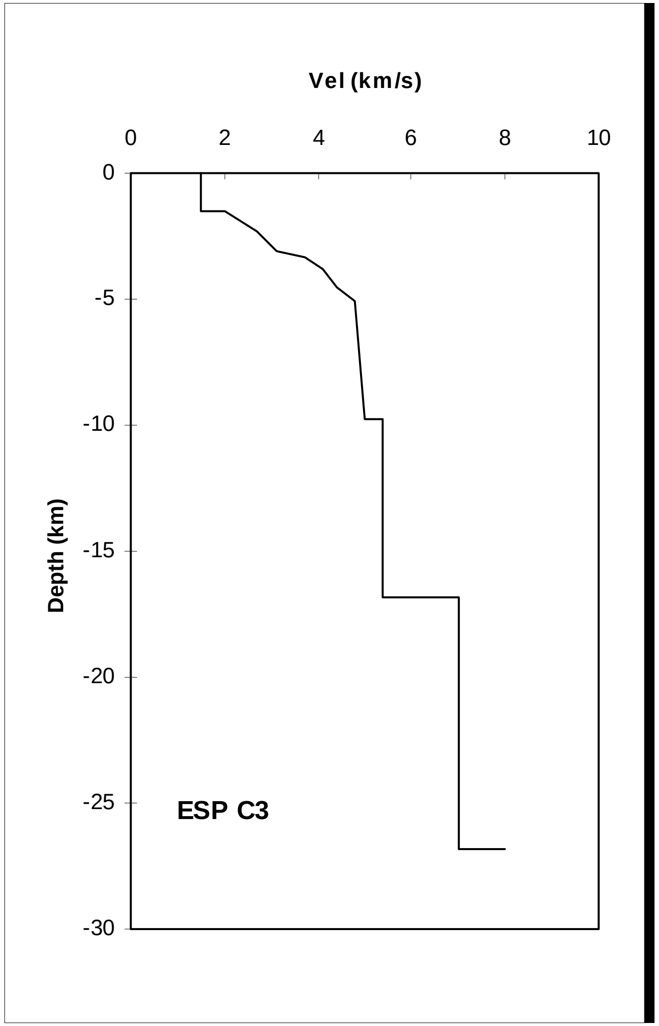
6
8
10
0
-2
-4
-6
-8
-10
Depth (km)
ESP C2A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10
Depth (km)
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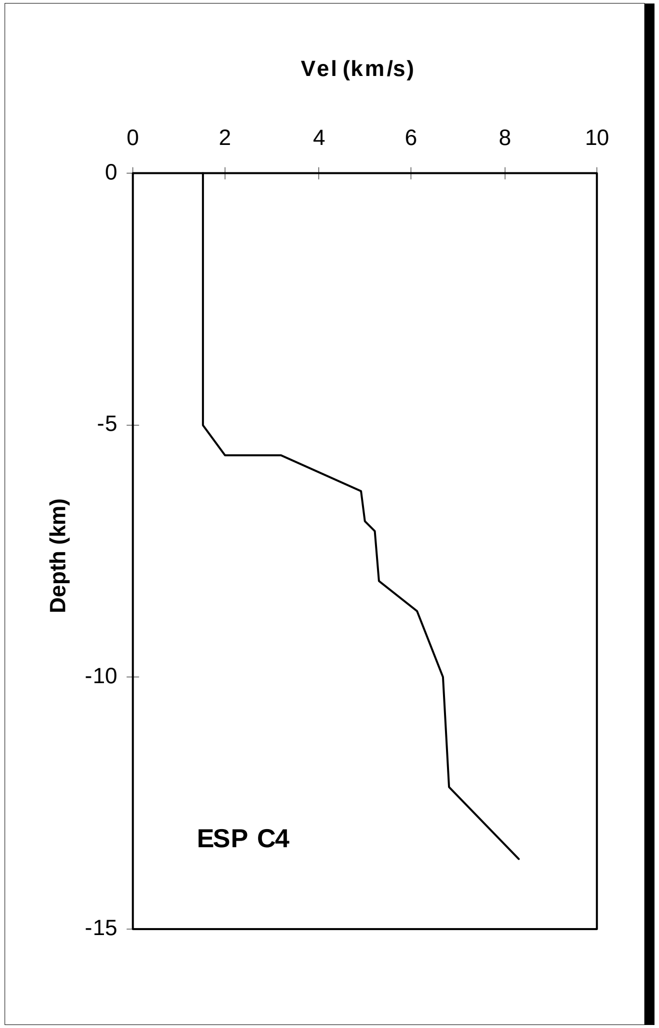
-10
-15
-20
-25
-30
ESP C3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2
4
6
8
10
Depth (km)
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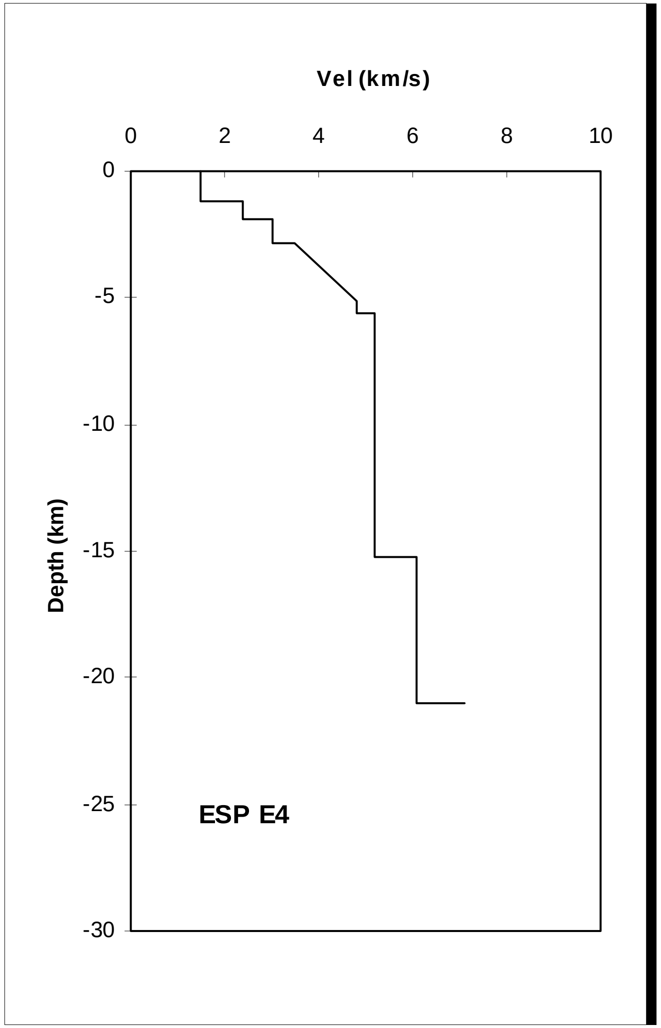
-5
-10
-15
ESP C4


Vel (km/s)
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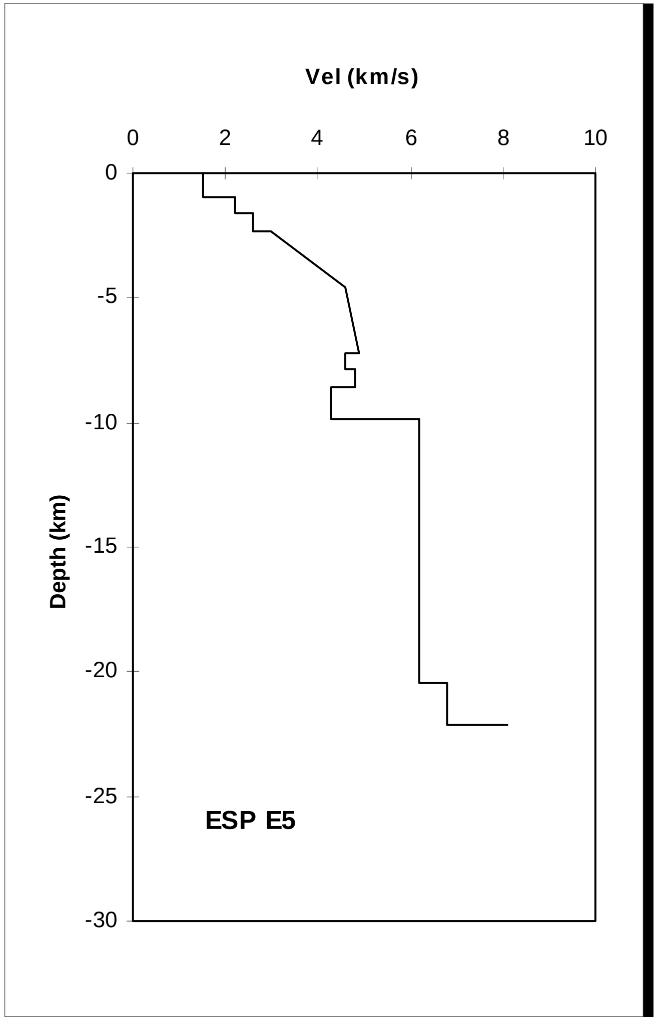
4
6
8
10
0
-5
-10
-15
-20
-25
-30
Depth (km)
ESP E4


Vel (km/s)
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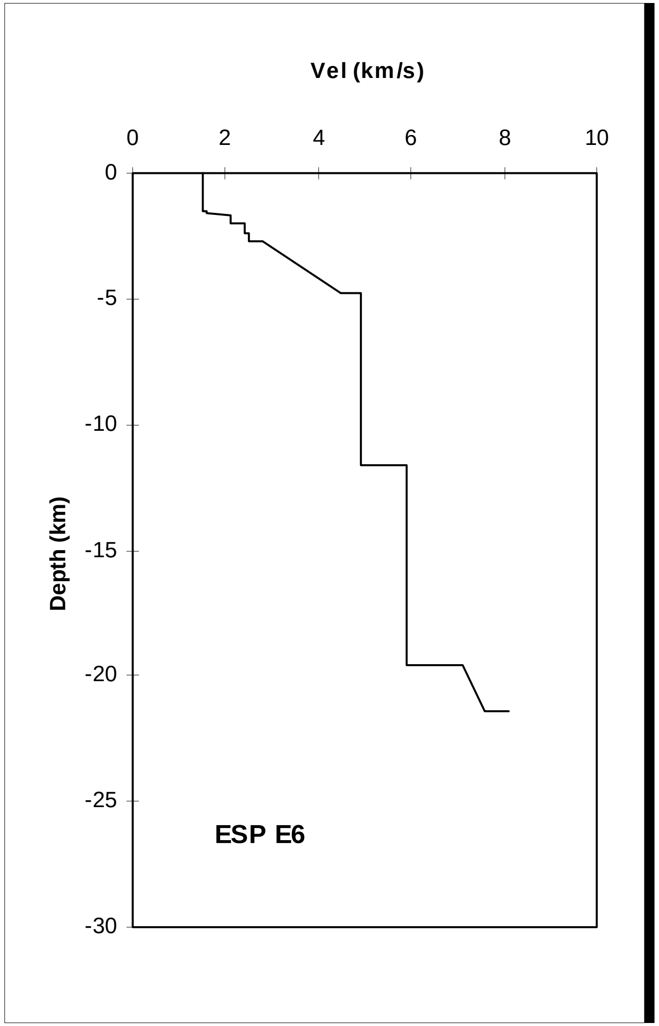
4
6
8
10
0
-5
-10
-15
-20
-25
-30
Depth (km)
ESP E5


Vel (km/s)
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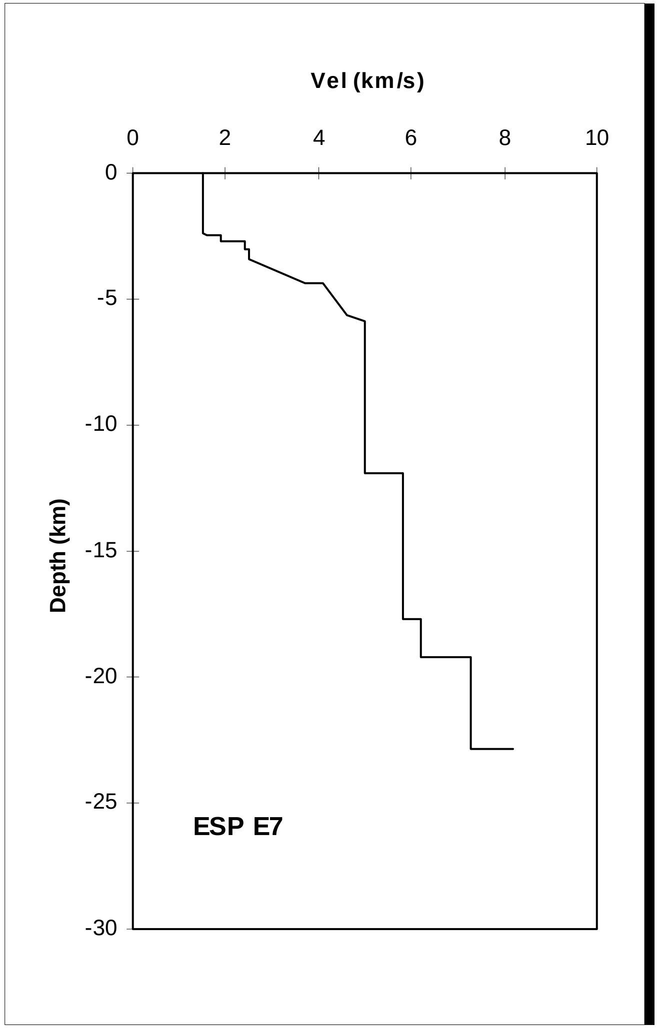
2
4
6
8
10
0
-5
-10
-15
-20
-25
-30
Depth (km)
ESP E6


Vel (km/s)
0
2
4
6
8
10
0
-5
-10
-15
-20
-25
-30
Depth (km)
ESP E7

APPENDIX 7: SOME UNRESOLVED QUESTIONS

General Distribution of Volcanics

- *Why are volcanics extruded along north side of the major transforms, whether those transforms are sinistral or dextral?*
- *What is the cause of the differences between the SDRS province of the southwest Exmouth Plateau and the more massive buildup province of the Platypus Spur and Joey Rise.?*

Seaward-Dipping Reflector Sequences

- *Why are SDRS distributed on the southeast Cuvier Abyssal Plain and on the Gascoyne margin of the Exmouth Plateau, but not on the margins of the Argo Abyssal Plain?.*
- *Are SDRS fault-controlled? Why do faults all dip landwards?*
- *What is the geometry of individual SDRS – are they linear wedges or overlapping fans, or both?*
- *Why are SDRS asymmetric – ie they are all oriented with the thickened side of the wedge oceanward?*
- *How are SDRS emplaced?*
- *What is the relative importance of tectonism and magmatism in SDRS emplacement?*
- *What is the origin of the volcanic buildups between adjacent SDRS? Are these buildups related to the emplacement of the SDRS, or do they post-date the SDRS?*
- *What is the temporal relationship between the SDRS and the large-relief volcanic ridges that incorporate SDRS off the southwest corner of the Exmouth Plateau?*

Magmatic/oceanic Crust

- *Why is Gascoyne oceanic crust 50-100% thicker than normal adjacent to the Exmouth Plateau?*
- *What is the distribution of highly-reflective deep oceanic crust and does it correlate with a smooth oceanic basement surface? Is the distribution related to seafloor spreading rates or to the volume of magma available?*

Exmouth Plateau Deep Crust

- *Exmouth Plateau margins are underlain by laminated deep crust with velocities >7 km.s^{-1}. Is the interpretation of the distribution of underplating and intruded lower crust correct? Are the different interpretations related to transform vs rifted margins?*
- *What is the cause of the deep crustal reflectors that can be traced beneath much of the Exmouth Plateau at depths of 8-10 s TWT; are they related to the thinning processes that caused the Northern Carnarvon Basin to form?*
- *How has crustal thinning operated beneath the Exmouth Plateau? How valid is the Driscoll & Karner (1998) model of an eastward-dipping detachment?*

- *Role of deep-thinning at Valanginian breakup– why has the whole plateau been thinned at this time and not just the outer edge?*
- *What is the origin of the strong E-W boundary beneath the northern Exmouth Plateau? What is the origin of the high-standing blocks along this margin (and also on the Scott Plateau margin)? Are these blocks related to isolated pods of underplating, to structural control by an underlying extension of the Canning Basin, or both?*
- *The appearance of the continent/volcanic margin - ocean boundary varies markedly between the different margins of the Exmouth Plateau. What can these variations tell us about the nature of the COB (or continent-ocean transition) on rifted and transform margins?*

Exmouth Plateau Sedimentary Section

- *While the distribution of the Mesozoic-Cainozoic sedimentary section on the Exmouth Plateau is well-documented, the origin and distribution of the thick Lower-Middle Jurassic sediments on the Cuvier and Argo margins of the plateau is not well-understood. What thinning process(es) produced the subsidence that led to the deposition of this sequence, and are there any implications for prospectivity?*
- *Fault trends in the Mesozoic section vary widely between the main Exmouth Plateau and the northern margin and are not obviously related to pre-breakup extension directions. How much control has the underlying Palaeozoic (and older) structural grain had on these trends?*
- *What is the impact of volcanic margin development on facies development and resource potential?*

LIST OF FIGURES

13. Stratigraphic table from Woodside Delambre-1, modified from company well completion report (after von Rad et al., 1992b).

14. BMR seismic profile 56/13 across the Wombat Plateau, with four ODP drill sites projected on to it (after Exon et al., 1992).

15. Composite lithological log for Wombat Plateau ODP Sites 759, 760, 761 and 764, showing maximum thicknesses of representative facies (after Exon & von Rad, 1994). Note the major unconformity separating Upper Triassic and Lower Cretaceous sediments.

16. Composite lithological log for ODP Site 762, and Esso Vinck-1 exploration well (near Site 763; after Exon & von Rad, 1994).

17. Lithological log for ODP Site 765 (after Dumoulin & Bown, 1992). Depths are metres below sea floor.

18. Lithological log for ODP Site 766 (after Exon & Buffler, 1992). Depths are metres below sea floor.

19. Type seismic section, line 162/01 – upper continental crust; transparent crust; intruded lower crust.

20. Type seismic section, line 110/12 – mid continental crust.

21. Type seismic section, line 135/11 – smooth oceanic basement; laminated deep oceanic crust; Moho.

22. Type seismic section, line 128/08 – sills in continental crust.

23. Type seismic section, line 135/01 – igneous intrusions in continental crust.

24. Type seismic section, line 162/11 – intruded continental crust.

25. Type seismic section, line 162/11 – intact volcano on continental crust.

26. Type seismic section, line 162/09 – intact volcano on probable oceanic crust.

27. Type seismic section, line 162/11 – composite volcanic buildup.

28. Type seismic section, line 128/08 – landward flows on continental crust.

29. Type seismic section, line 128/08 – slope volcanics.

30. Type seismic section, line 162/03 – seaward-dipping reflector sequence (SDRS).

31. Type seismic section, line 162/03 – inter-SDRS buildup.

32. Type seismic section, line 162/04 – oceanic volcanic buildup.

33. Type seismic section, line 162/06 – transform volcanics.

34. Type seismic section, line 128/06 – layered oceanic basement.

35. Interpretation of OBS line from the outer Exmouth Plateau (after Fomin et al., 2000). (a) Seismic velocity model from the OBS data; (b) seismic section along the coincident reflection seismic line depth-converted with OBS velocities; and (c) depth-converted with stacking velocities.

36. Seismic lines showing interpreted extended continental blocks underlying SDRS in the 'magmatic crust' province on the Gascoyne margin. (a) line 162/01, showing the outboard edge of unequivocal continental crust with interpreted fault blocks lying beyond the major bounding fault. (b) and (c) line 162/03, showing alternative interpretations of fault blocks of possible continental crust underlying SDRS.

37. Present-day heatflow on the Exmouth Plateau and adjacent ocean basins. Heatflow stations are shown as black dots. 0.2, 1, 3 and 5 km bathymetric contours are also shown.

38. Composite depth profile from the northern margin of the Pilbara Block, across the Dampier Sub-basin and Exmouth Plateau, to the Gascoyne Abyssal Plain. The model is derived from Geoscience Australia deep-seismic data, expanding-seismic profiles (Mutter et al., 1989), and the work of Drummond (1981) on the Pilbara Craton (after Stagg & Colwell, 1994).

39. Conceptual evolution of the North West Shelf basin system (after AGSO North West Shelf Study Group, 1994). (a) Late Devonian – Early Carboniferous. (b) Mid-Carboniferous – Early Permian. (c) Late Triassic – Early Jurassic.

40. Palaeogeographic sketch maps for eight periods in the development of the Exmouth Plateau and adjacent areas (after Exon et al., 1992). Drawn from information from ODP Sites, commercial exploration wells, dredges and seismic profiles. A. Carnian-Norian (Mungaroo Formation): palaeolatitude 50-55°S. B. Rhaetian: palaeolatitude 25-30°S. C. Hettangian-Sinemurian: palaeolatitude 35-40S°. D. Bathonian-Callovian: palaeolatitude 35-40°S. E. Late Oxfordian-Kimmeridgian: palaeolatitude 35-40°S. F. Berriasian-Valanginian (Barrow Group): palaeolatitude 33-38°S. G. Aptian (Muderong Shale: palaeolatitude 35-40°S. H. Albian (Gearle Siltstone & Haycock Marl): palaeolatitude 35-40°S. Declination was in the range 280-330°.

LIST OF PLATES

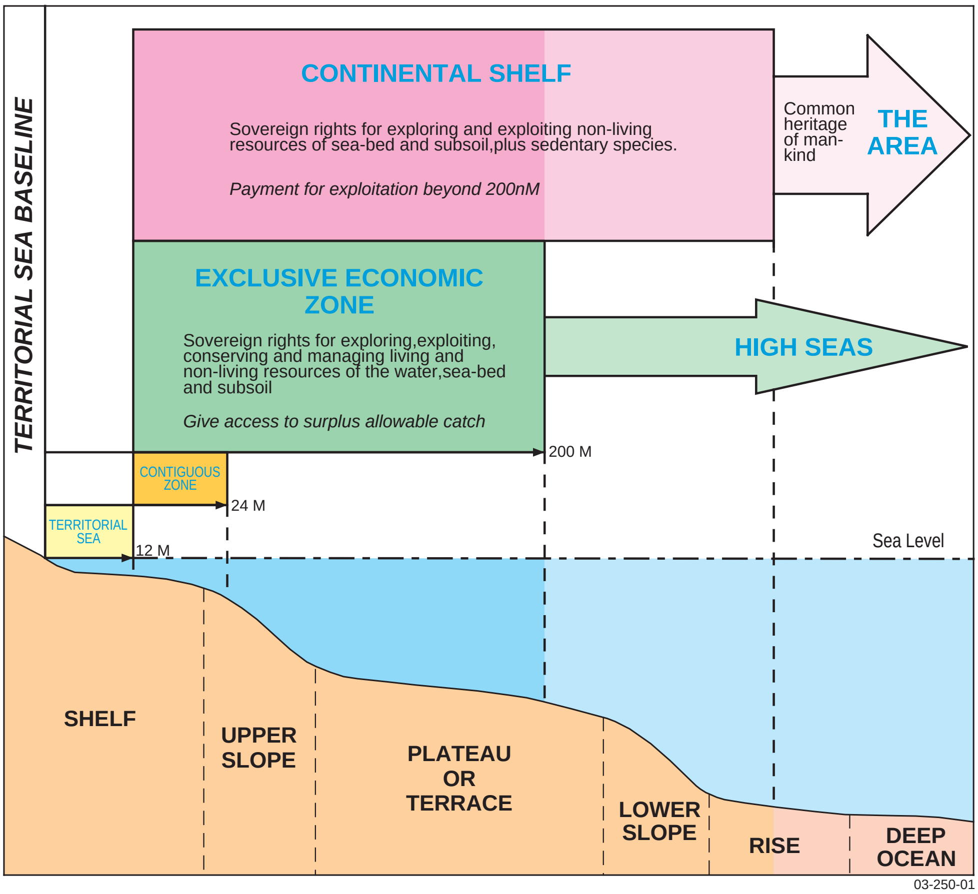


Figure 1. Marine jurisdictional zones contained in the 1982 United Nations Convention on the Law of the Sea.

