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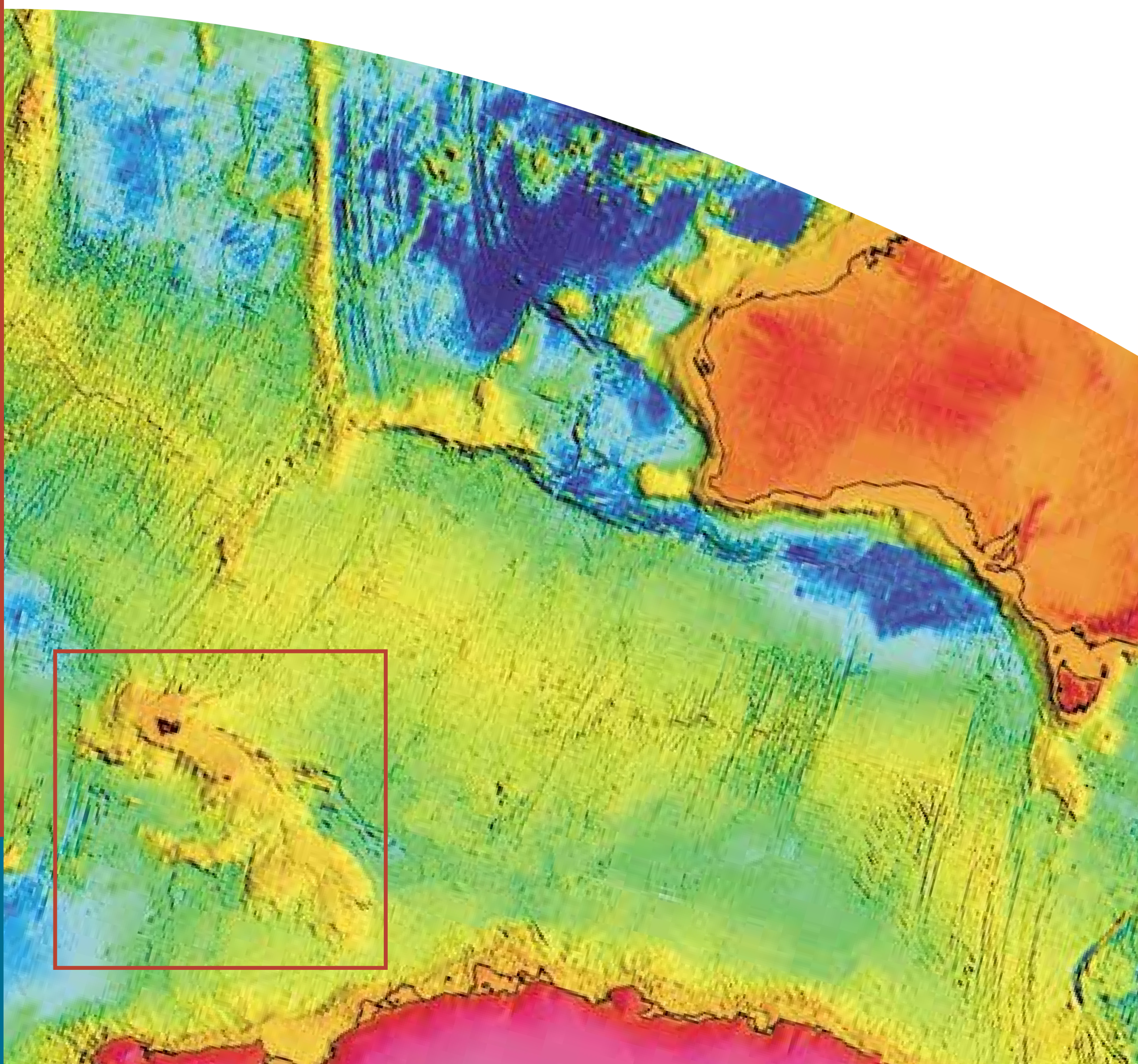

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GEOLOGICAL FRAMEWORK OF THE KERGUELEN PLATEAU AND ADJACENT OCEAN BASINS