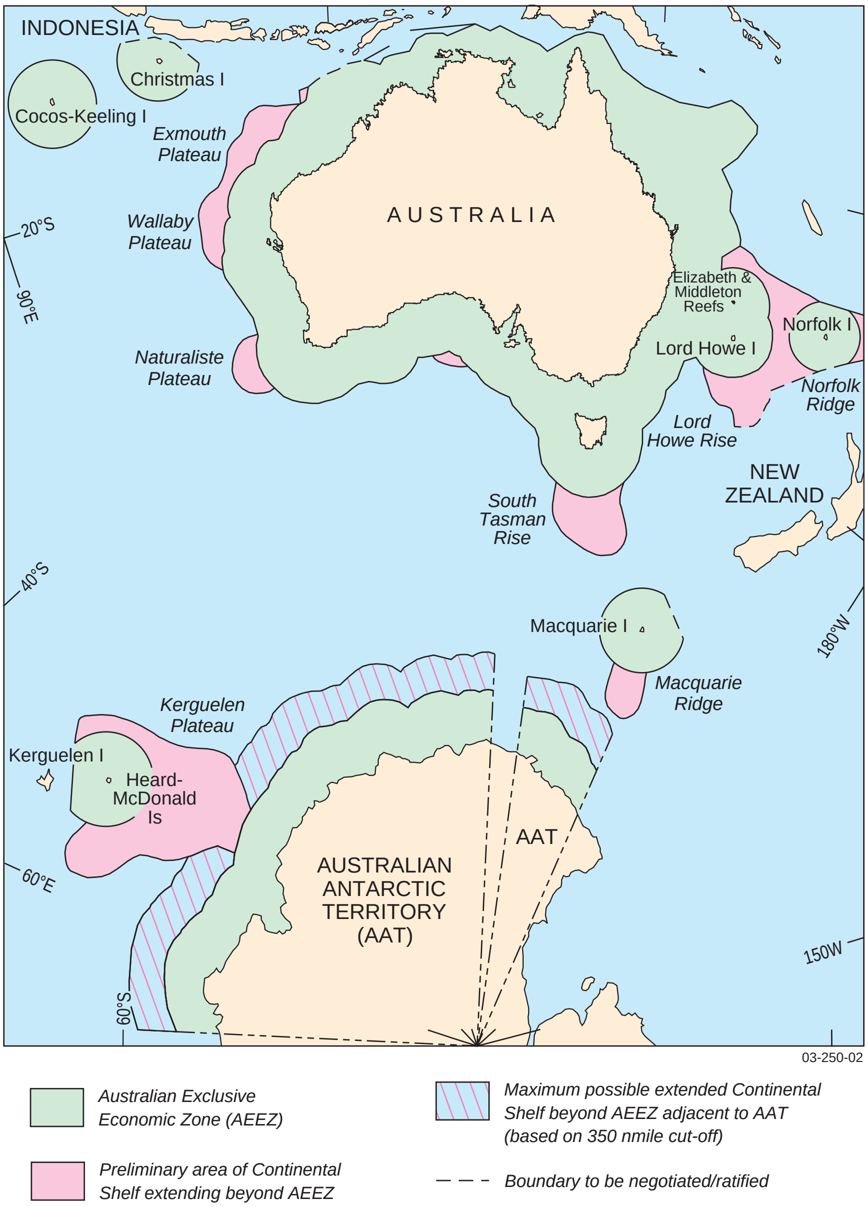


Figure 2. Map showing the main marine jurisdictional zones around Australia and its territories (after Symonds et al., 1998b).

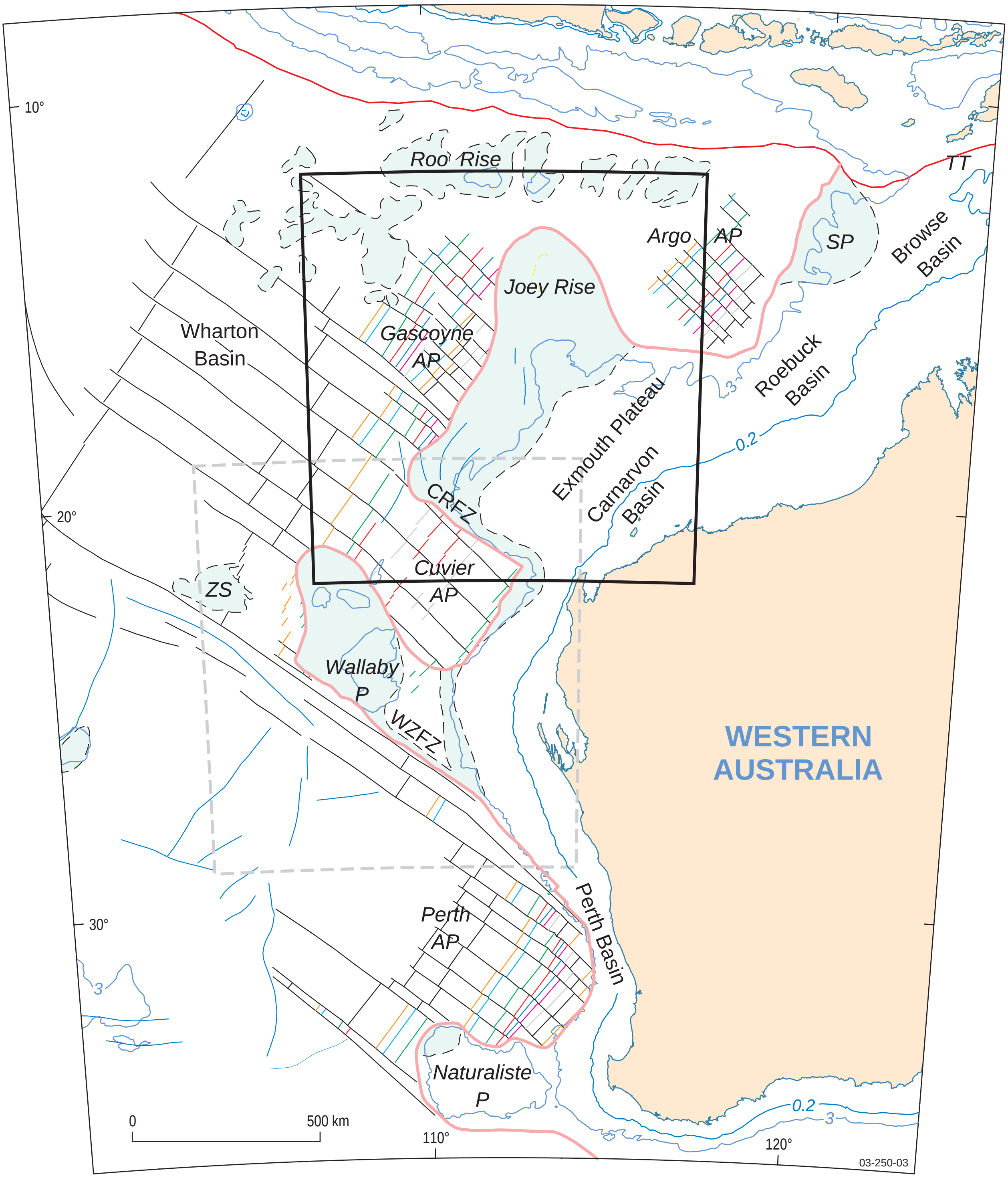


Figure 3. Regional setting of the eastern Indian Ocean showing the study area for this report (solid box) and the adjacent Wallaby Plateau study area of Sayers et al. (2002; dashed box). Bathymetric contours in kilometres. Solid pink line is the approximate continent/ volcanic margin - ocean boundary.Seafloor spreading magnetic anomaly identifications are modified from Muller et al. (1998) and Mihut & Muller (1998). Green areas are volcanic-rich provinces on continental, volcanic margin, or oceanic crust. ZS- Zenith Seamount;SP - Scott Plateau; AP- abyssal plain; TT- Timor Trough; CRFZ- Cape Range Fracture Zone;WZFZ- Wallaby- Zenith Fracture Zone.

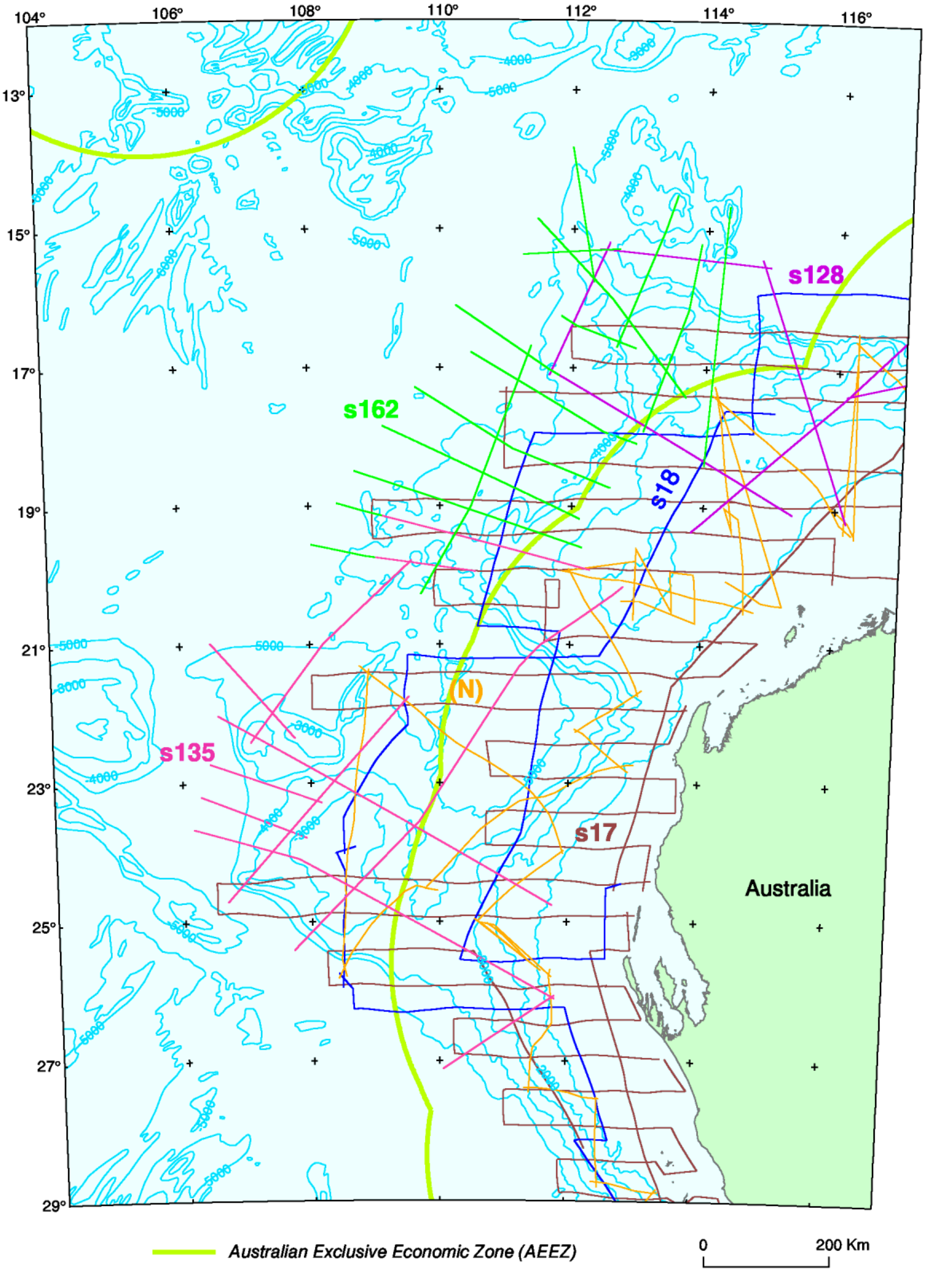


Figure 4. Locations of seismic lines used in this study with survey number identification. Shot point locations are shown in Plate 2. Bathymetry is from the GEBCO data set.

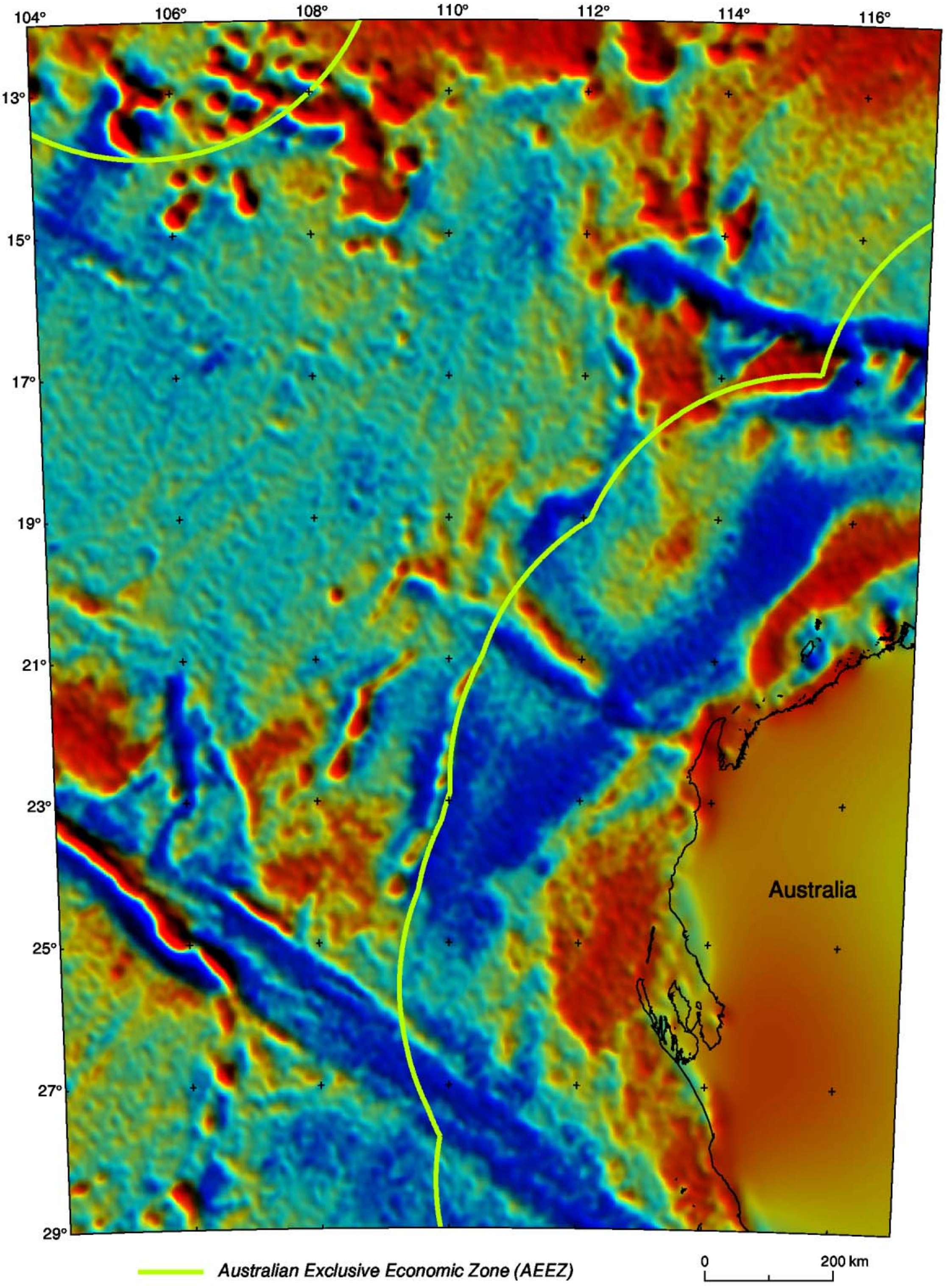


Figure 5. Satellite gravity image of the Exmouth and Wallaby Plateaus. The green line is the 200 M Australian Exclusive Economic Zone.

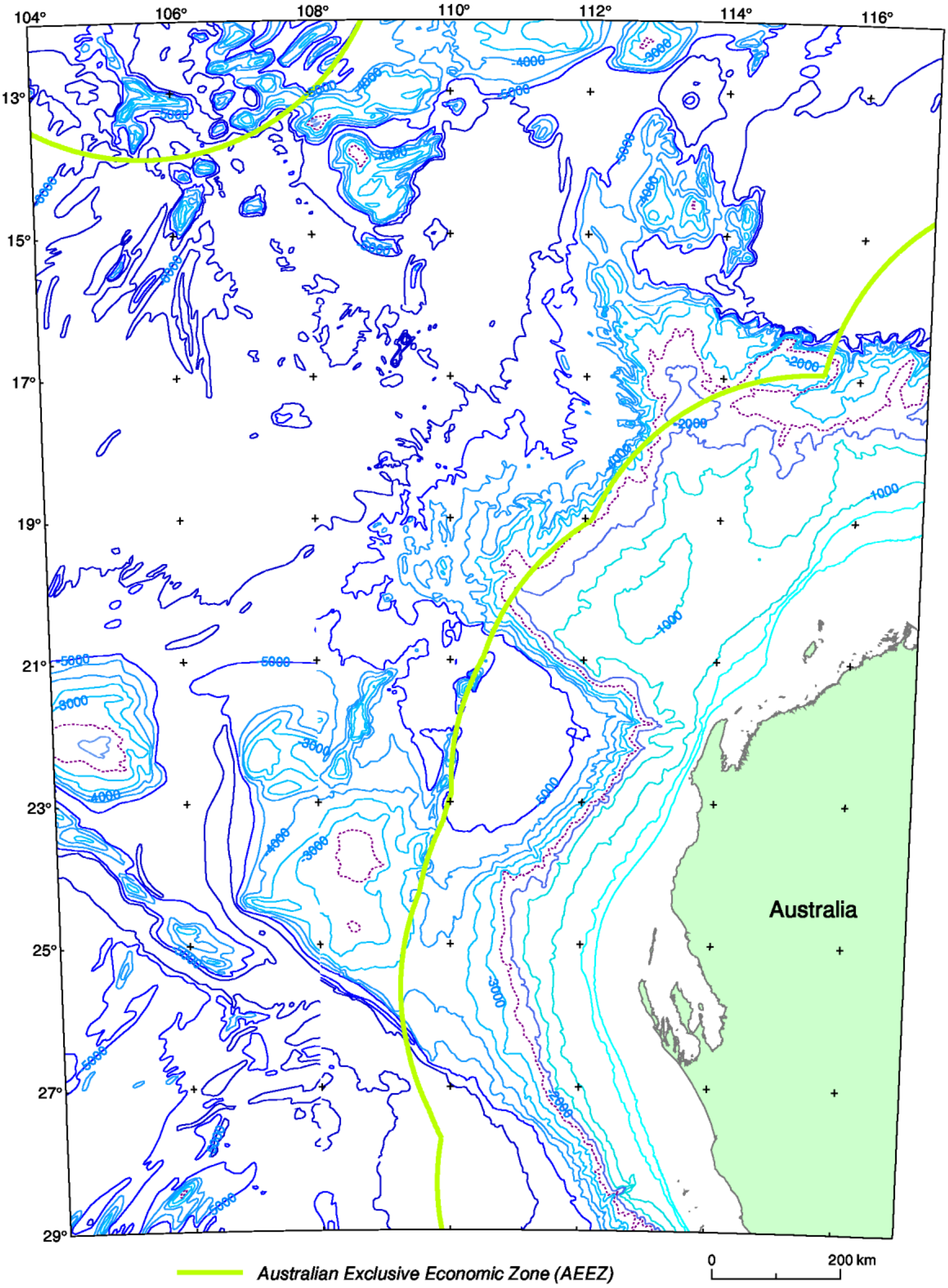


Figure 6. Bathymetric contours for the Exmouth Plateau study area from the GEBCO data set. Also shown is the 200 M Australian Exclusive Economic Zone (green line).

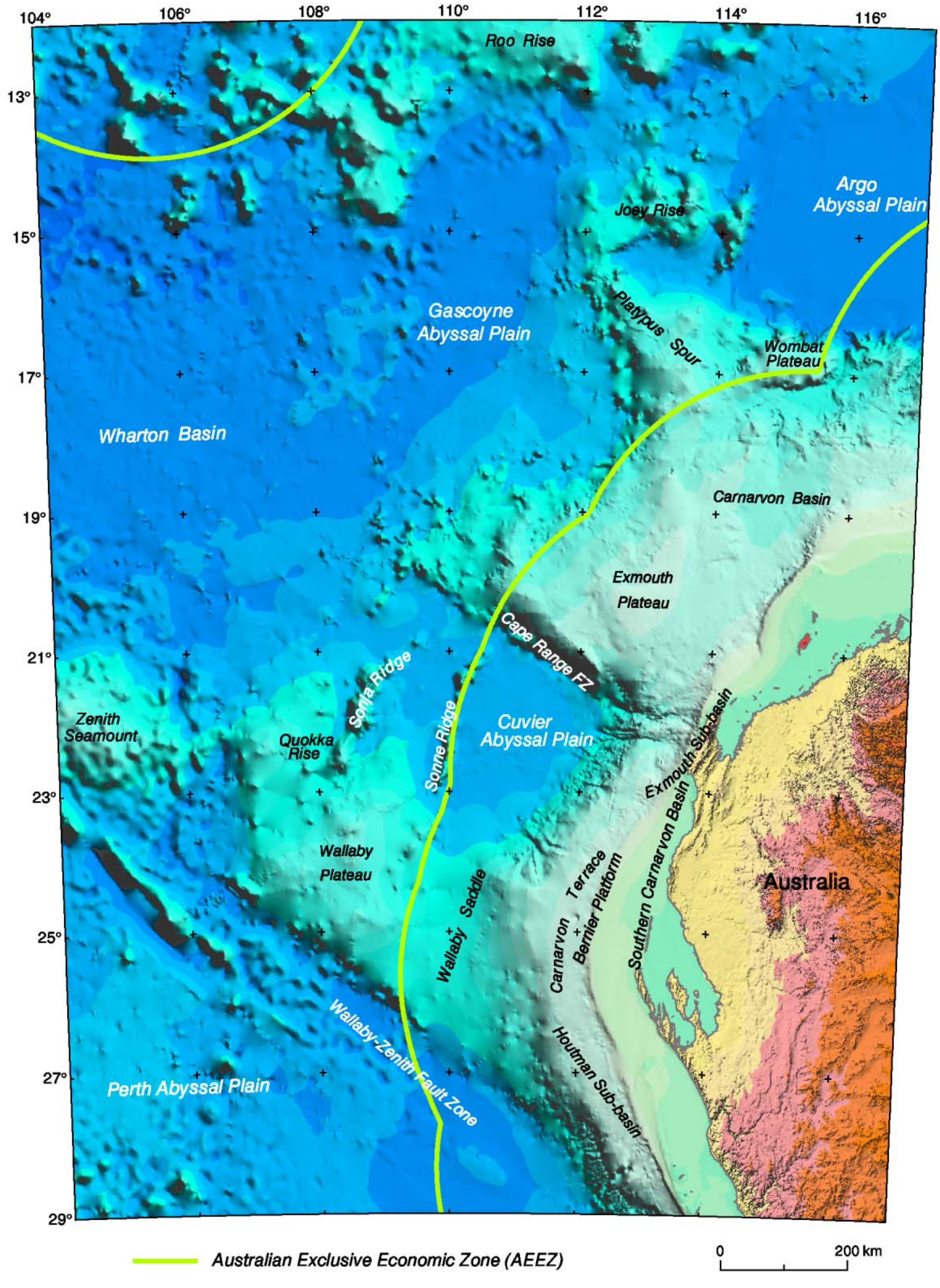


Figure 7. Bathymetric image of the Exmouth and Wallaby Plateaus (after Petkovic & Buchanan, 2002). The green line is the 200 M Australian Exclusive Economic Zone.

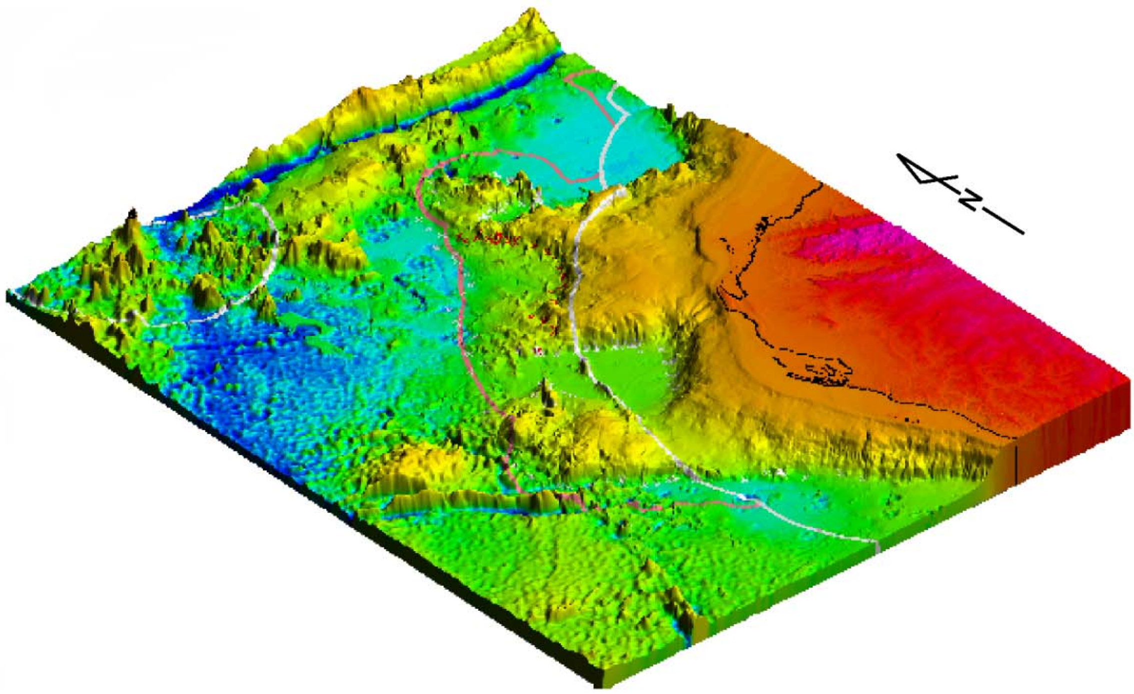


Figure 8. Bathymetry perspective of the Exmouth and Wallaby Plateaus.

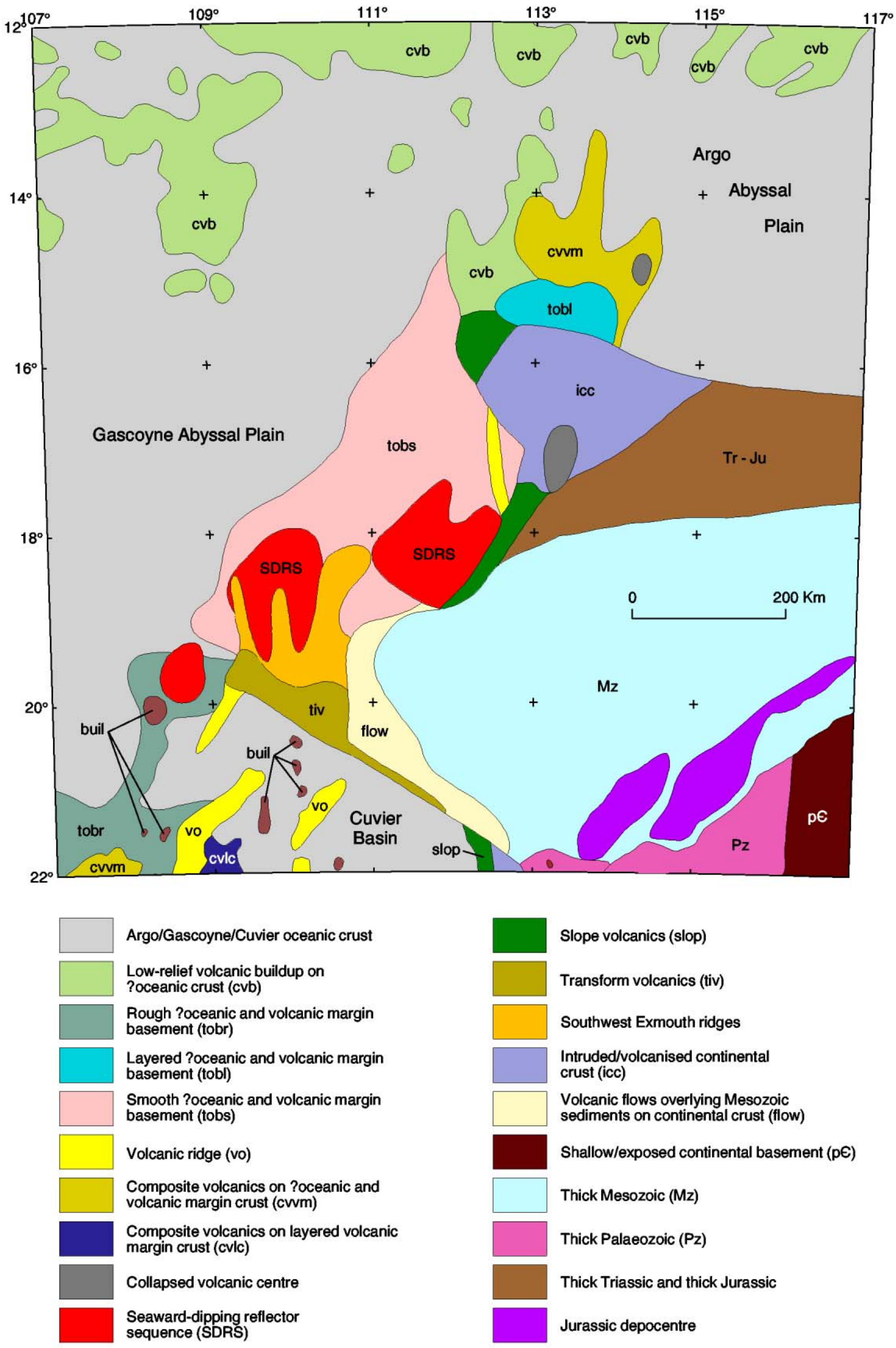


Figure 9. Tectonic elements

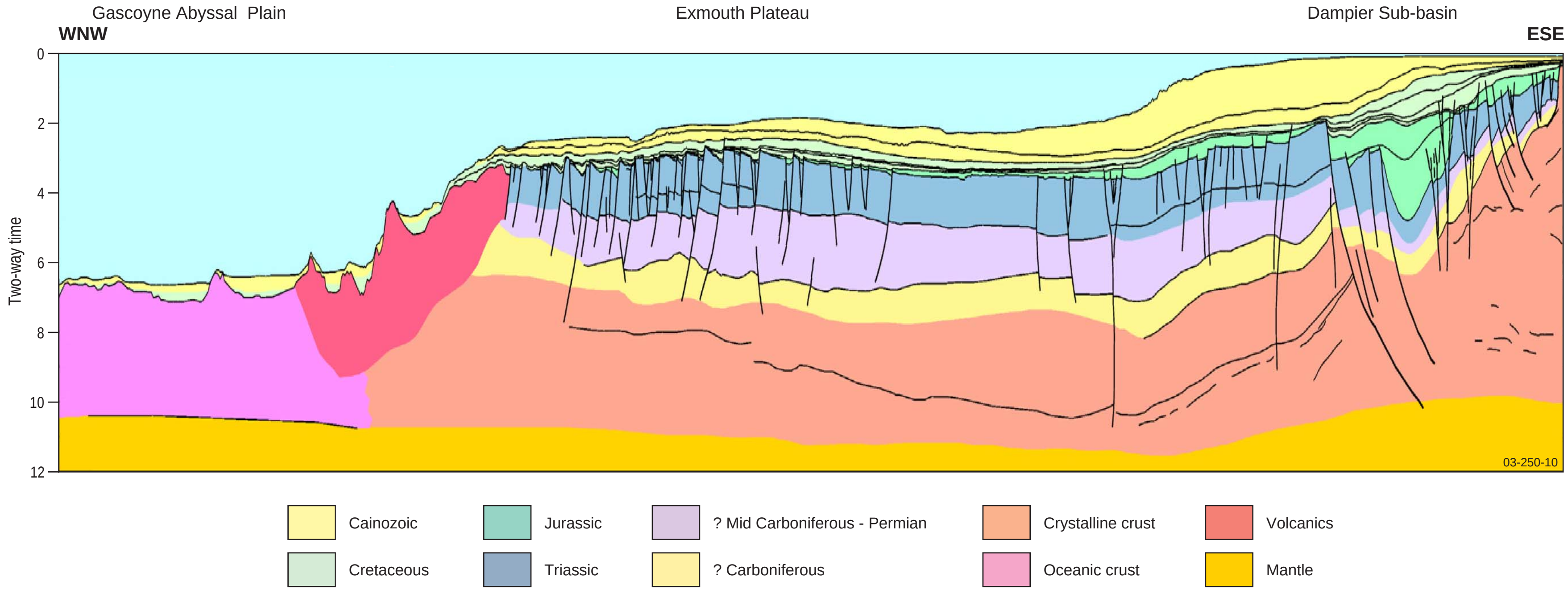


Figure 10. Line drawing of reflection seismic profile from the inner margin of the Northern Carnarvon Basin, across the Exmouth Plateau to the Gascoyne Abyssal Plain, showing the main structural elements (after AGSO North West Shelf Study Group, 1994)

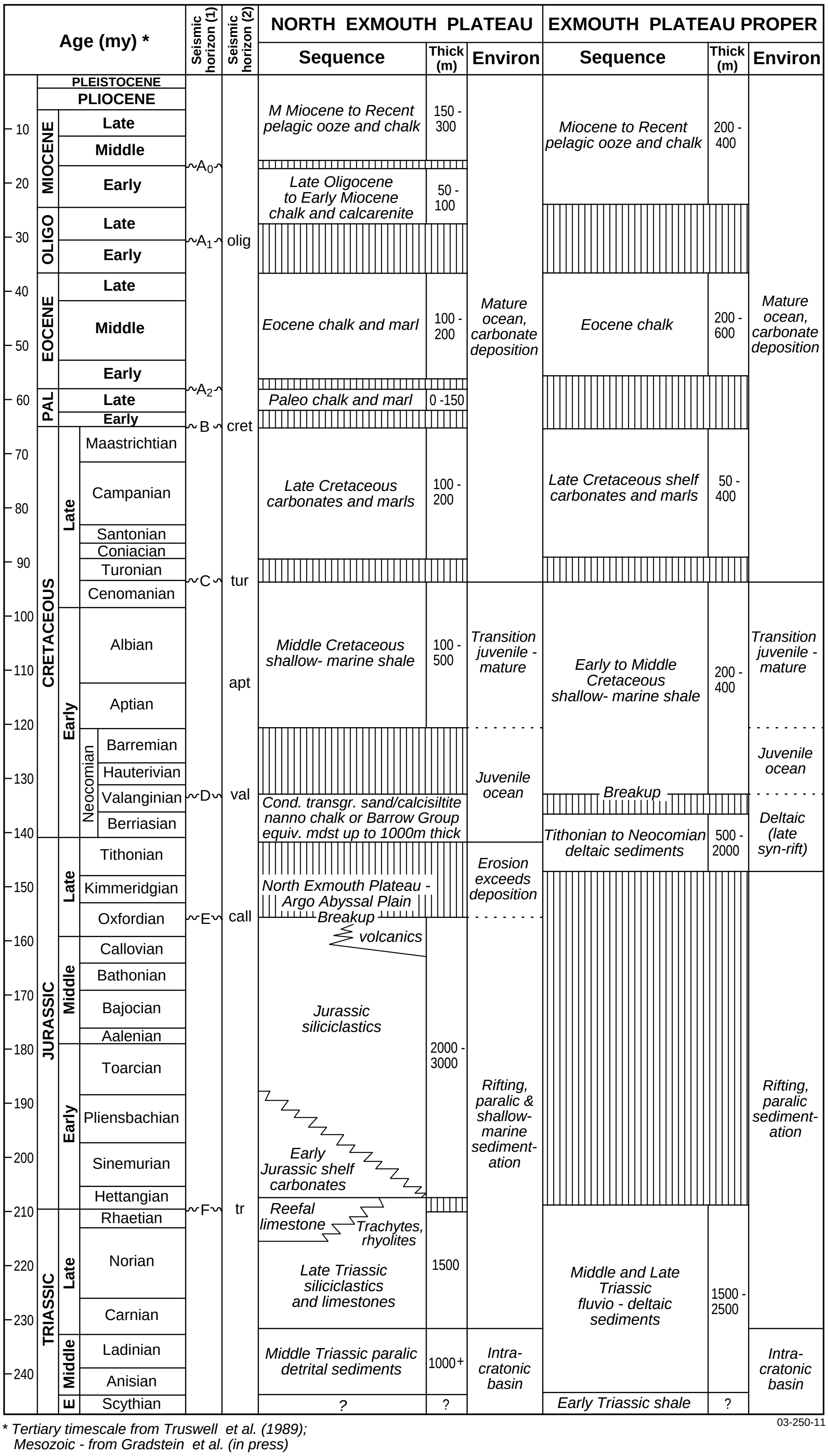


Figure 11. Simplified stratigraphy of the Exmouth Plateau. incorporating well, dredge and seismic data (after Exon & Colwell, 1994). The 'North Exmouth Plateau' lies north of 18°S.

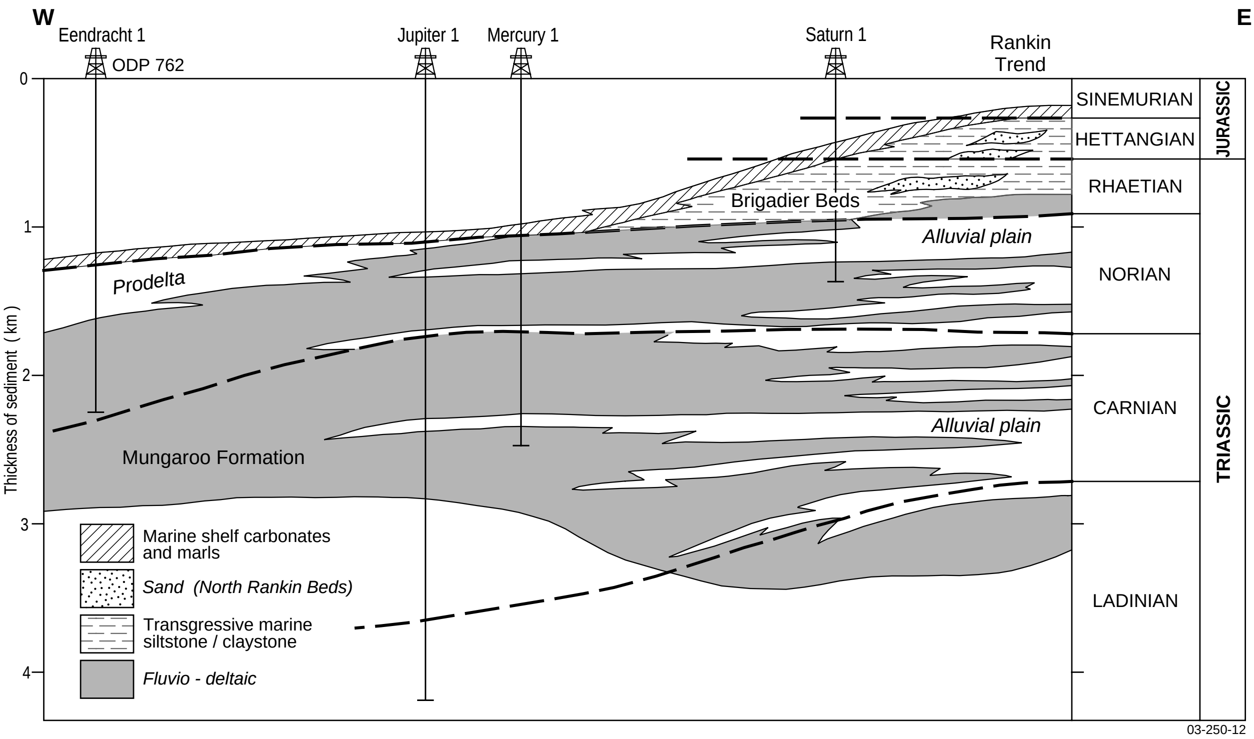


Figure 12. Depositional environments in the Upper Triassic and Lower Jurassic sequences between ODP Site 762 and the Rankin Platform.

STRATIGRAPHIC TABLE : DELAMBRE 1

Latitude: 18°31'05"S Longitude: 116°41'48"E RT 10m

AGE				LITHOLOGY	Depth (m)	Thickness (m)	Reflector	Two-way time (s)
						10		
				Sea level	10	884		
			NOT SAMPLED	Sea bed	894	343		
CAINOZOIC	NEOGENE		LATE PLIOCENE	*Upper slope forามininferal argillaceous calcilutite*	1237	59		
			EARLY PLIOCENE		1296	174		
			LATE MIOCENE	*Upper slope claystone and calcisiltite*	1470	251		
			MIDDLE MIOCENE	*Upper slope calcareous claystone, marl and calcilutite*	1721	109		
			EARLY MIOCENE	*Upper slope argillaceous calcilutite*	1820	37	A_0	2.17
	PALAEOGENE		LATE OLIGOCENE		1857	12		
			MIDDLE EOCENE	*Outer shelf to upper slope argillaceous calcilutite*	1869	47	A_1	2.18
			EARLY EOCENE		1916	75		
			LATE PALEOCENE	*Outer shelf argillaceous calcilutite and calcarous claystone*	1991	69	A_2	
			PALEOCENE UNDIFFERENTIATED		2060	6		
			EARLY PALEOCENE	*Shelf claystone*	2066	3		
MESOZOIC	CRETACEOUS	LATE	LATE MAASTRICHTIAN	*Outer shelf marl*	2069	32	B	2.34
			EARLY MAASTRICHTIAN	*Outer shelf marl*	2101	19		
			LATE CAMPANIAN		?2120	36		
			INDETERMINABLE	*Outer shelf marl and calcilutite*	2156	13		
			LATE SANTONIAN		2169	24		
			EARLY SANTONIAN		?2193	7		
			CONIACIAN		2200	22		
			? TURONIAN	*Inner shelf calcilutite*	2222	18		
			LATE CENOMANIAN	*Outer shelf to upper slope marl and calcilutite*	2240	5	C	2.46
		EARLY	EARLIEST CENOMANIAN TO LATE ALBIAN	*Outer shelf to upper slope marl*	?2245	8		
			MIDDLE TO EARLY ALBIAN	*Outer shelf marl*	2253	33		
			INDETERMINABLE	*Shelf claystone with siliceous plankton*	2286	2		
			BARREMIAN		2288	30		
			BERRIASIAN	*Inner shelf sandstone and claystone*	2318	28	D	2.51
	JURASSIC	MID	BATHONIAN TO BAJOCIAN	*Inner shelf and paralic sandstone, siltstone, claystone and minor coal*	2346	1007	E	2.53
		EARLY	AALENIAN TO TOARCIAN	*Inner shelf claystone; minor sandstone and dolomite*	3353	611		
			PLIENSBACHIAN TO HETTANGIAN	*Inner shelf claystone, limestone and sandstone*	3964	323		
	TRIASSIC	LATE	RHAETIAN	*Inner shelf claystone and sandstone; minor dolomite*	4287	317	F	3.71
			NORIAN		4604	61		
			NORIAN TO CARNIAN	*Inner shelf and paralic claystone, sandstone, minor coal*	4665	599		
			CARNIAN		5264	231		
					TD 5495			

03-250-13

Figure 13. Stratigraphic table from Woodside Delambre 1, modified from company well completion report (after von Rad et al., 1992)

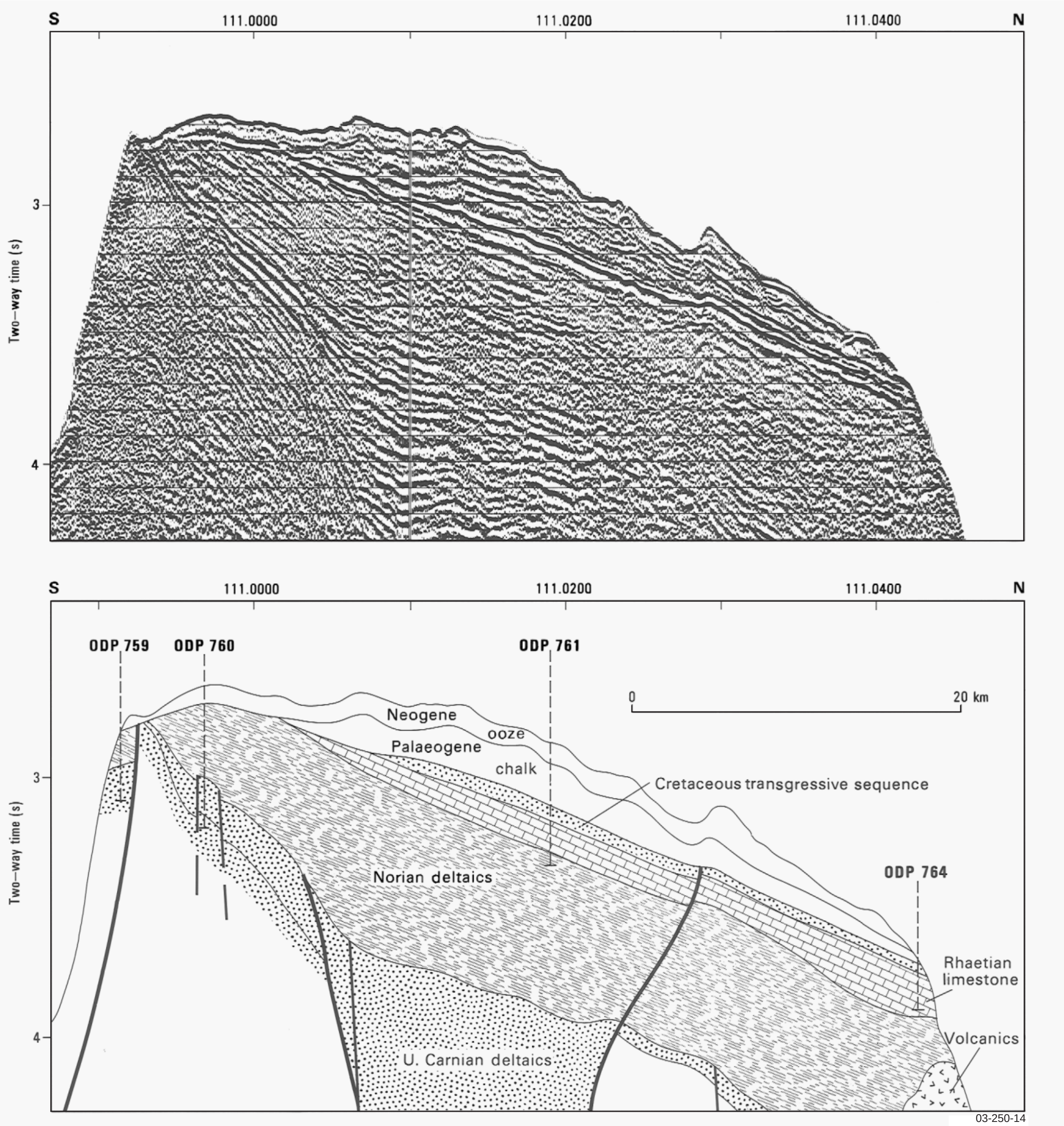


Figure 14. BMR seismic profile 56/13 across the Wombat Plateau, with four ODP drills sites projected on to it (after Exon et al., 1992).

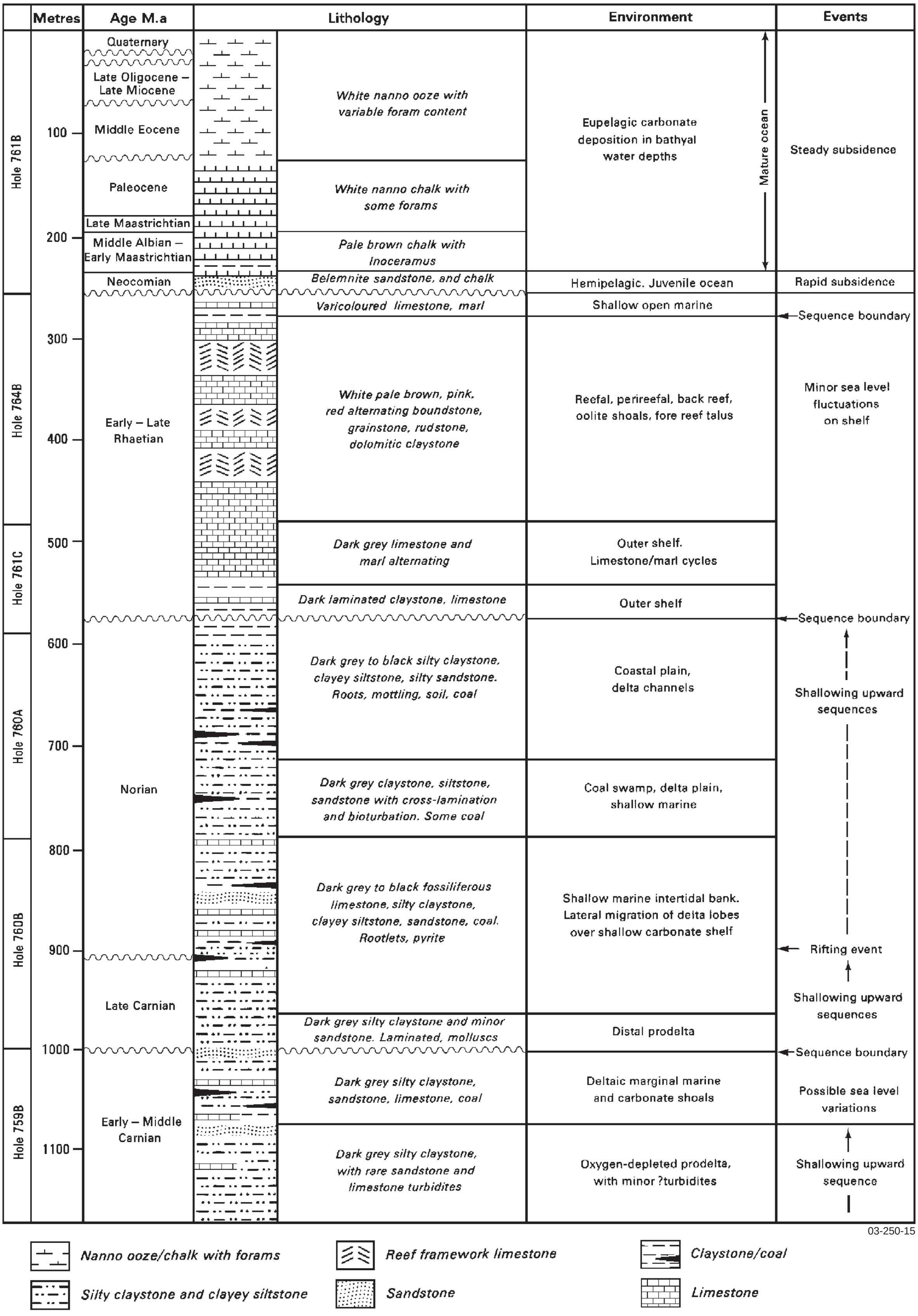


Figure 15. Composite lithological log for Wombat Plateau ODP Sites 759, 760. 761 and 764, showing maximum thickness of representative facies (after Exon & von Rad, 1994). Note the major unconformity separating Upper Triassic and Lower Cretaceous sediments.

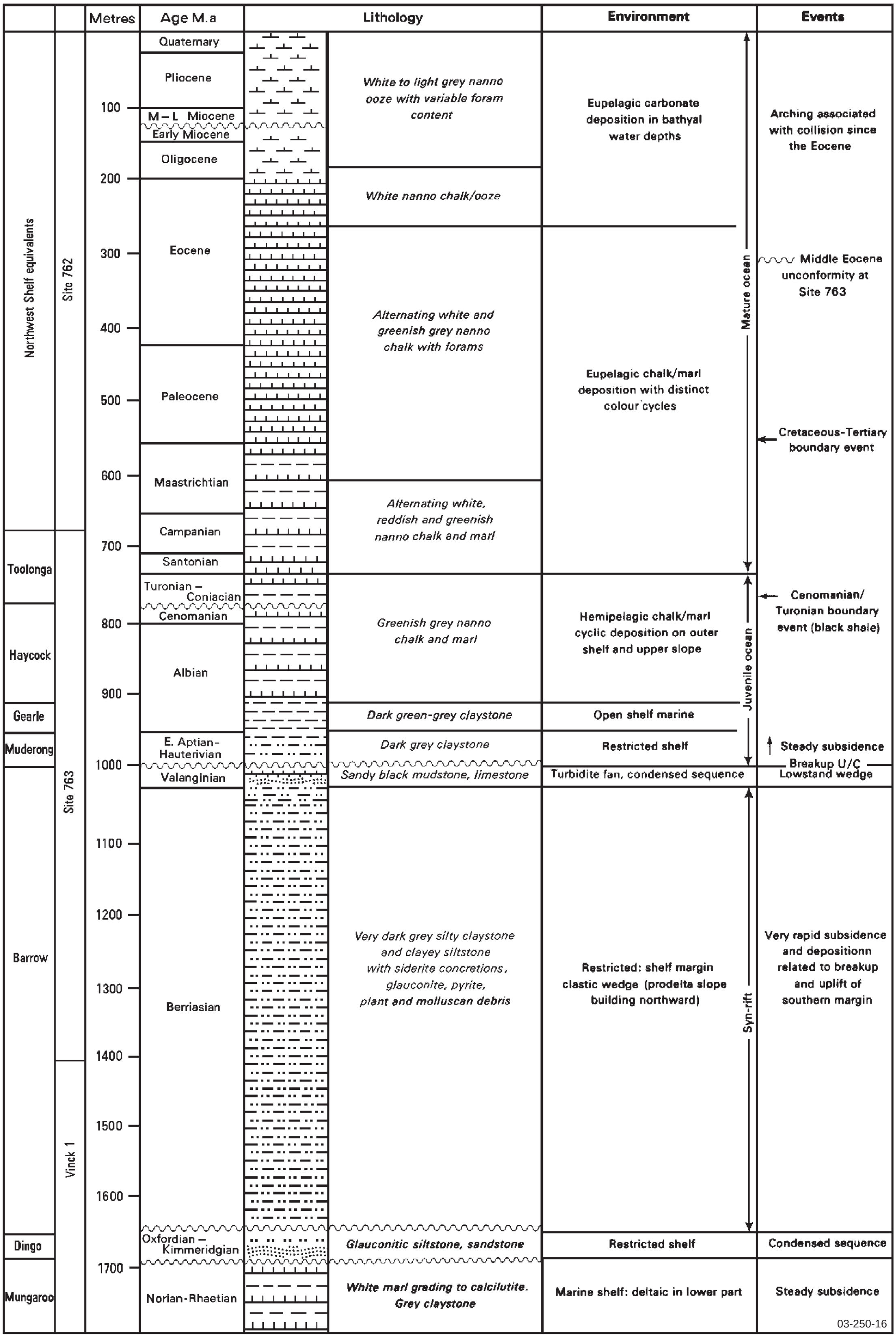


Figure 16. Composite lithological log for ODP Site 762, and Esso Vinck 1 exploration well (near Site 763; after Exon & von Rad, 1994).

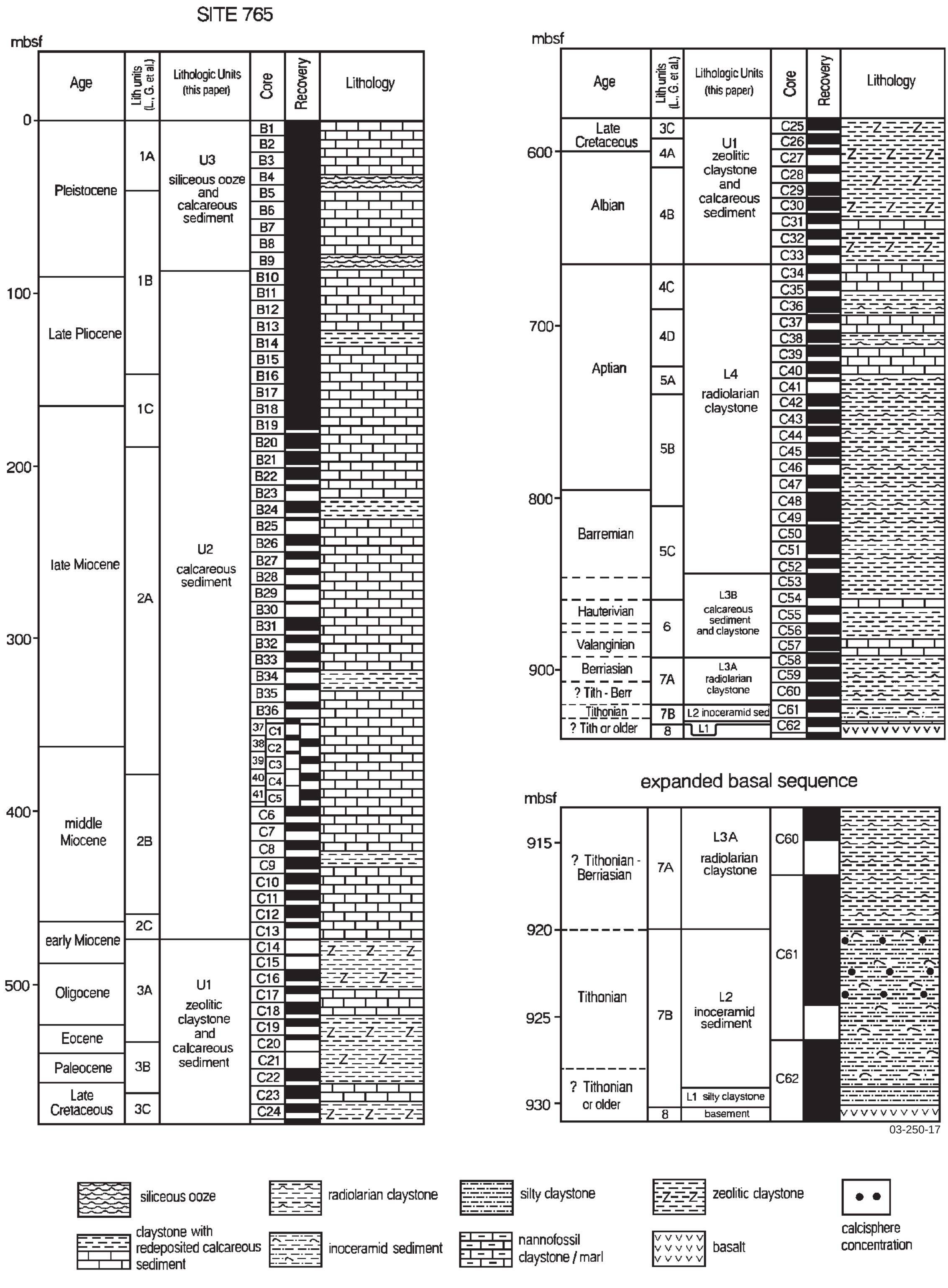


Figure 17. Lithological log for ODP Site 765 (after Dumoulin & Brown, 1992). Depths are metres below sea floor.

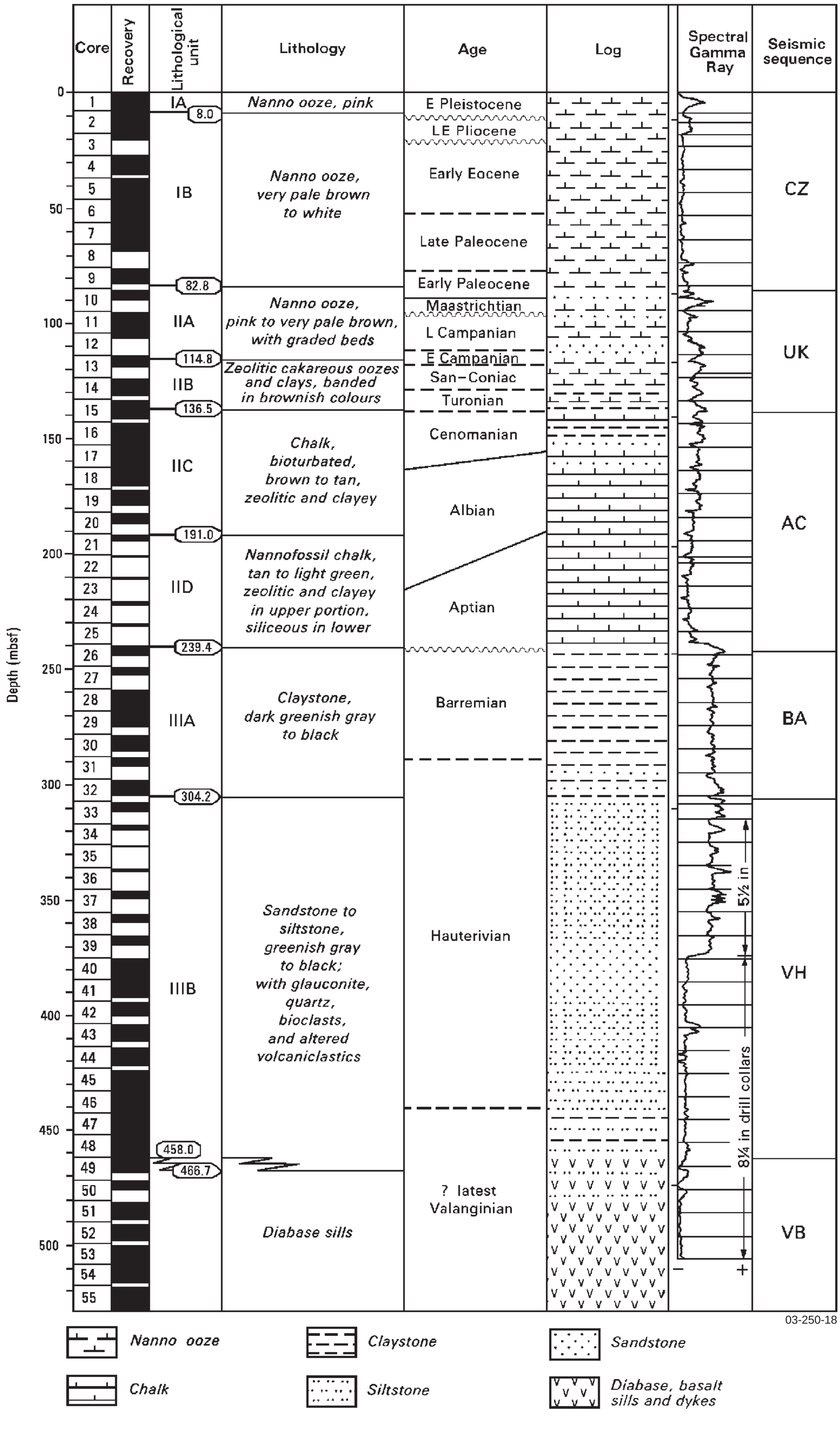


Figure 18. Lithological log for ODP Site 766 (after Exon & Buffler, 1992). Depths are metres below sea floor.

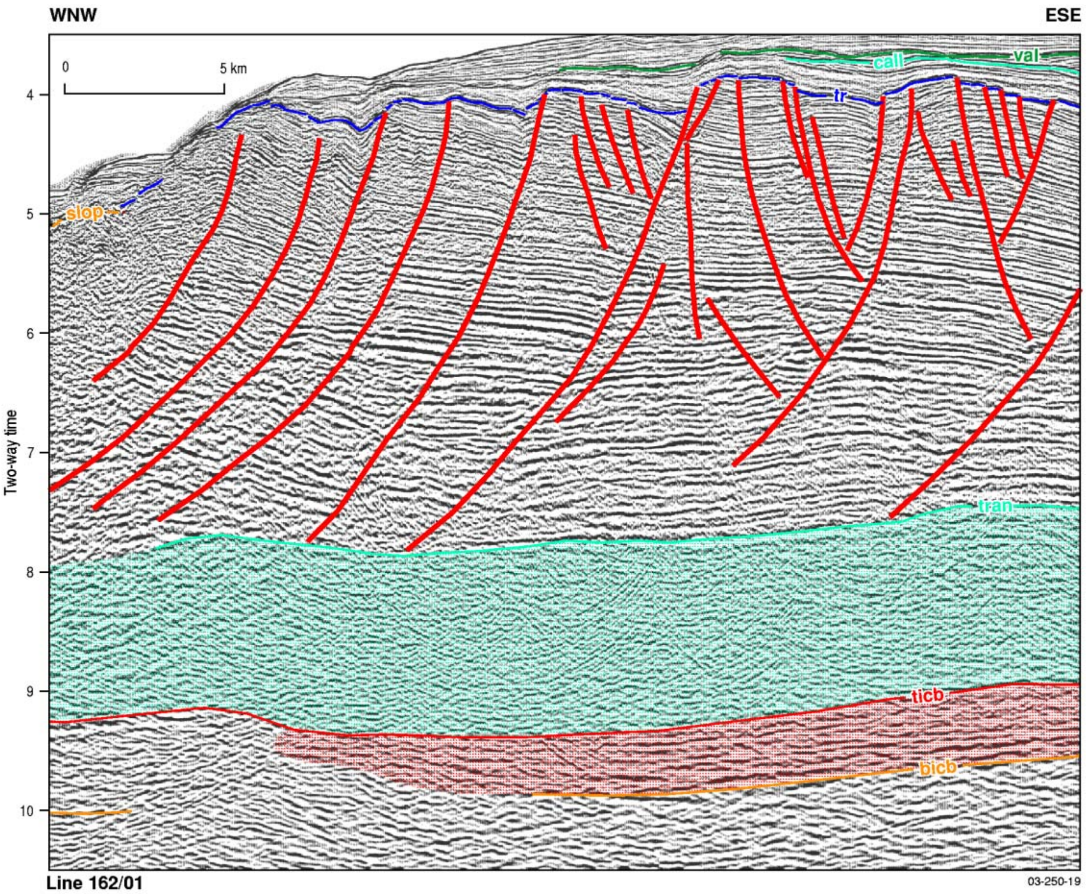


Figure 19 Type seismic section, Line 162/01 - upper continental crust; transparent crust; intruded lower crust.

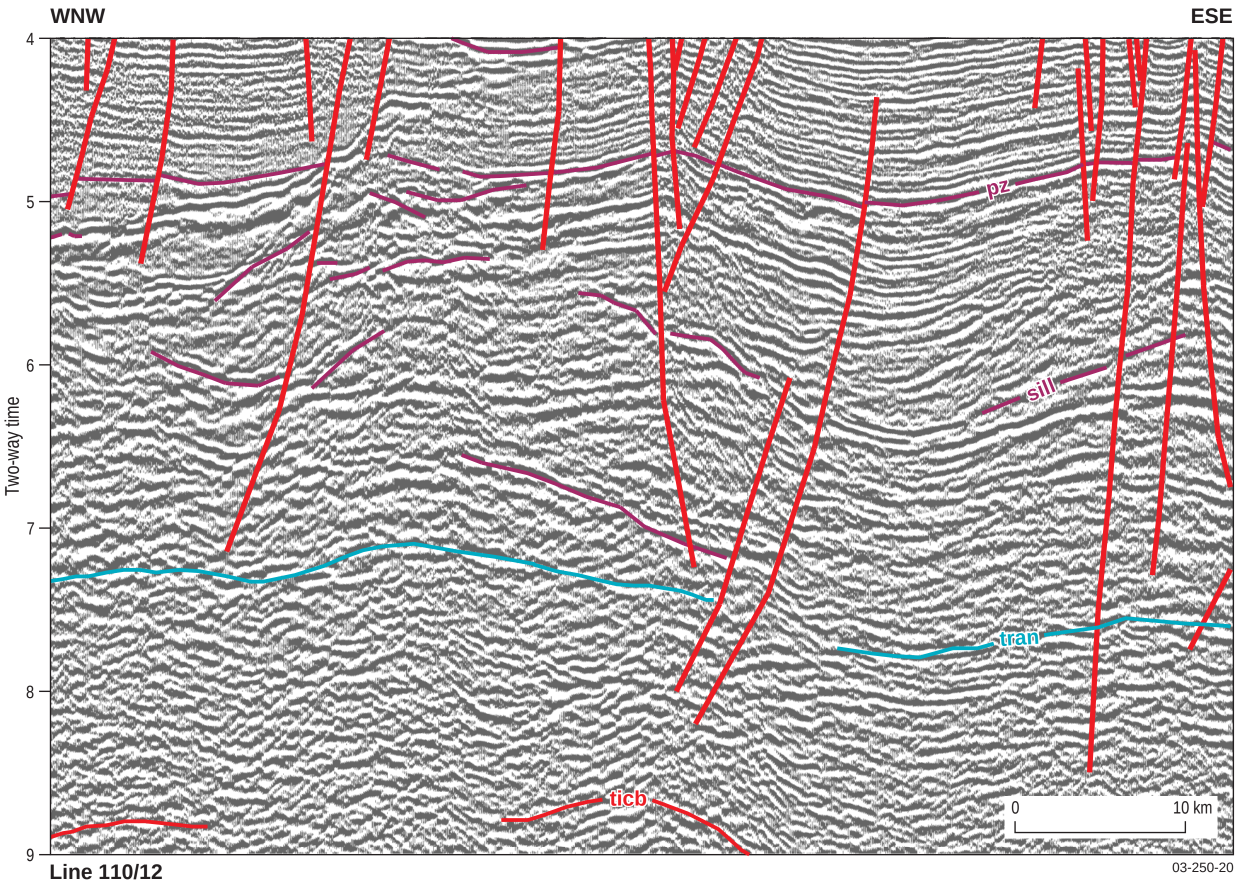


Figure 20. Type seismic section, Line 110/12 - mid continental crust.

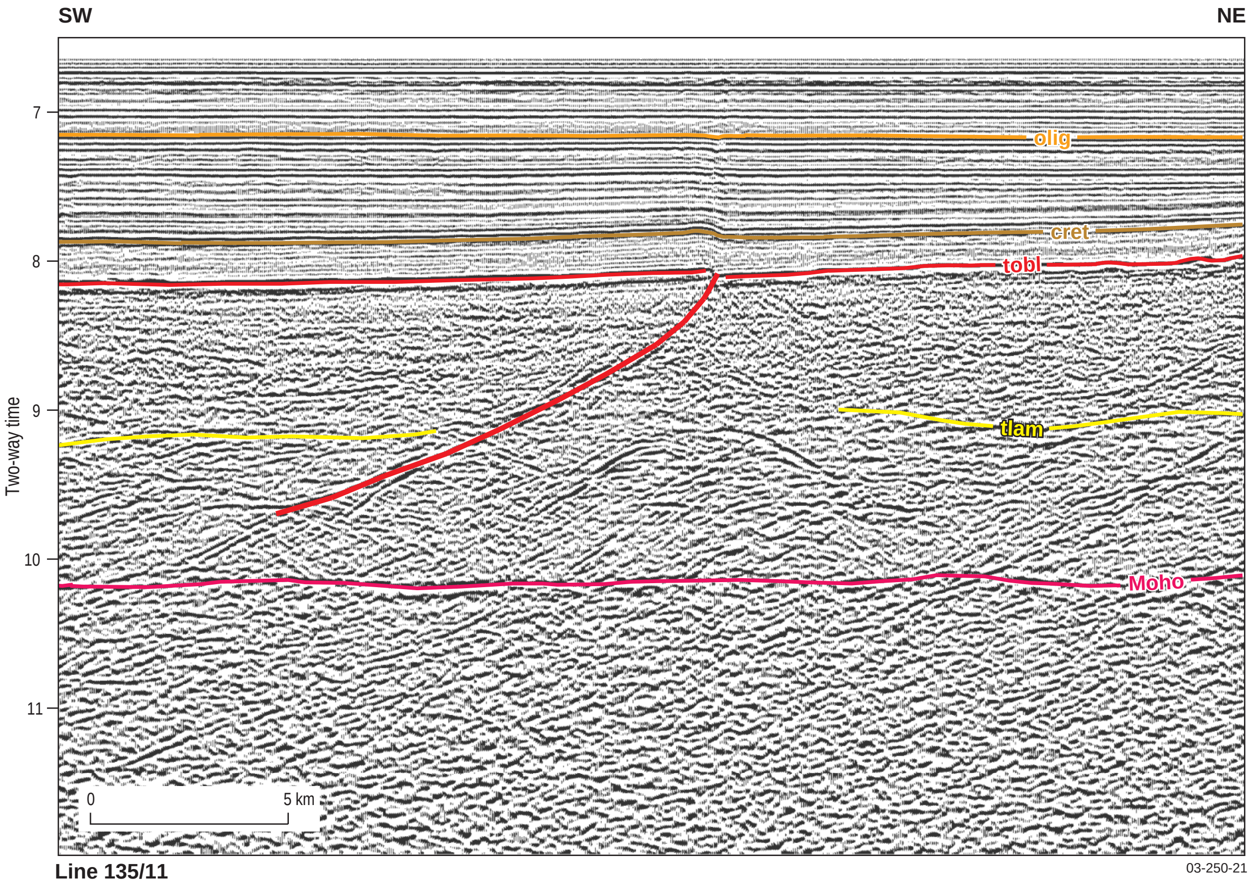


Figure 21. Type seismic section, Line 135/11 - smooth oceanic basement; laminated deep oceanic crust; Moho

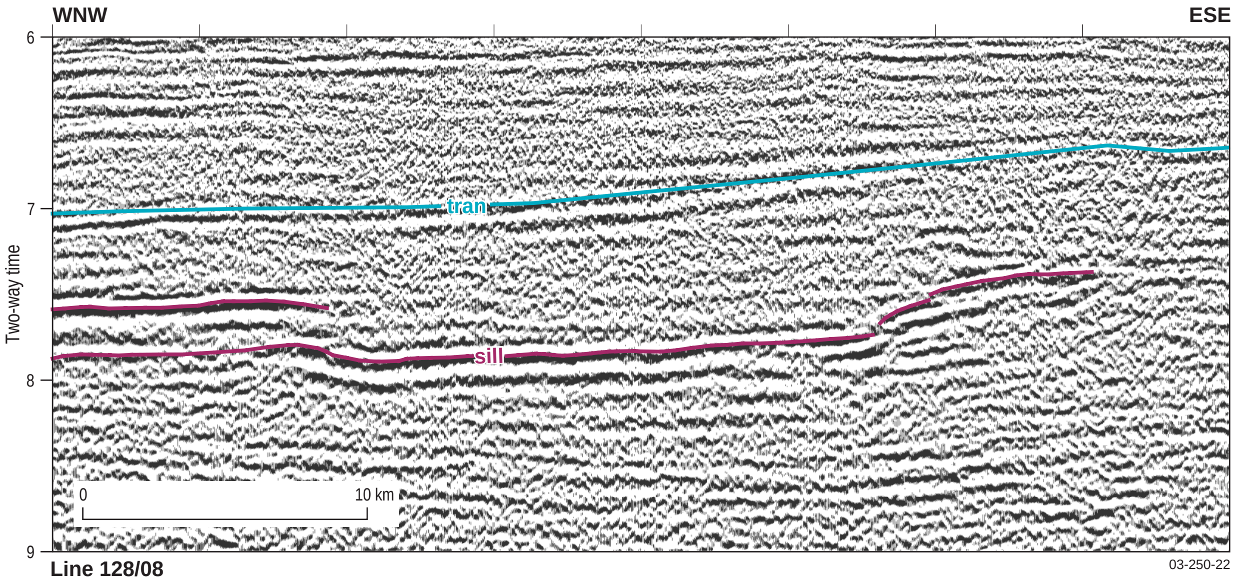


Figure 22. Type seismic section, Line 128/08 - sills in continental crust.

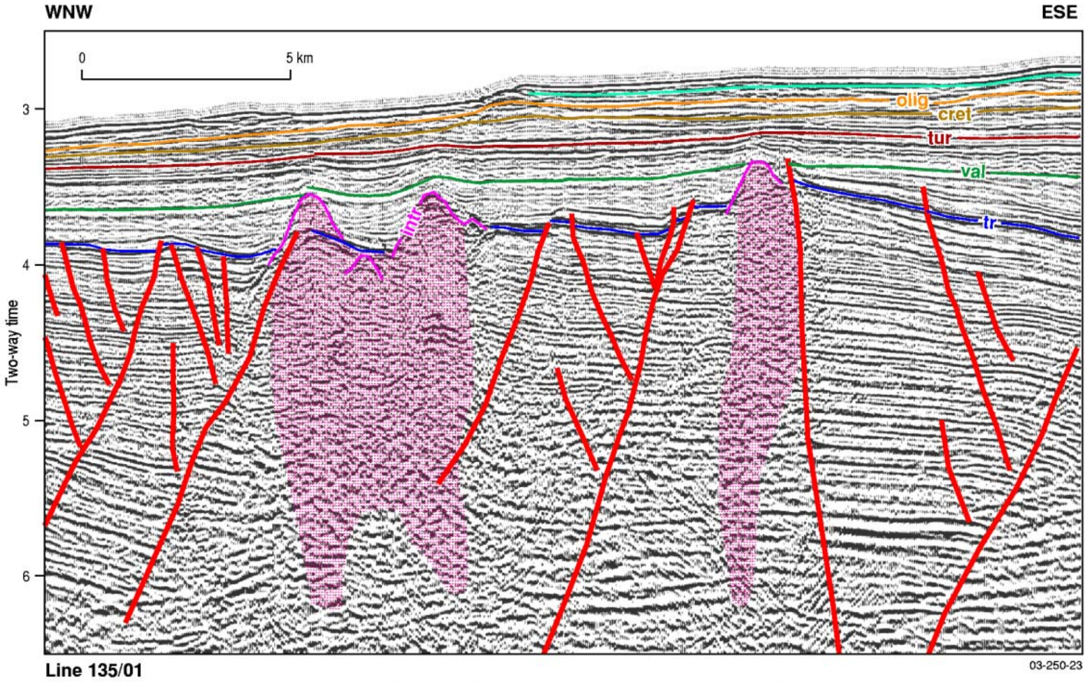


Figure 23. Type seismic section, Line 135/01 - igneous intrusions in continental crust.

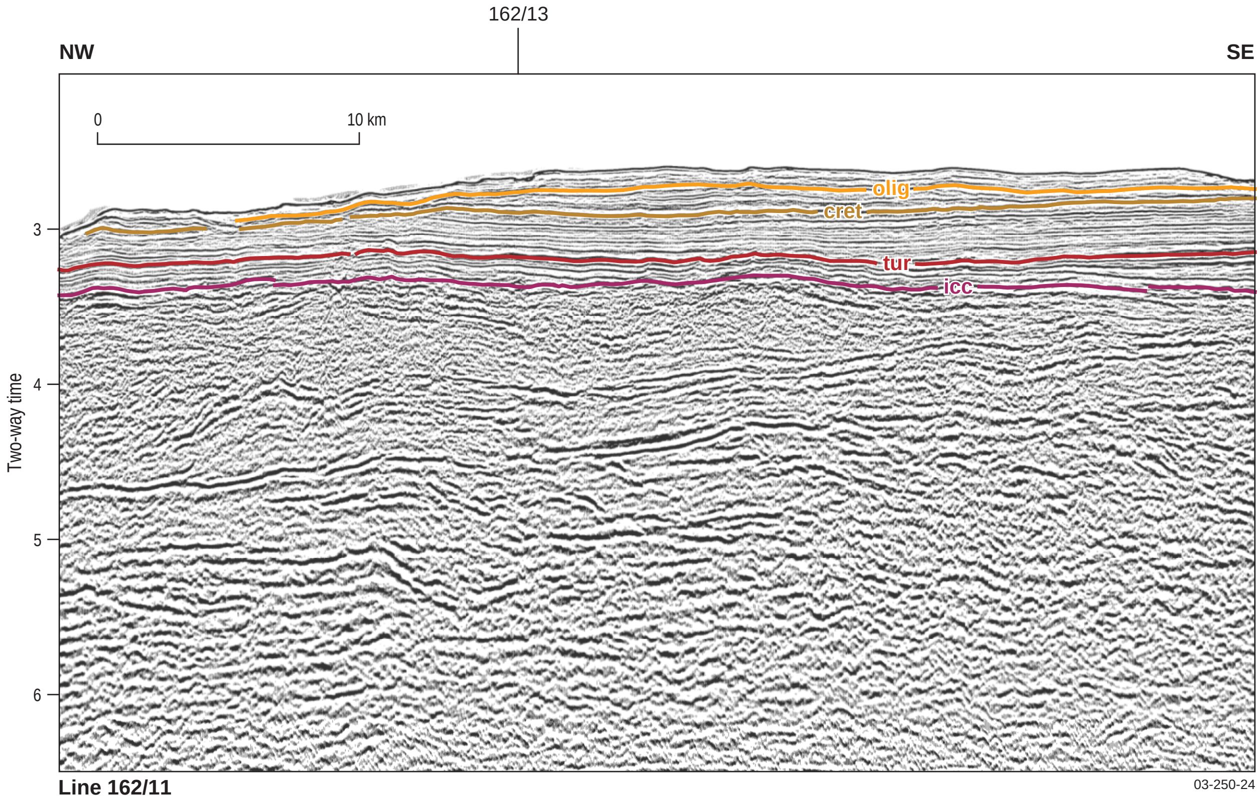


Figure 24. Type seismic section, Line 162/11 - intruded continental crust.

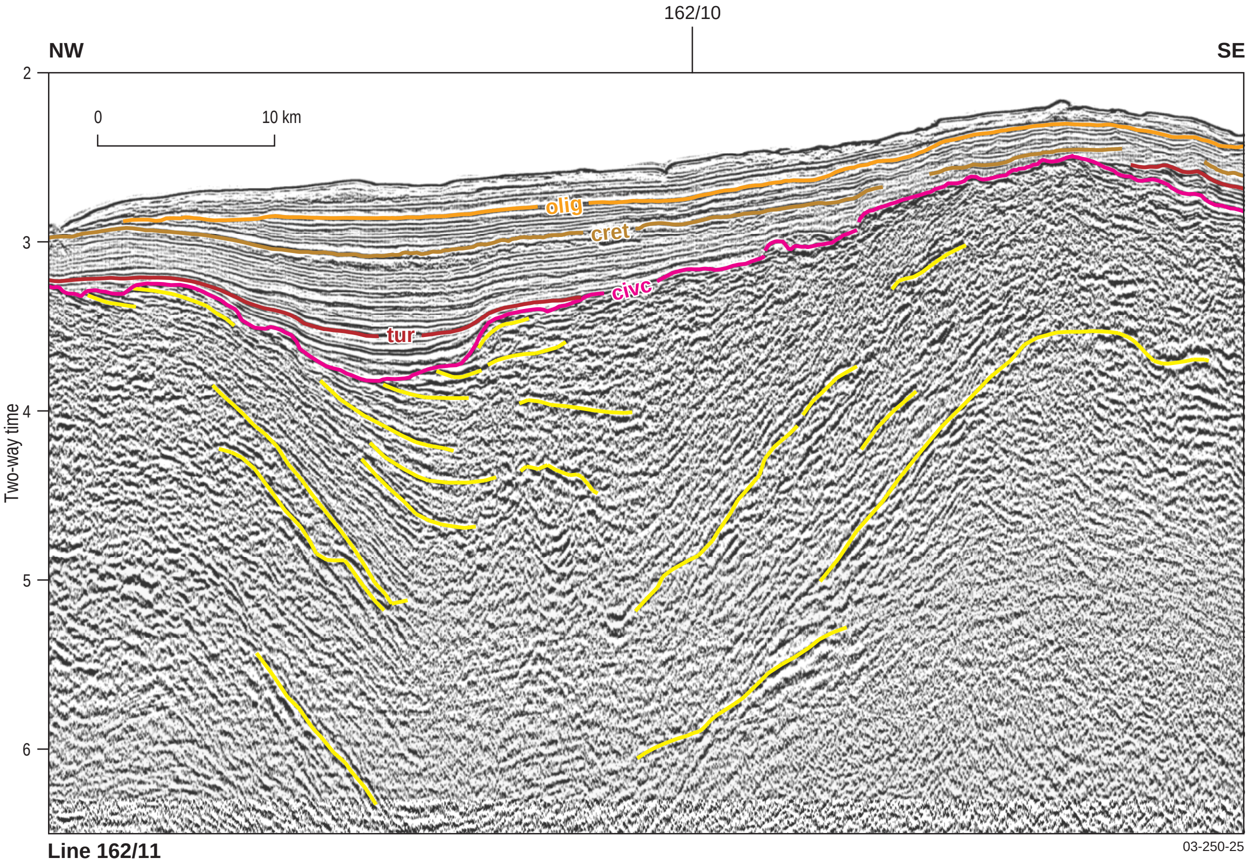


Figure 25. Type seismic section, Line 162/11 - intact volcano on continental crust.

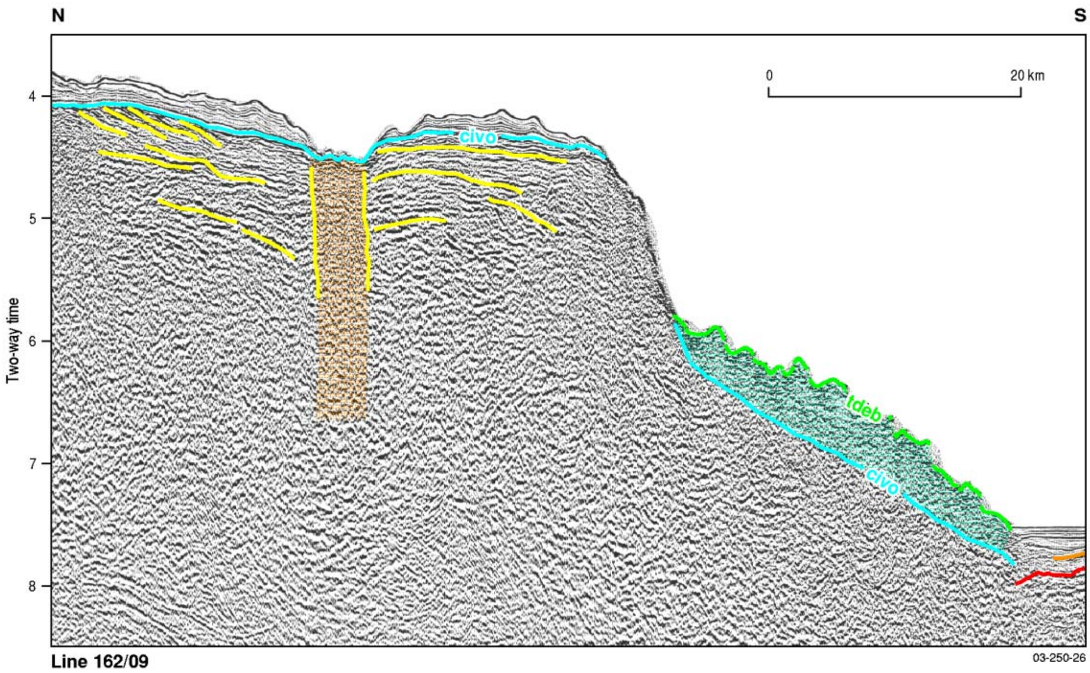


Figure 26. Type seismic section, Line 162/09 - intact volcano on probable oceanic crust.

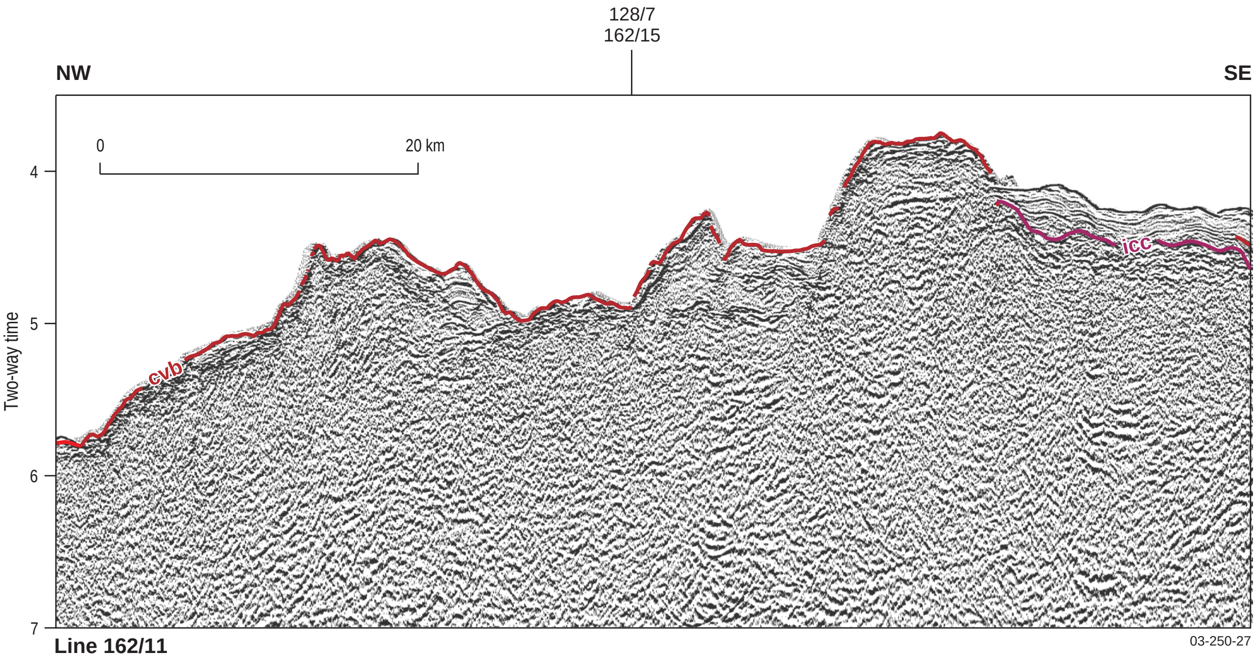


Figure 27. Type seismic section, Line 162/11 - composite volcanic buildup.

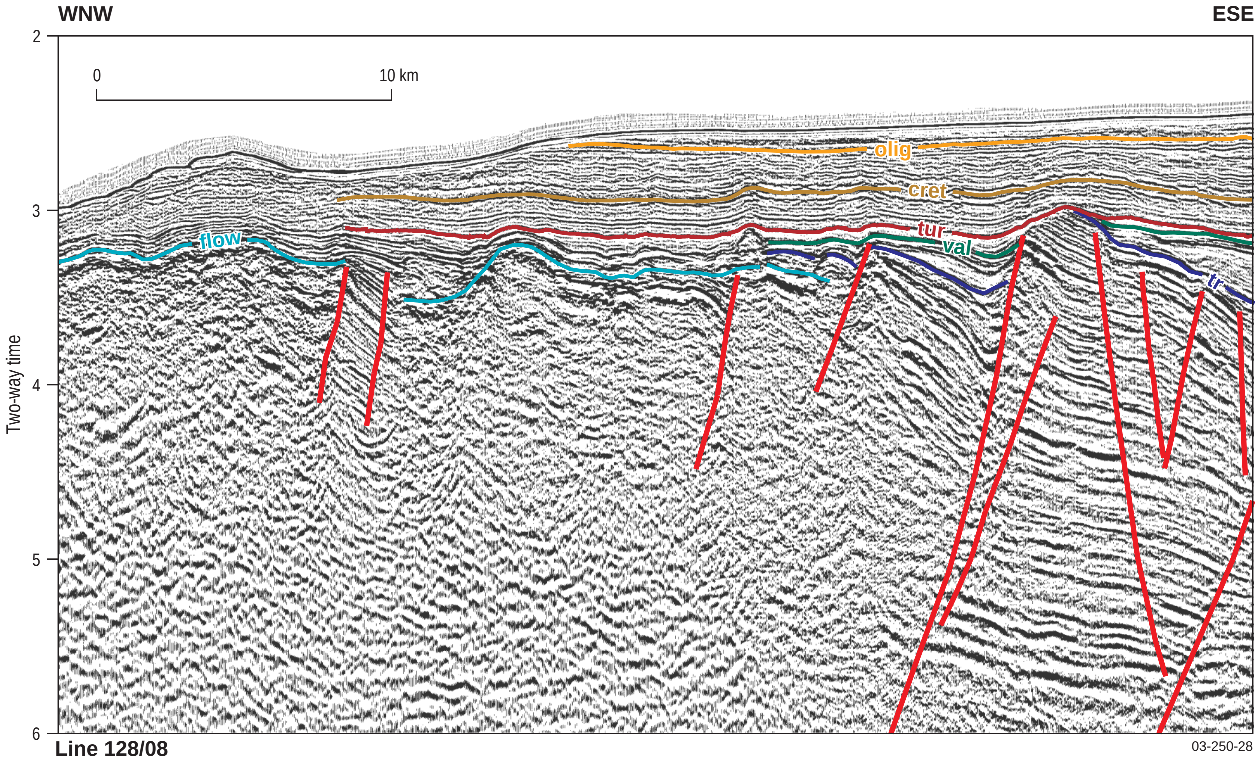


Figure 28. Type seismic section, Line 128/08 - landward flows on continent crust.

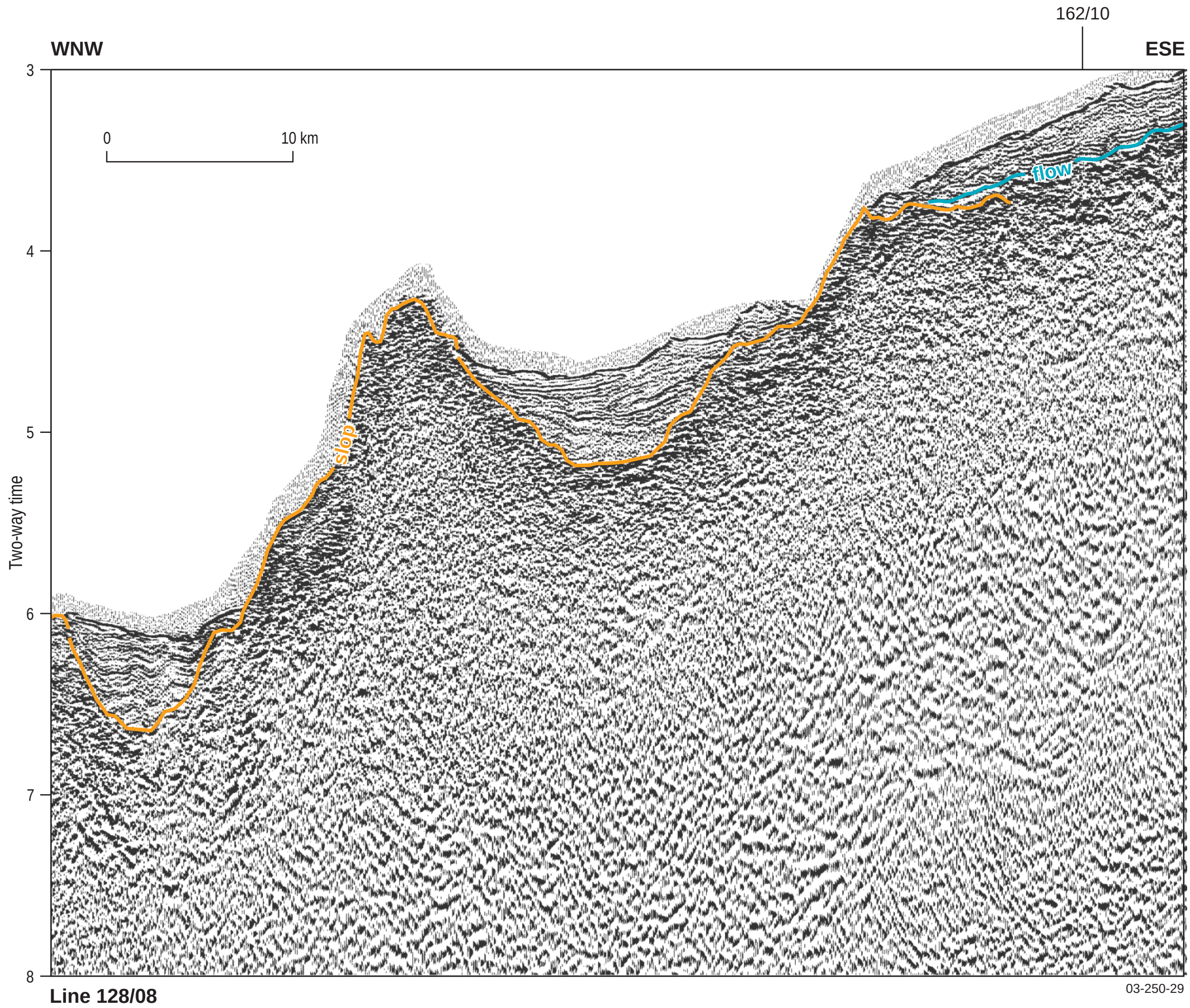


Figure 29. Type seismic section, Line 128/08 - slope volcanics.

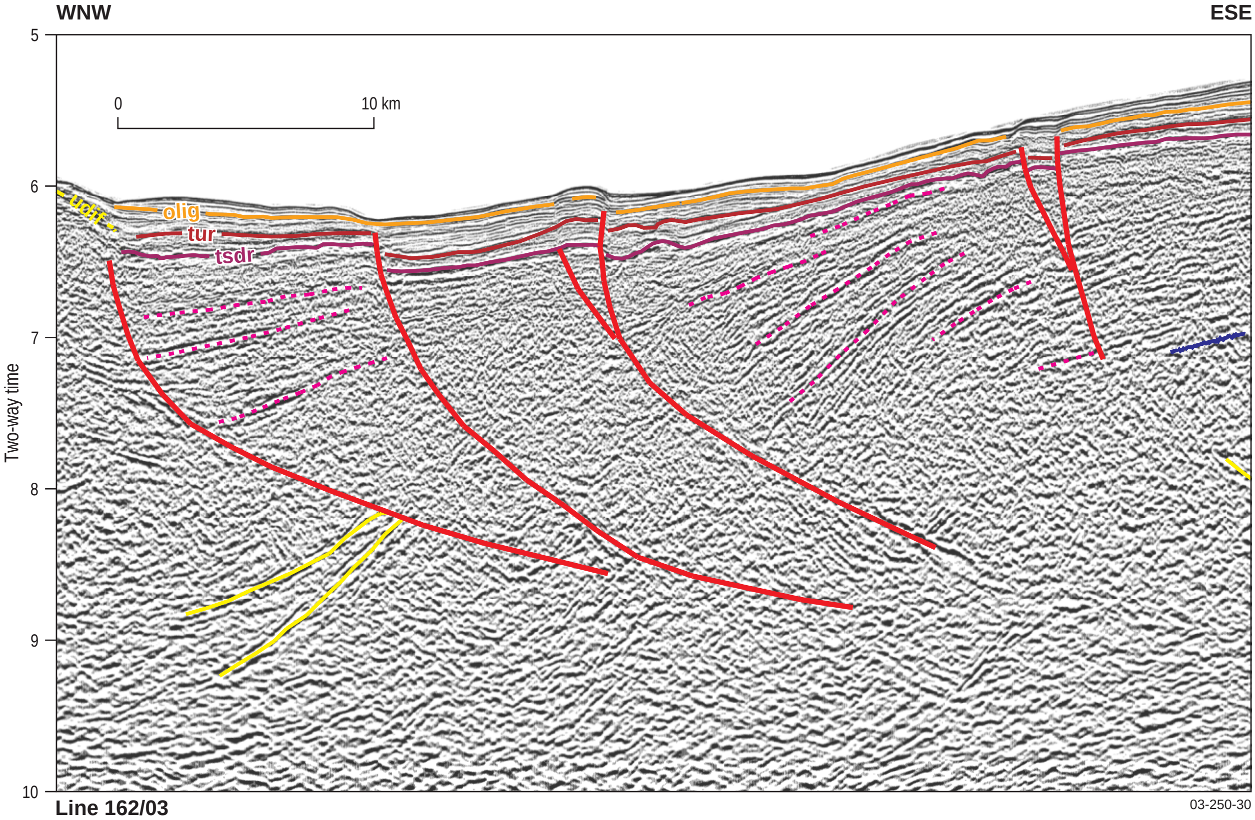


Figure 30. Type seismic section, Line 162/03 - seaward-dipping reflector sequence (SDRS).

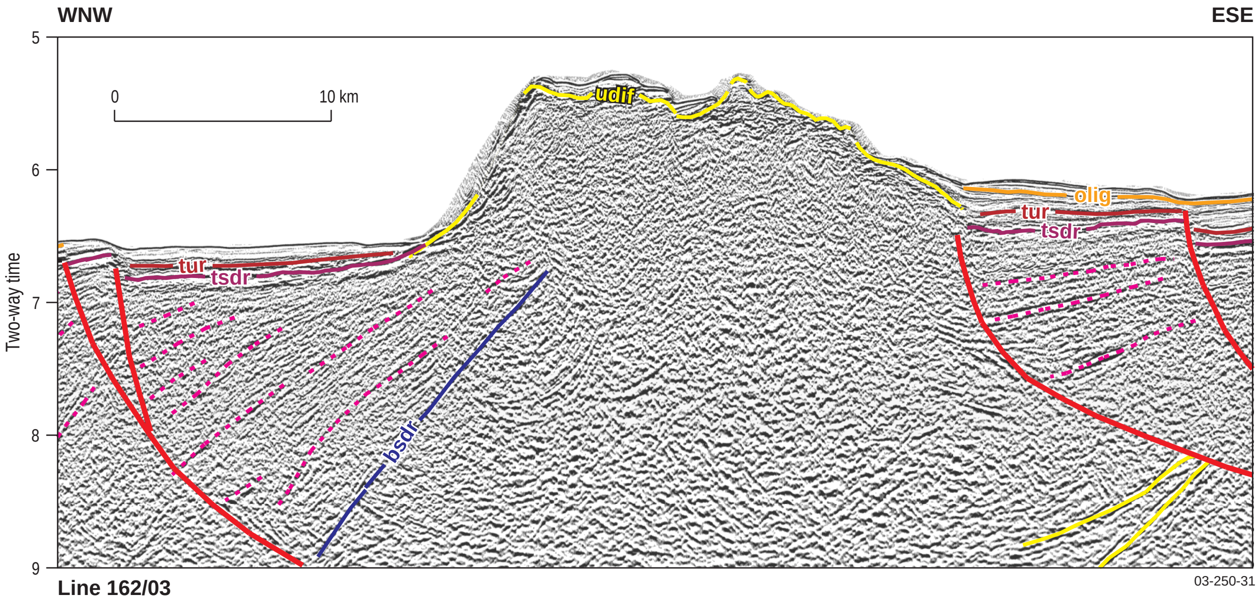


Figure 31. Type seismic section, Line 162/03 - inter-SDRS buildup.

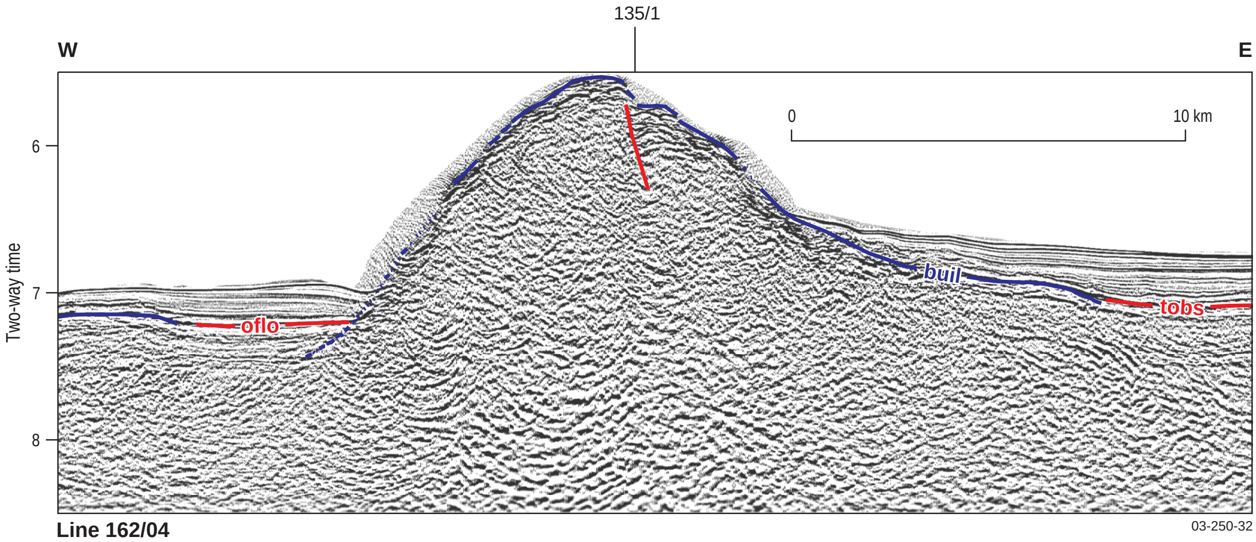


Figure 32. Type seismic section, Line 162/04 - oceanic volcanic buildup.

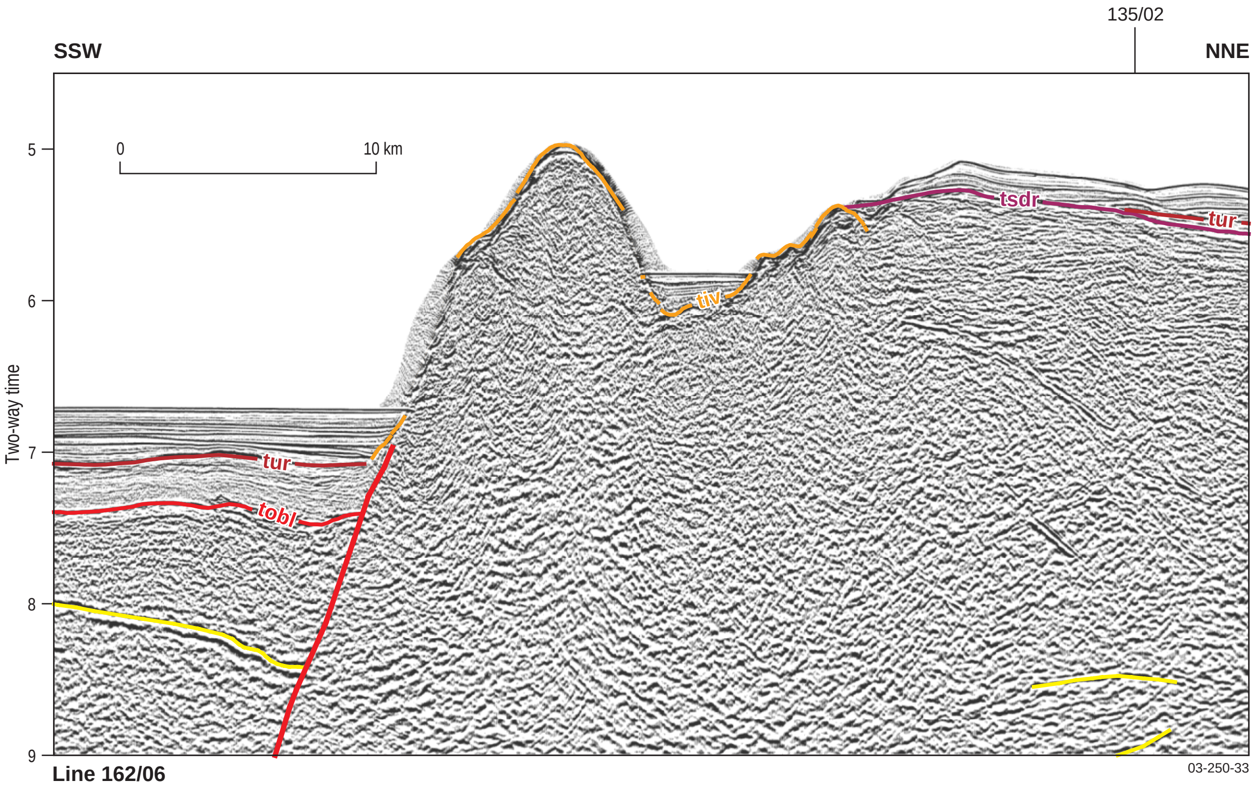


Figure 33. Type seismic section, Line 162/06 - transform volcanics.

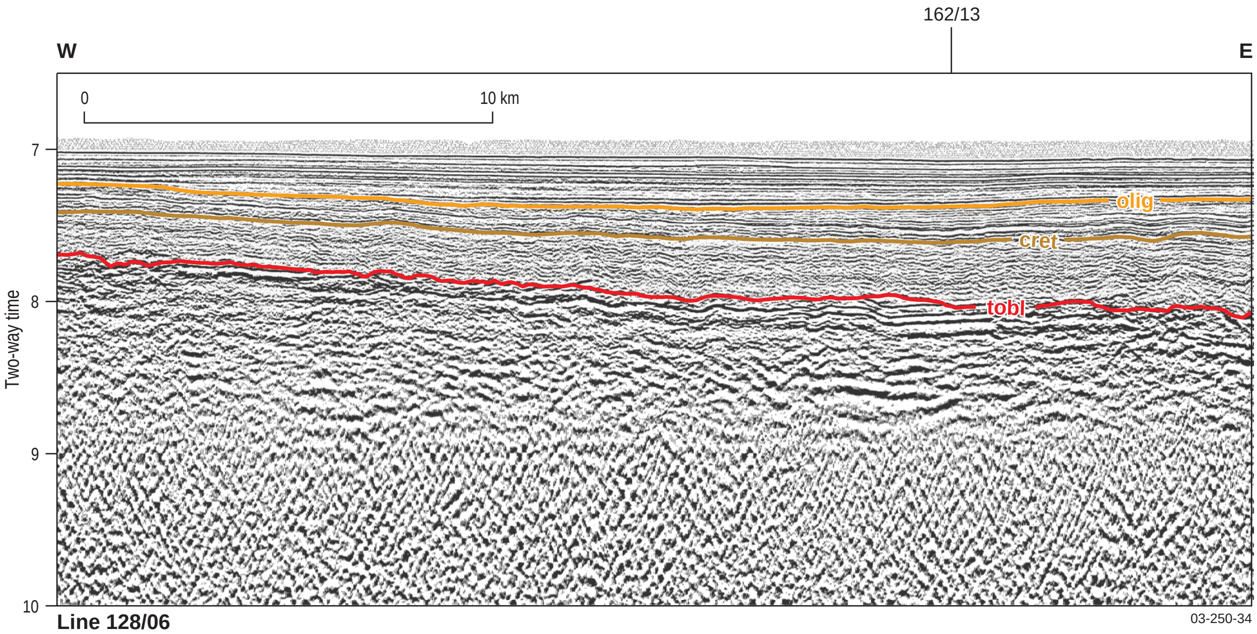


Figure 34. Type seismic section, Line 128/06 - layered oceanic basement.

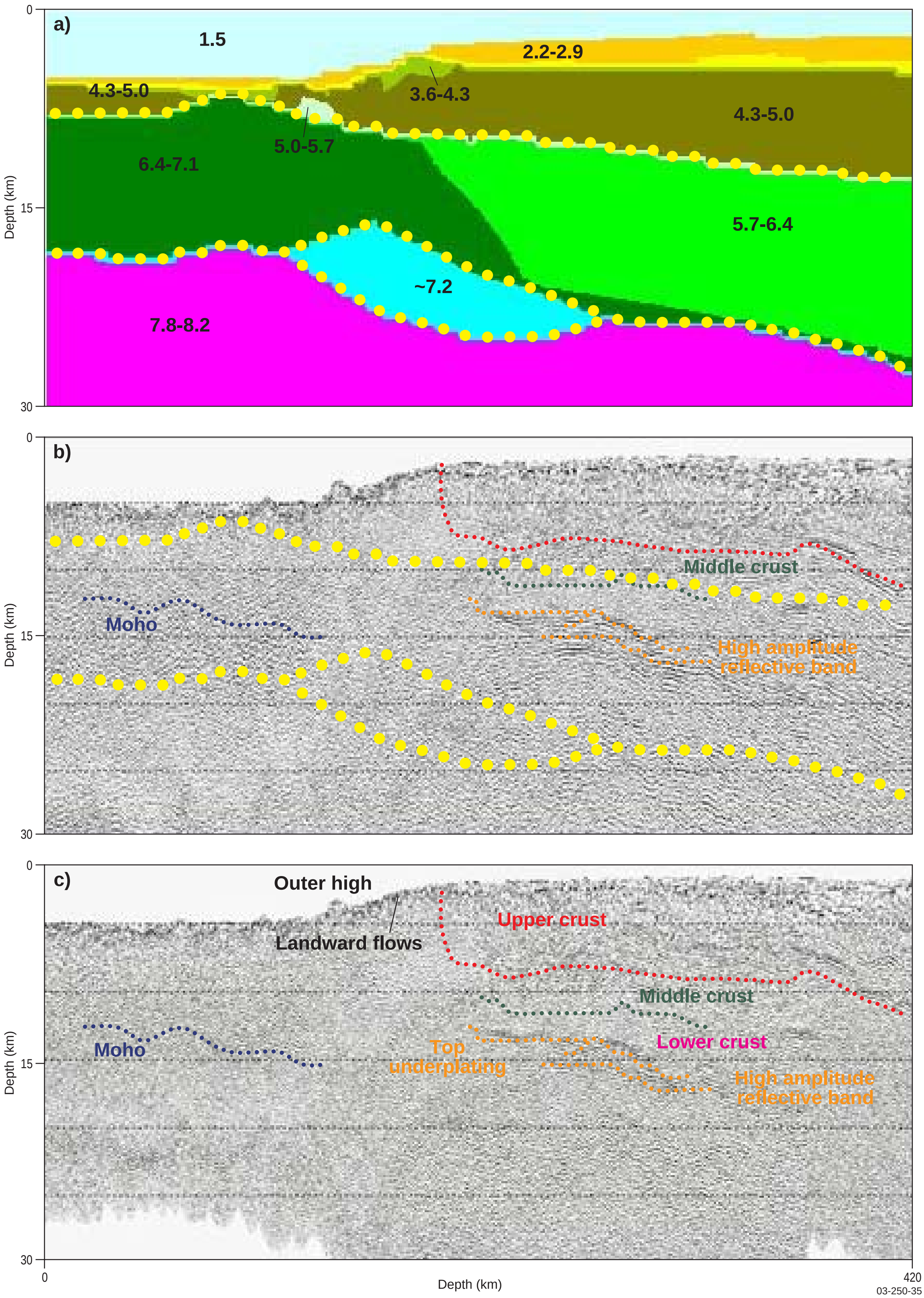


Figure 35. Interpretation of OBS line from the outer Exmouth Plateau (after Fomin et al., 2000). (a) Seismic velocity model from the OBS data; (b) Seismic section along the coincident reflection seismic line depth-converted with OBS velocities; and (c) Depth-converted with stacking velocities.

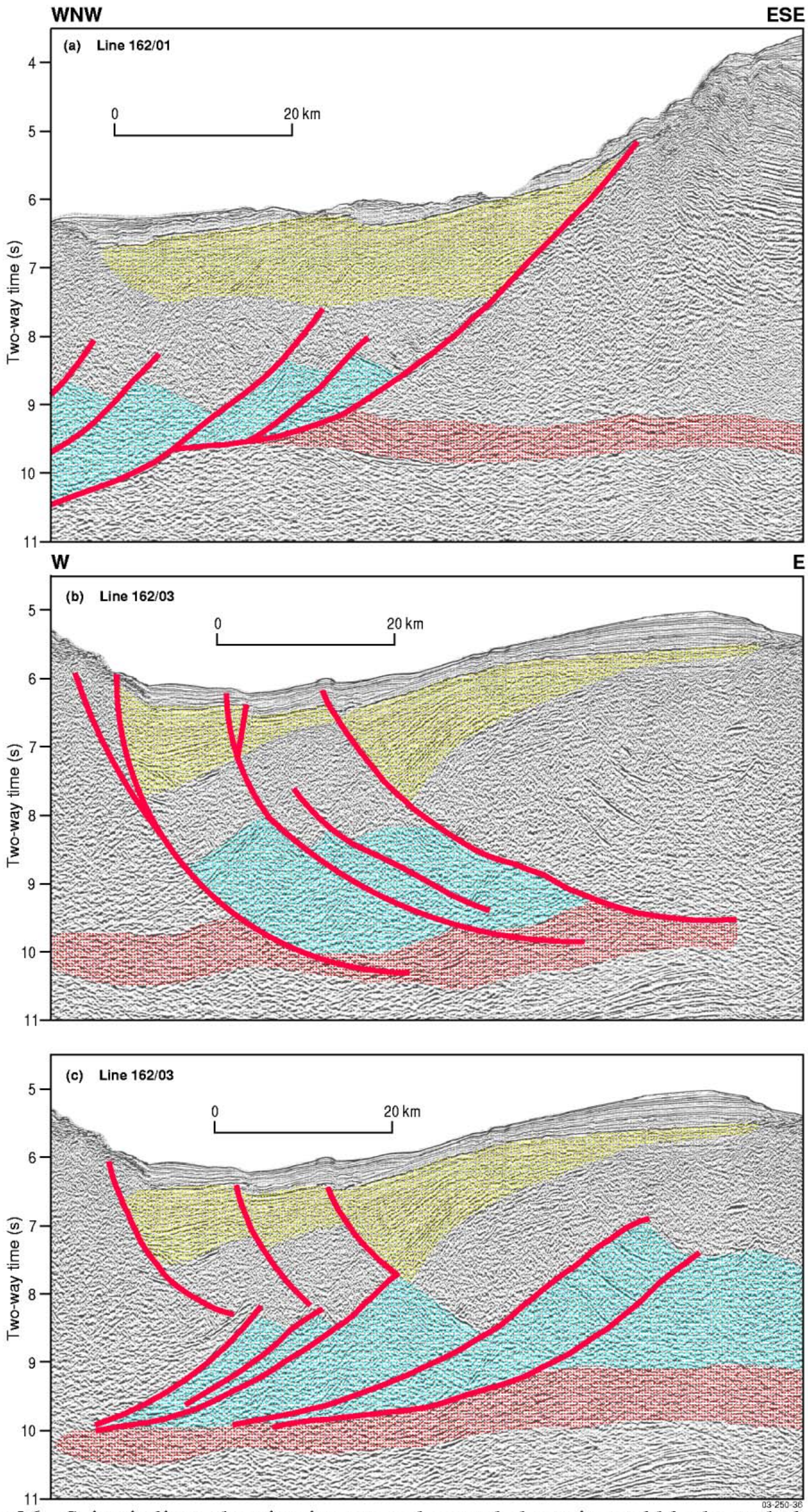


Figure 36. Seismic lines showing interpreted extended continental blocks underlying SDRS in the 'magmatic crust' province on the Gascoyne margin. (a) Line 162/01, showing the outboard edge of unequivocal continental crust with interpreted fault blocks lying beyond the major bounding fault. (b) and (c) Line 162/03, showing alternative interpretations of fault blocks of possible continental crust underlying SDRS.

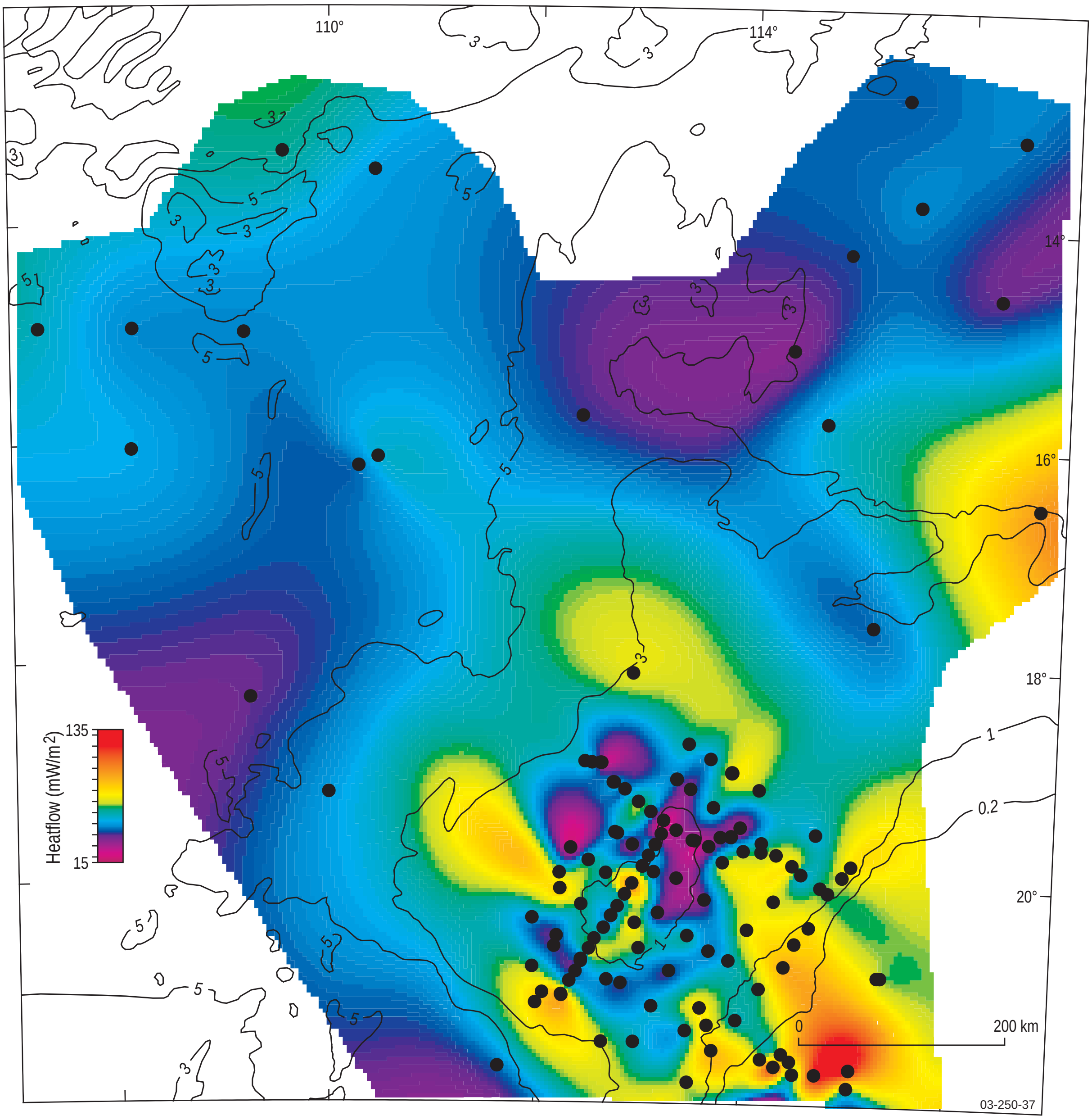


Figure 37. Present-day heatflow on the Exmouth Plateau and adjacent ocean basin. Heatflow stations are shown as black dots. 0.2, 1, 3, 5 km bathymetric contours are also shown.

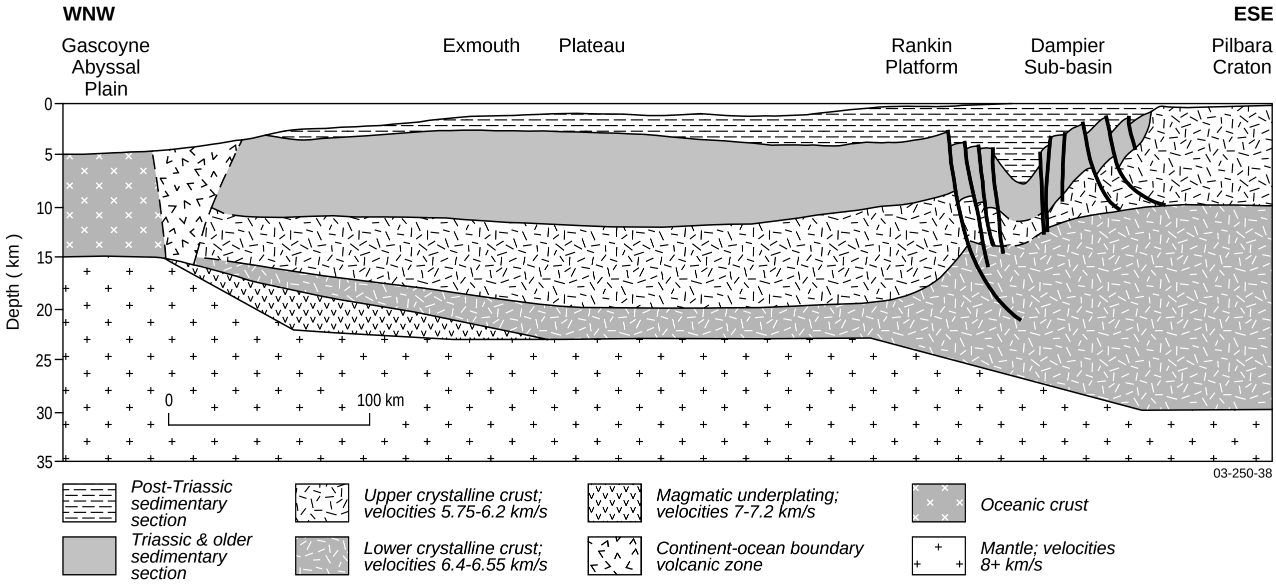


Figure 38. Composite depth profile from the northern margin of the Pilbara Block, across the Dampier Sub-basin and Exmouth Plateau, to the Gascoyne Abyssal Plain. The model is derived from Geoscience Australia deep-seismic data, expanding-seismic profiles (Mutter et al., 1989), and the work of Drummond (1981) on the Pilbara Craton (after Stagg & Colwell, 1994).

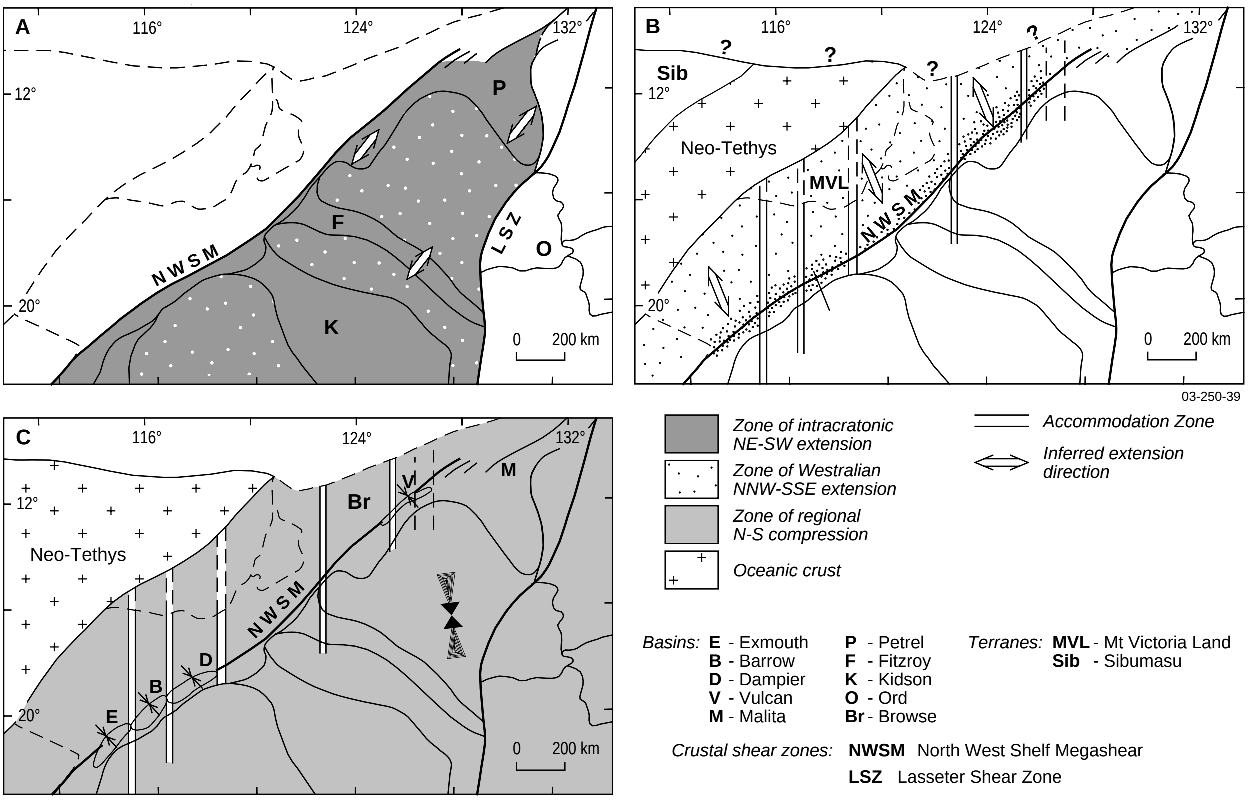


Figure 39. Conceptual evolution of the North West Shelf Basin System (after AGSO North West Shelf Study Group, 1994). (a) Late Devonian - Early Carboniferous. (b) Mid-Carboniferous - Early Permian. (c) Late Triassic - Early Jurassic.

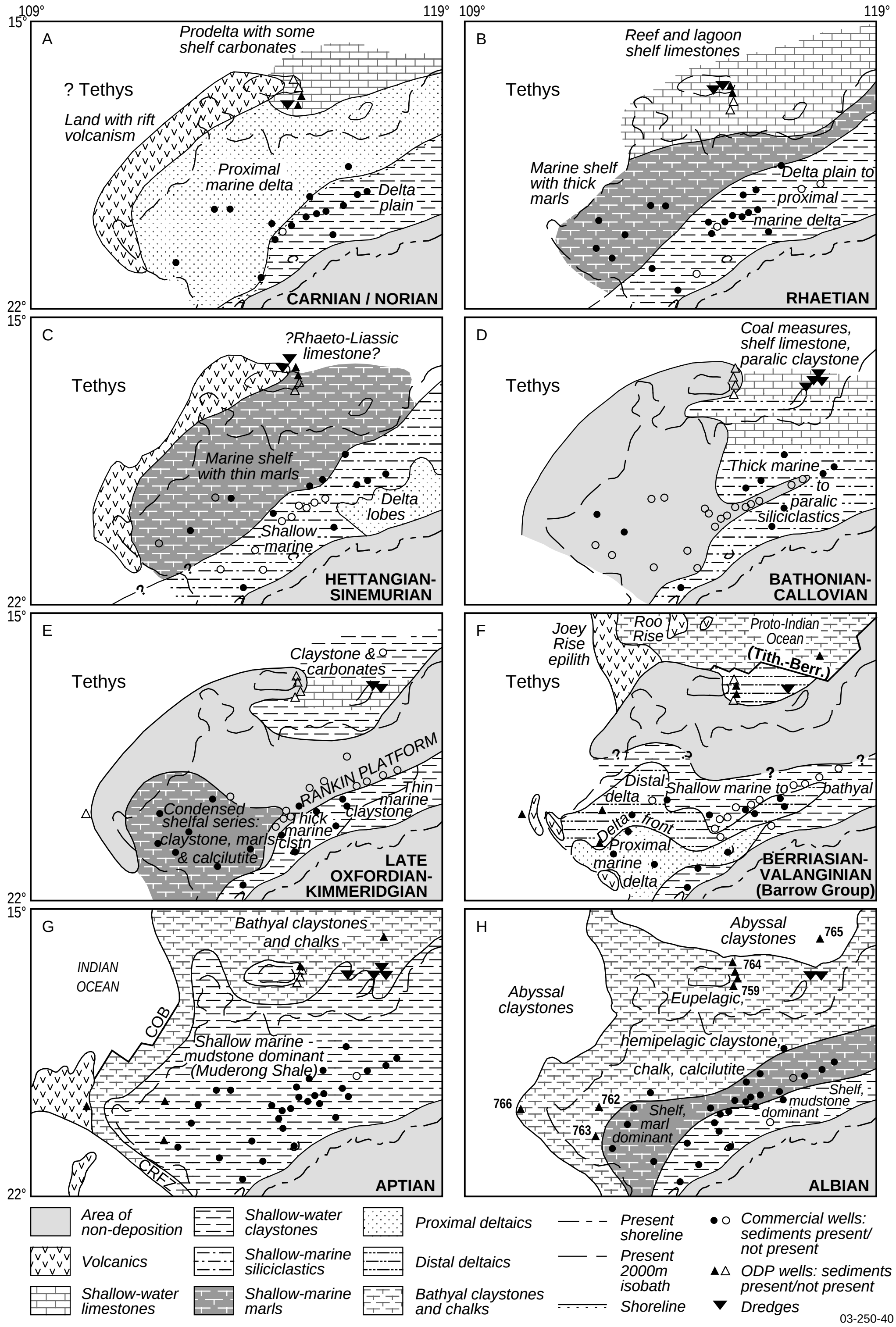
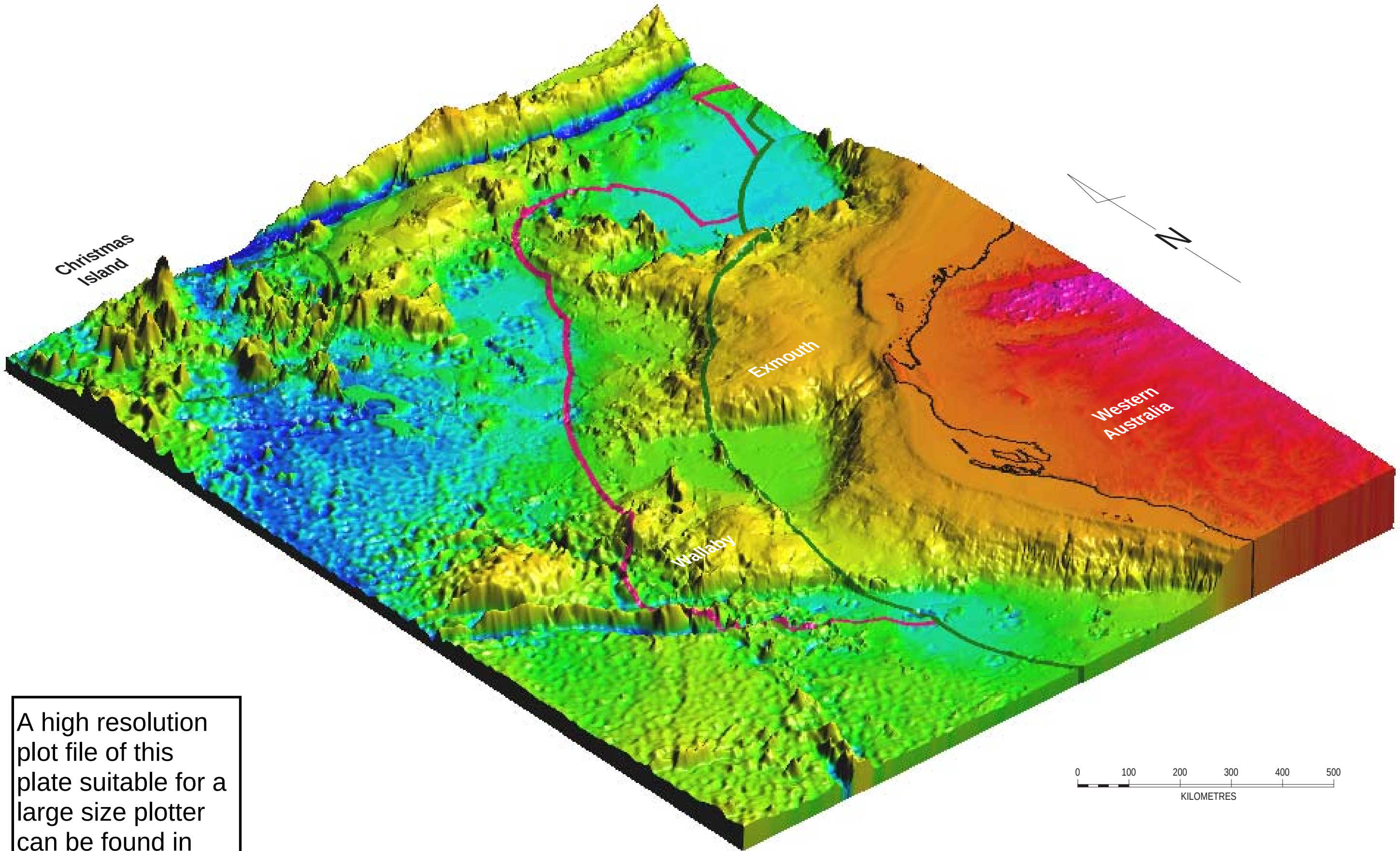


Figure 40. Palaeogeographic sketch maps for eight periods in the development of the Exmouth Plateau and adjacent areas (after Exon et al., 1992). Drawn from information from ODP Sites, commerical exploration wells, dredges and seismic profiles.A. Carnian-Norian(Mungaroo Formation):palaeo-latitude 50-55°S. B. Rhaetian: palaeolatitude 25-30°S. C. Hettangian-Sinemurian: palaeolatitude 35-40°S. D. Bathonian-Callovian: palaeolatitude 35-40°S. E. Late Oxfordian-Kimmeridgian: palaeolatitude 35-40°S. F. Berriasian-Valanginian (Barrow Group): palaeolatitude 33-38°. G. Aptian (Muderong Shale: palaeolatitude 35-40°S.H. Albian(Gearle Siltstone & Haycoc Marl): palaeolatitude 35-40°S. Declination was in the range 280-330°.



A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

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Plate 1
Shaded Bathymetric Image of the Exmouth Plateau Region

Australian Government
Geoscience Australia

Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13

03-250-41

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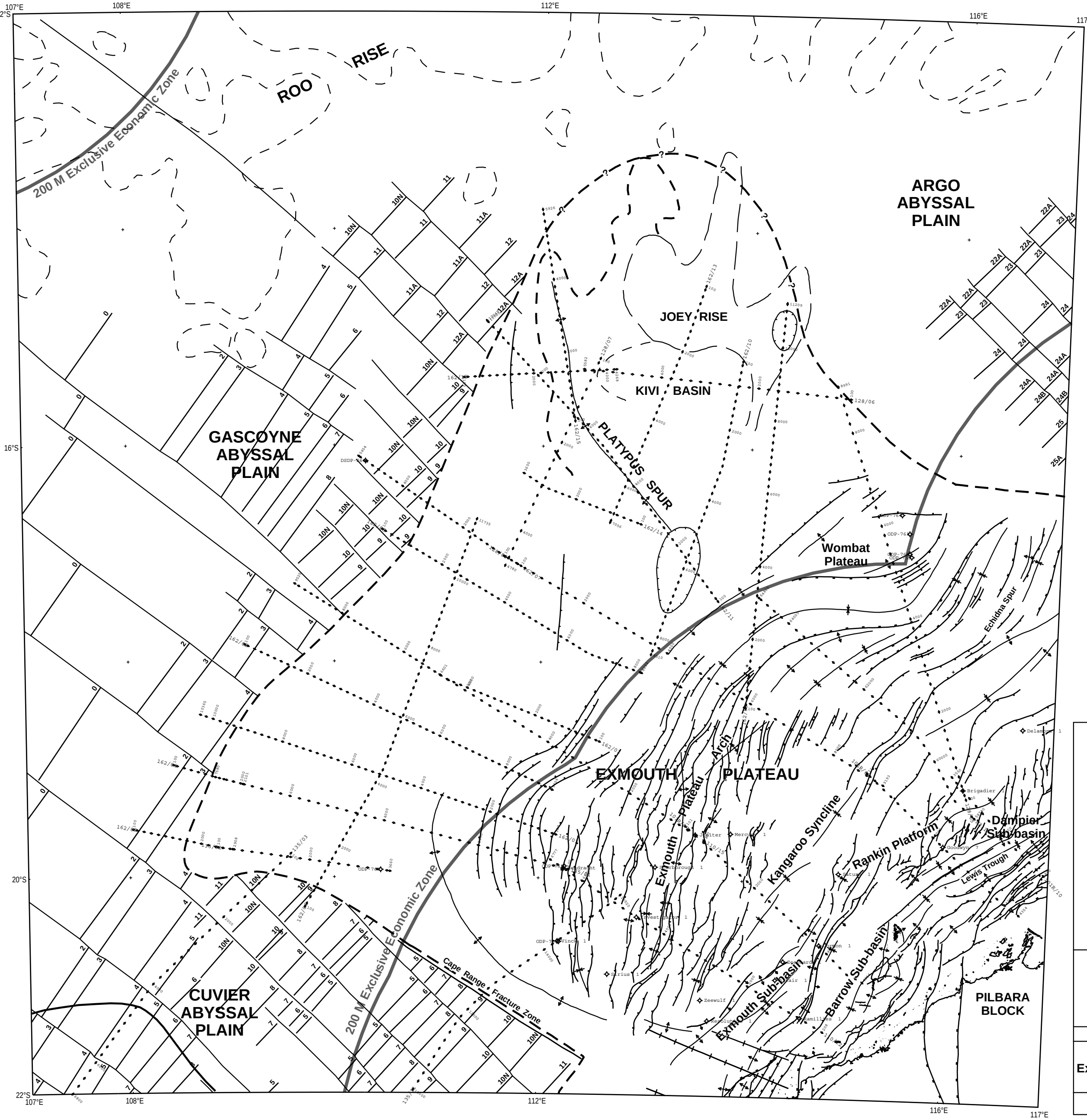

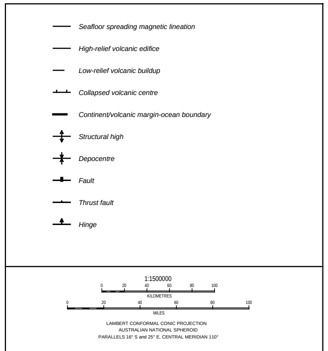

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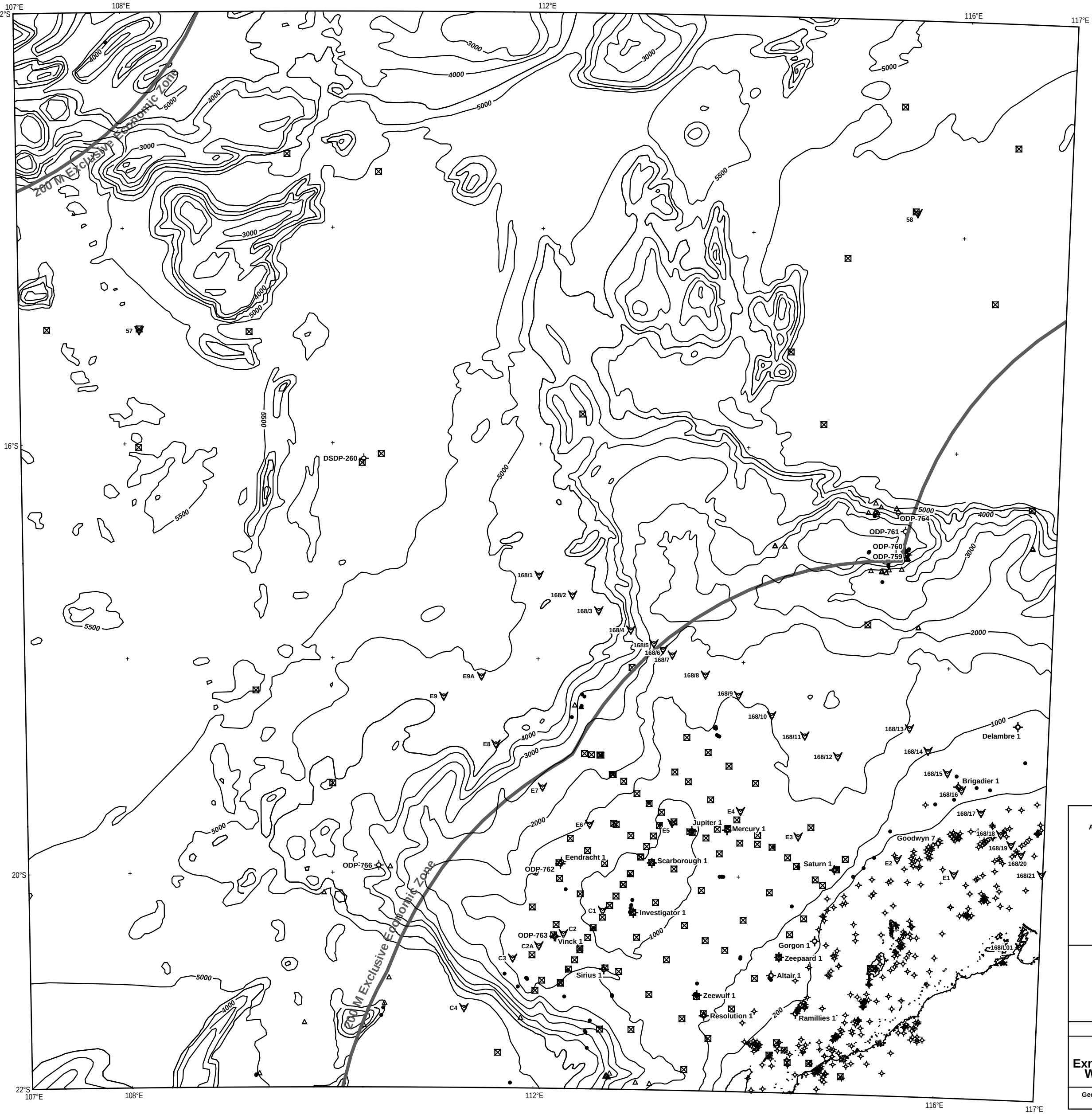
Plate 2
Exmouth Plateau Tectonic Elements, Seismic Line and Well Locations

Australian Government
Geoscience Australia

Geological framework of the outer Exmouth Plateau and adjacent ocean basins. Geoscience Australia, Record 2004/13



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Altair 1 — Well used in study

Well not used in study

Dredge station

Core station

Heat-flow station

168/14 — Crustal velocity measurement

1:1500000

KILOMETRES

MILES

LAMBERT CONFORMAL CONIC PROJECTION
AUSTRALIAN NATIONAL SPHEROID
PARALLELS 16° S and 25° E, CENTRAL MERIDIAN 110°

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Plate 3

Exmouth Plateau Bathymetry, Key Wells and Geological Stations

Australian Government
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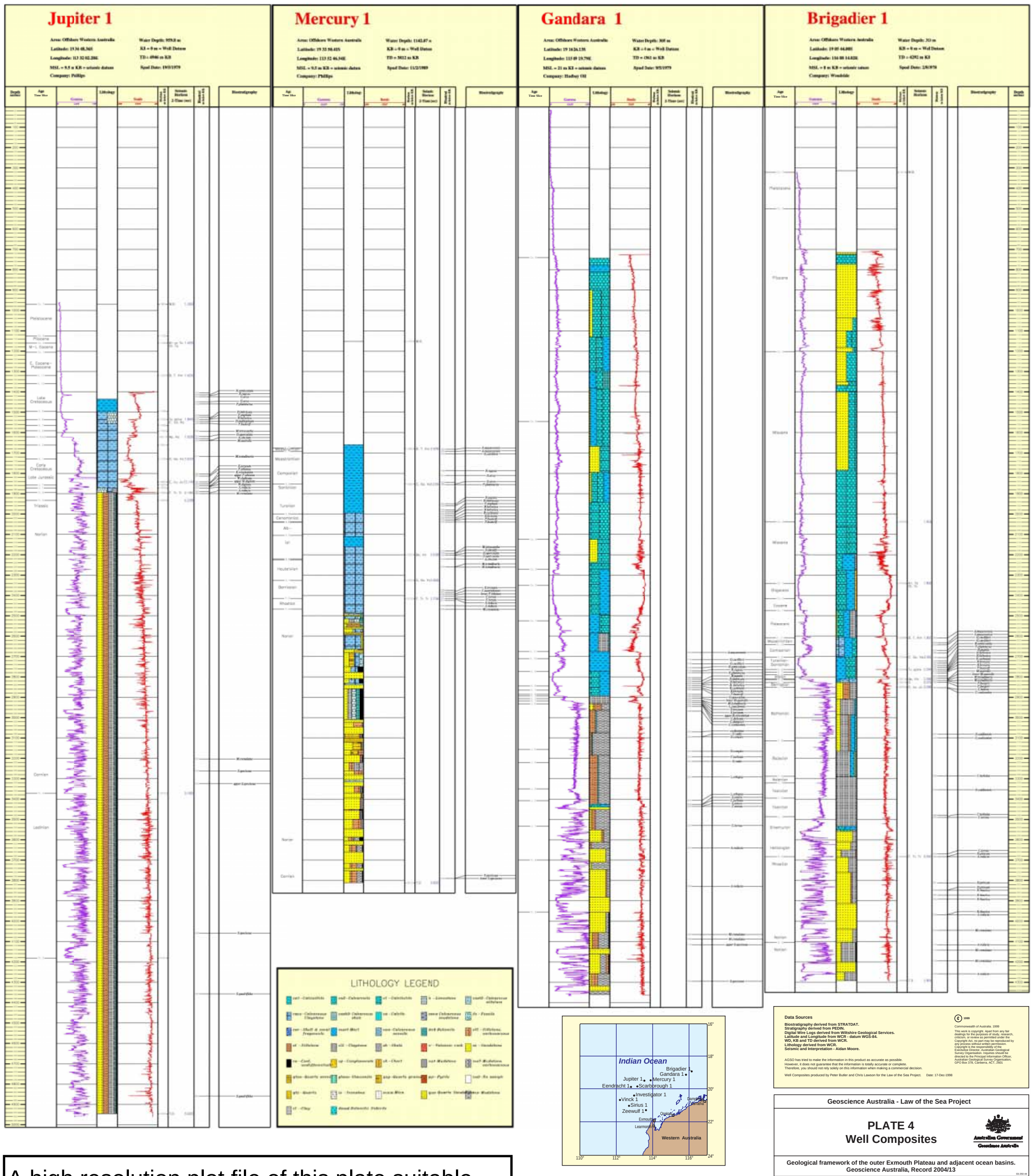
Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13



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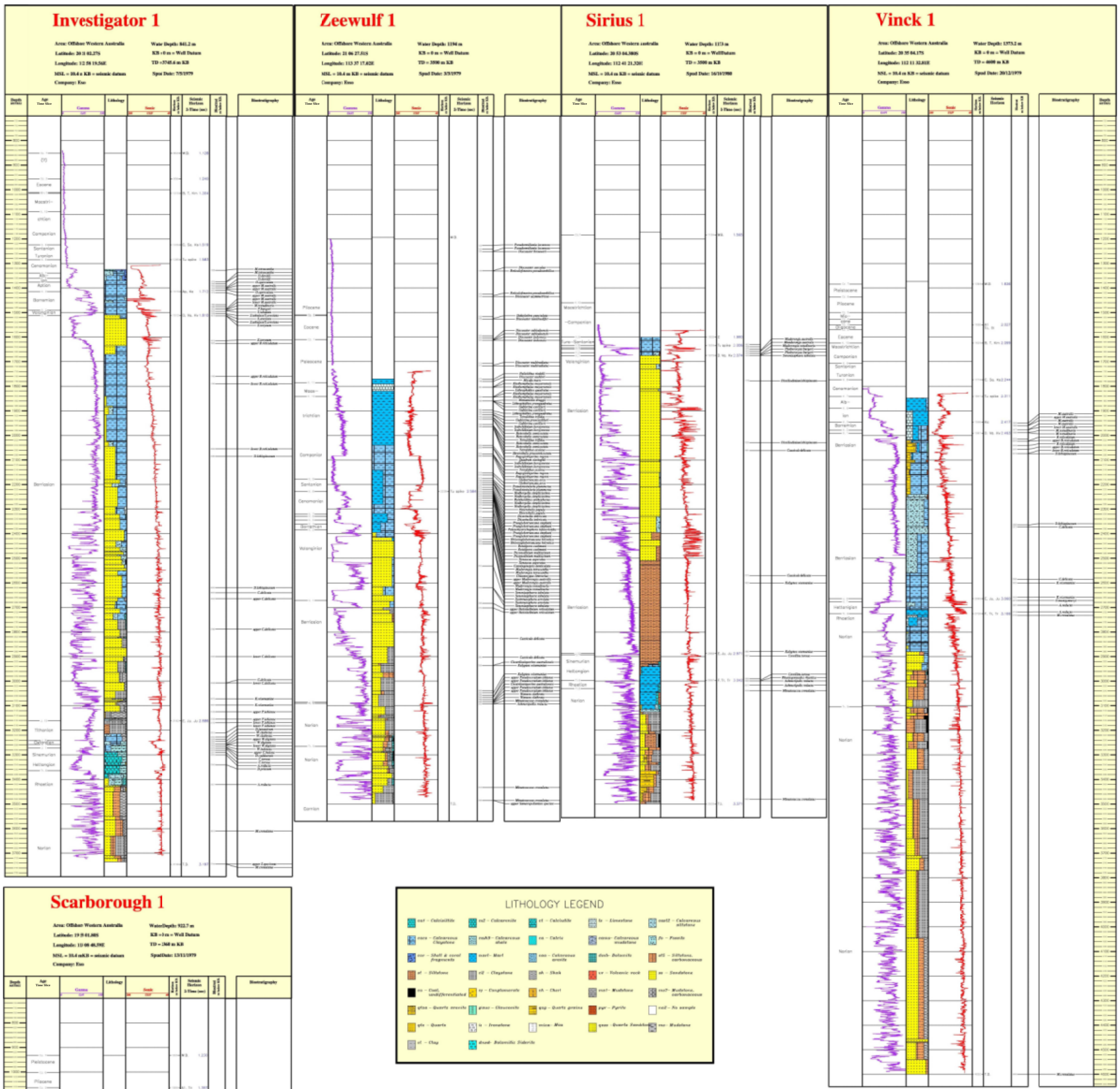

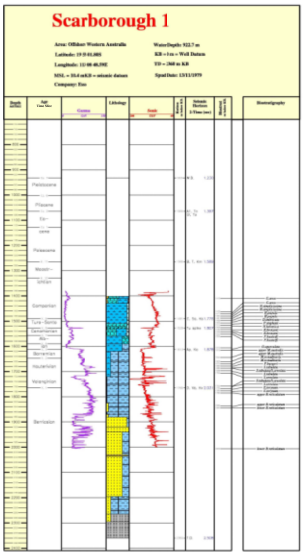

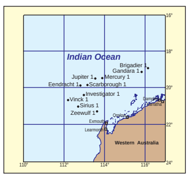

A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Data Sources

Biostratigraphy derived from STRATDAT.
Stratigraphy derived from PEDIN.
Digital Wire Logs derived from Wiltshire Geological Services.
Latitude and Longitude from WCR - datum WGS-84.
WD, KB and TD derived from WCR.
Lithology derived from WCR.
Seismic and Interpretation - Aidan Moore

AGSO has tried to make the information in this product as accurate as possible. However, it does not guarantee that the information is totally accurate or complete. Therefore, you should not rely solely on this information when making a commercial decision.

Well Composites produced by Peter Butler and Chris Lawson for the Law of the Sea Project. Date: 17-Dec-1998

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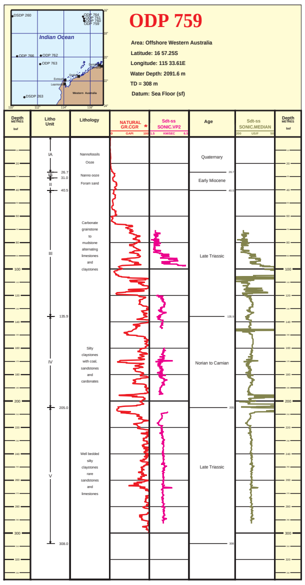
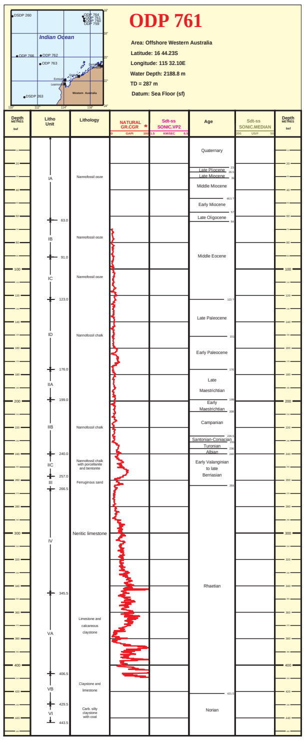
PLATE 5
Well Composites

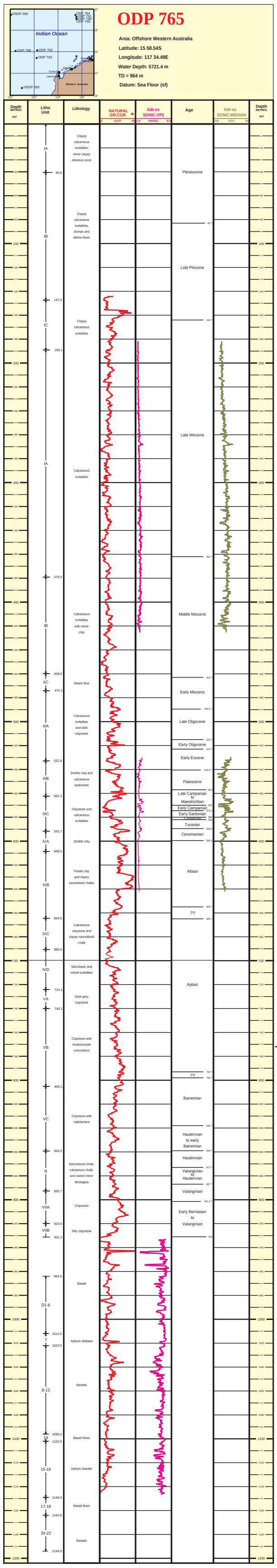
Australian Government
Geoscience Australia

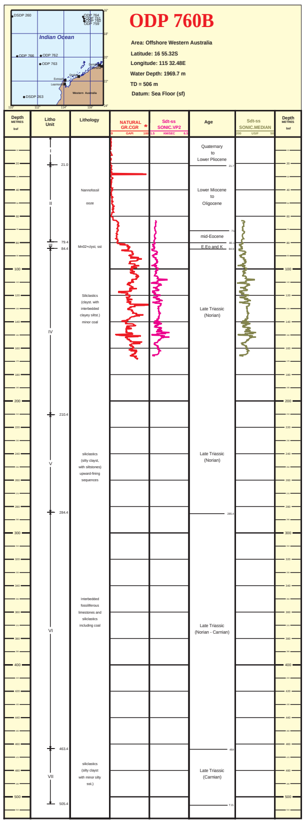
Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13

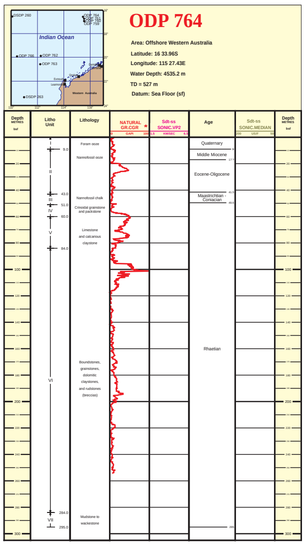
03-250-45











A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Data Sources

Latitude, Longitude, Water Depth, Total Depth, Lithology, Lithology Unit and Age derived from Proceedings of the Ocean Drilling Program, ODP Volume 122 and 123, Scientific Results.

Digital Wire Logs derived from ODP web site.

*** Note the range of the scale for gamma logs on this display has been reduced because of low log readings. The range is shown at the top of the display.**

AGSO has tried to make the information in this product as accurate as possible. However, it does not guarantee that the information is totally accurate or complete. Therefore, you should not rely solely on this information when making a commercial decision.

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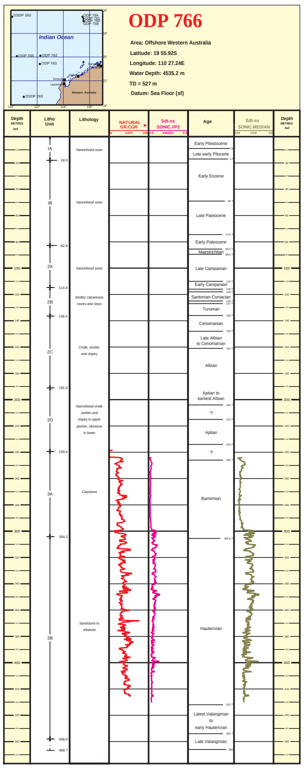
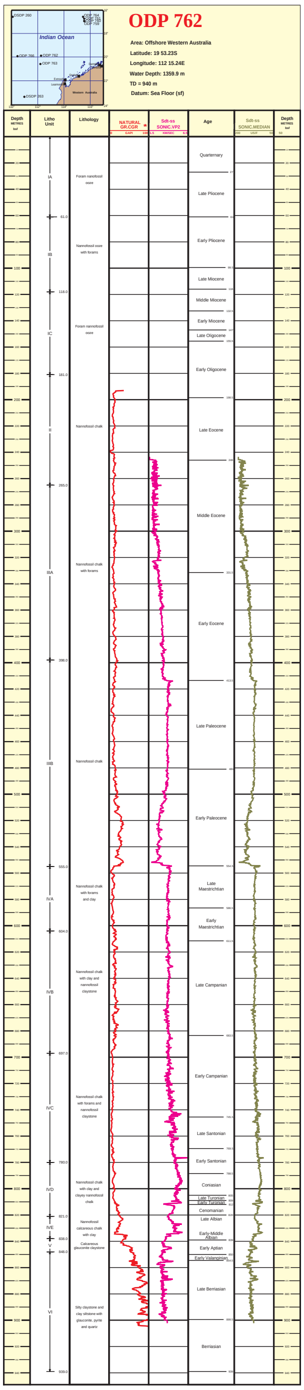
PLATE 6
Well Composites

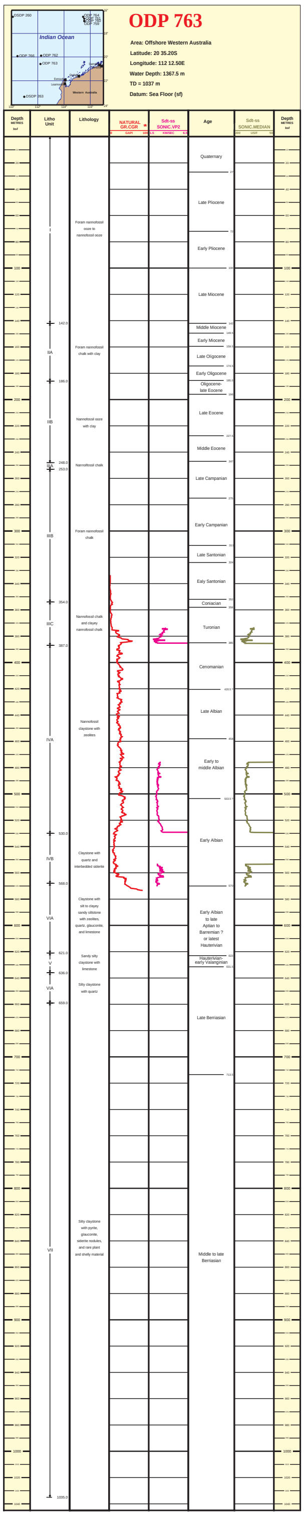
Australian Government
Geoscience Australia

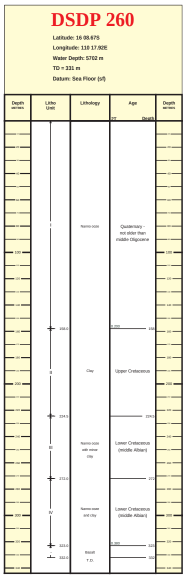
Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13

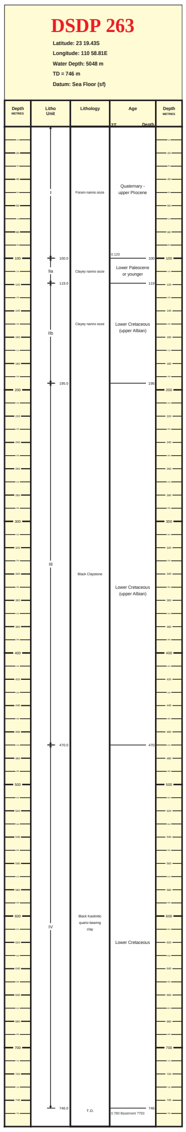
03-250-46











A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Data Sources

Latitude, Longitude, Water Depth, Total Depth, Lithology, Lithology Unit and Age derived from Proceedings of the Ocean Drilling Program, ODP Volume 122 and 123, Scientific Results.

Digital Wire Logs derived from ODP web site.

*** Note the range of the scale for gamma logs on this display has been reduced because of low log readings. The range is shown at the top of the display.**

AGSO has tried to make the information in this product as accurate as possible. However, it does not guarantee that the information is totally accurate or complete. Therefore, you should not rely solely on this information when making a commercial decision.

Well Composites produced by Peter Butler and Chris Lawson for the Law of the Sea Project. Date: 17-Dec-1998

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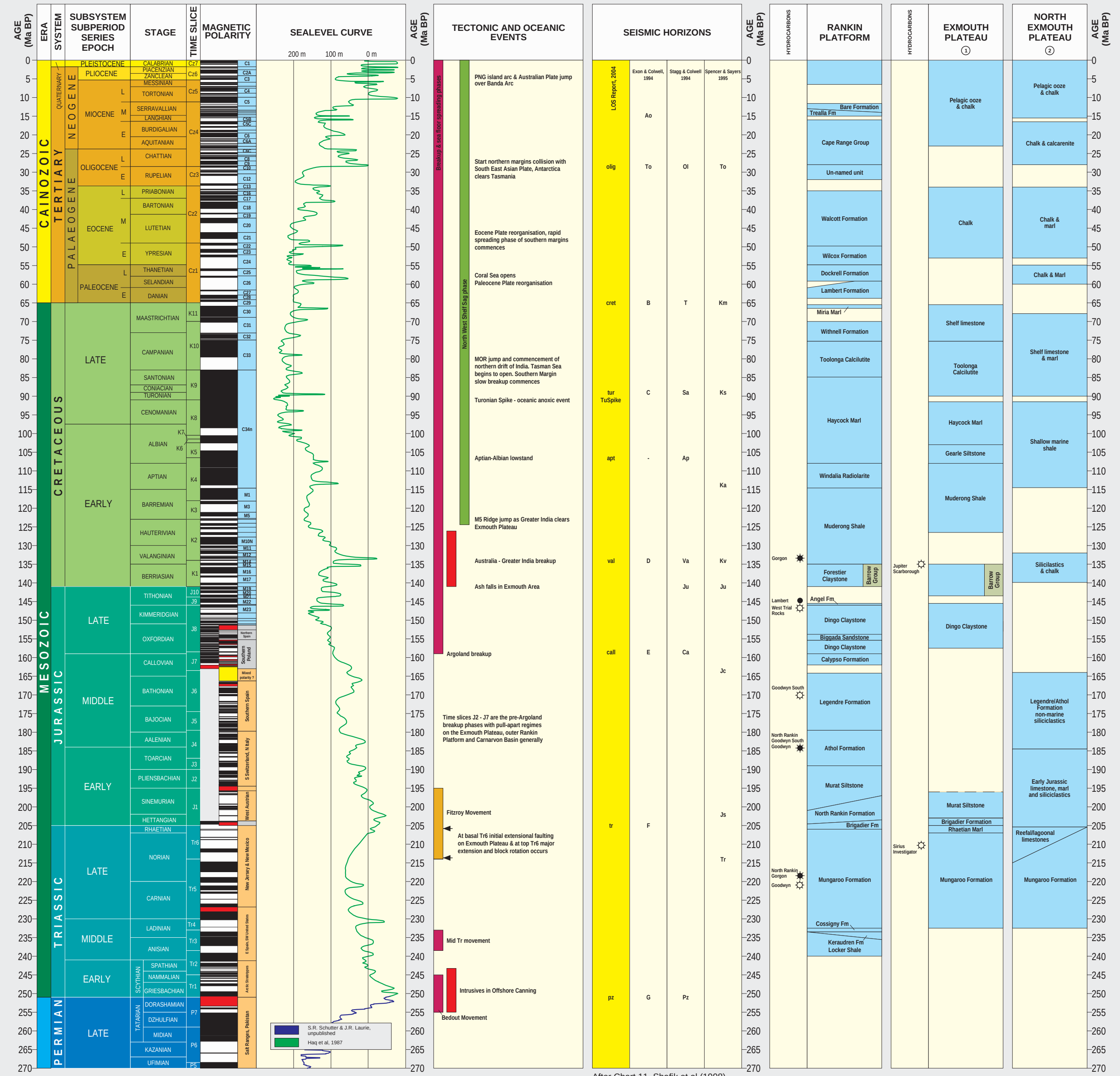
PLATE 7
Well Composites

Australian Government
Geoscience Australia

Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13

03-250-47



After Chart 11, Shafik et al (1998), modified extensively for Exmouth Plateau after Exon & Colwell (1994) and Exon & Von Rad (1994)

1 Southern & Central Plateau ODP & exploration wells

2 Northern Plateau ODP sites, Delambre 1 well dredging

A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

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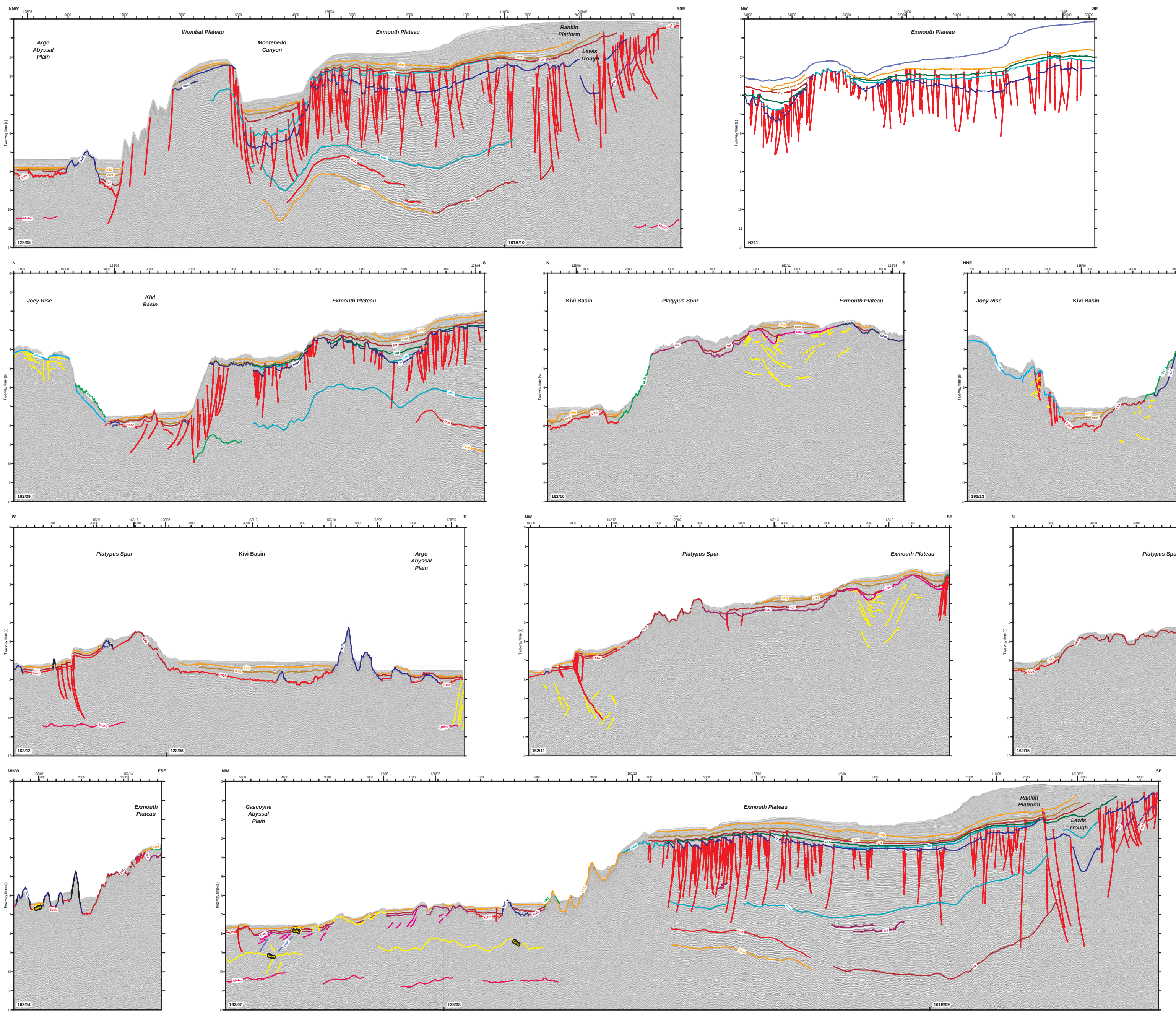
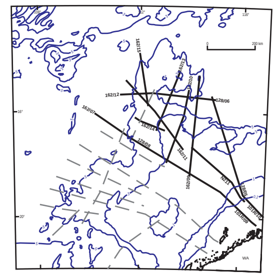
Plate 8
Exmouth Plateau
Stratigraphy, Sealevel, Tectonic and Ocean Events and Seismic Horizons

Australian Government
Geoscience Australia

Geological framework of the outer Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13





A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD

Seismic horizon	Description
olig	Oligocene
cret	Top Cretaceous
tur	Turonian; base carbonate section
val	Valanginian; Cuvier-Gascoyne breakup
call	Callovian; Argo breakup
tr	Top Triassic
pz	Near top Permian
xtal	Crystalline continental basement
tran	Top transparent continental crust
tlcb	Top laminated deep continental crust
blcb	Base laminated deep continental crust
c2	Deep crustal reflector beneath Exmouth Plateau
intr	Intrusions in continental crust (sub-vertical)
sill	Sills in continental crust (sub-horizontal)
icc	Strongly intruded ?continental crust
cvvm	Composite volcanics on ?oceanic and volcanic margin crust
civo	Composite intact volcano; oceanic setting
cvb	Really extensive, low-relief volcanic buildup
tdeb	Top debris flows
slop	Slope volcanics
tsdr	Top Seaward Dipping Reflector Sequence (SDRS)
bsdr	Base Seaward Dipping Reflector Sequence (SDRS)
flow	Volcanic flows overlying sediments on continental crust
udif	Inter-SDRS volcanic buildup
buil	Volcanic buildups; oceanic setting; no associated SDRS
tobs	Top smooth ?oceanic and volcanic margin basement
tobl	Top layered ?oceanic and volcanic margin basement
tobr	Top rough ?oceanic and volcanic margin basement
oflo	Flows/sills above oceanic basement
tlam	Top reflective oceanic crust
tiv	Volcanics extruded along transform faults
Moho	Moho

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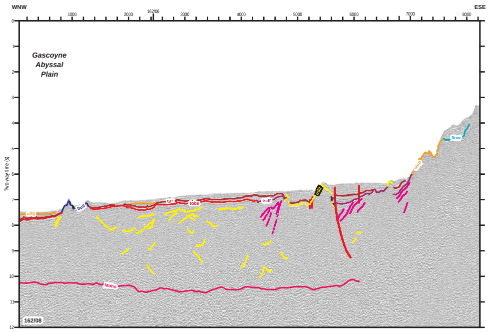
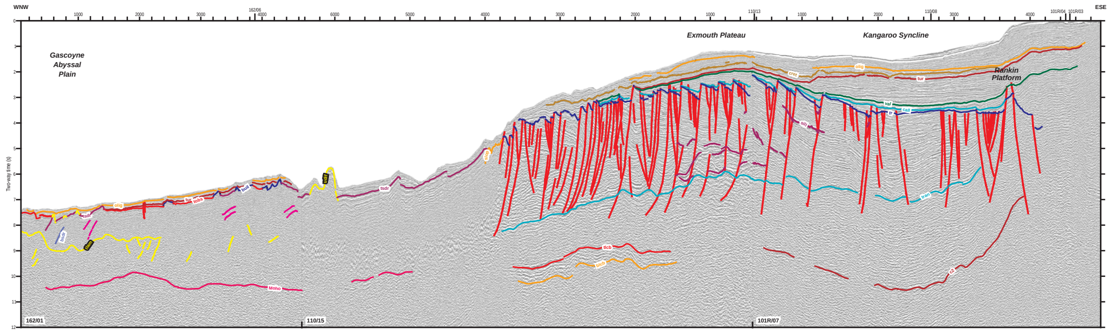
PLATE 9
Interpreted Seismic Sections - Northern part of Plateau

Australian Government
Geoscience Australia

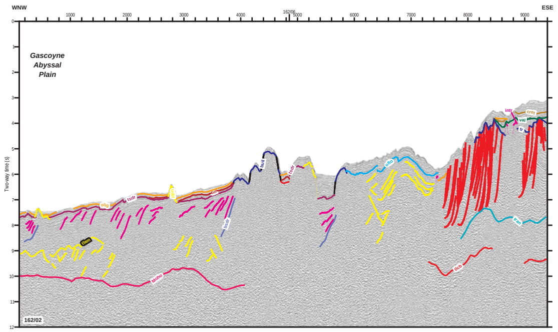
Geological framework of Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13

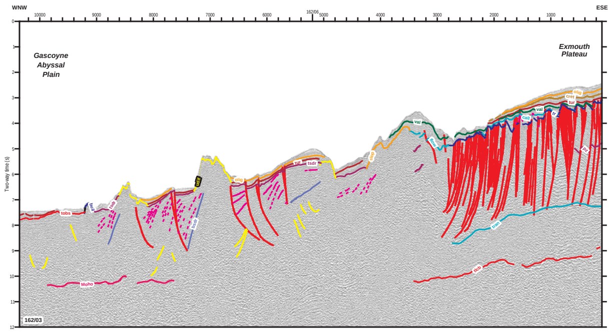
03-250-49

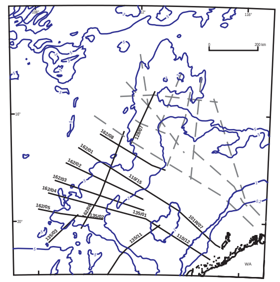


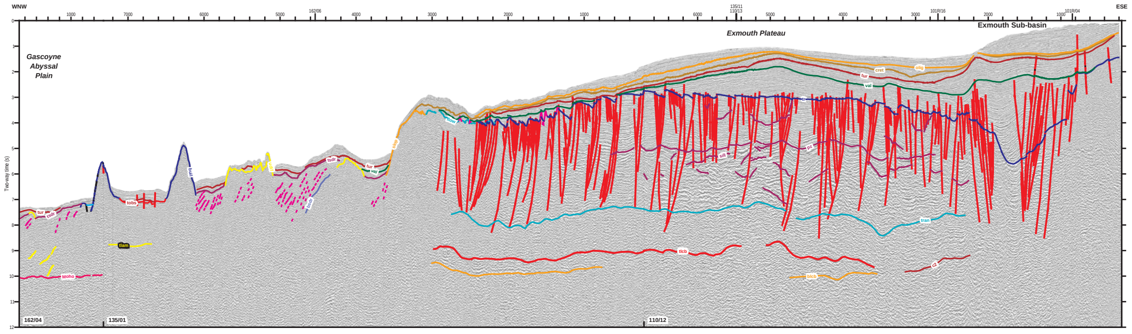


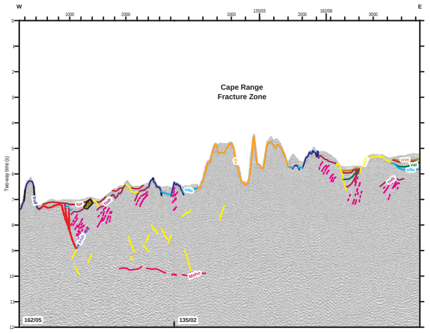
A high resolution plot file of this plate suitable for a large size plotter can be found in the Plot files sub-directory as .PS or .JPEG on this CD











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oflo	Flows/sills above oceanic basement
tlam	Top reflective oceanic crust
tiv	Volcanics extruded along transform faults
Moho	Moho

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PLATE 10
Interpreted Seismic sections - Southern part of Plateau

Australian Government
Geoscience Australia

Geological framework of Exmouth Plateau and adjacent ocean basins.
Geoscience Australia, Record 2004/13