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EXECUTIVE SUMMARY

The Kerguelen Plateau is one of the largest submarine plateaus in the world. It lies in water depths of 1000 to 4000 m and extends for more than 2500 km northwestwards from the Antarctic margin from about 65°S to 45°S. Because of the presence of Australian territory at Heard and McDonald Islands, a large part of the plateau lies within Australia's Exclusive Economic Zone (AEEZ) and potentially 'Extended Continental Shelf', as defined under the United Nations Convention on the Law of the Sea. The total area of the AEEZ around Heard and McDonald Islands and the potential Extended Continental Shelf amounts to about 1.4 million km^2. The northern part of the Kerguelen Plateau is under French jurisdiction and a boundary exists between the AEEZ and the French EEZ.

As part of its program to define the extents of the Australian Legal Continental shelf on the Kerguelen Plateau, Geoscience Australia (AGSO) acquired over 5500 km of new seismic data including the first regional datasets over Elan Bank and in the Labuan Basin. This report presents results of a geological framework study carried out to underpin Australia's seabed jurisdiction on the Kerguelen Plateau. It provides an up to-date analysis of the stratigraphy, structure, geological evolution and petroleum prospectivity of the Kerguelen Plateau region taking into account recent ODP drilling, geological sampling, seismic reflection and refraction data, as well as potential field data.

The Kerguelen Plateau can be subdivided into several provinces with distinctly different morphology, structure and tectonic history. These provinces are:

- Northern Kerguelen Plateau
- Central Kerguelen Plateau
- Southern Kerguelen Plateau
- Elan Bank
- William's Ridge
- Labuan Basin

Stratigraphy, tectonic and depositional history of each province have been summarised in this report.

The study addressed a number of important issues:

1. Kerguelen Plateau crustal structure

The Kerguelen Plateau has a long history of debate about the origin of its crust. Basement recovered by drilling is represented in most cases by magmatic crust. However, refraction and geochemical data indicate unusually thick crust and continental contamination in some parts of the plateau. Recent ODP drilling on the Elan Bank recovered continental rocks, which suggests that Kerguelen Plateau may be partly underlain by continental crust.

2. Age and origin of the Labuan Basin

New high-resolution seismic data in the Labuan Basin provided the first regional coverage of this remote basin. Its complex basement structure, refraction results and mapped sequences provide new insights into the possible crustal structure and evolution of this basin.

3. Volcano-seismostratigraphy of the Kerguelen Plateau

Seismic sections from Kerguelen Plateau display a range of volcanic features including dipping reflector sequences, multiple lava flows, volcanoclastic debris accumulations and sills. Their characteristics and possible origin are discussed.

4. Tectonic and depositional history of the region

The tectonic history of the Kerguelen Plateau and Labuan Basin are closely linked to the breakup of Indian Australia and Antarctica. Most of the plateau formed during Barremian-Albian as a large igneous province over the Kerguelen Hotspot. The plateau grew at or near the axis of the mid-ocean ridge separating India from Australia/Antarctica in close proximity to continental margins. The tectonic history of the region is very complex and includes several phases of volcanism, a major rifting episode in the Late Cretaceous, and differential vertical movements through the Tertiary. The northern part of the plateau is still volcanically active. The Labuan Basin appears to be older than the Kerguelen Plateau and its formation is linked to the long period of principally amagmatic extension between Australia and Antarctica.

5. Resource potential of the Kerguelen Plateau

The resource potential of the Kerguelen Plateau is largely unknown. Drilling results indicate that parts of the plateau were subaerial in Late Cretaceous and the climate was warm enough to sustain tree growth. There are two large sedimentary basins on the Kerguelen Plateau – the *Kerguelen-Heard Basin* to the north of the Heard Island and the *Raggatt Basin* in the southern part of the plateau. Sediment thickness in both basins is sufficient for generation of hydrocarbons under favourable circumstances. The prospective areas are not limited to the basins on the Kerguelen Plateau. The deep water Labuan Basin off the eastern flank of the plateau contains up to 5 km of sediment. Bottom simulating reflectors (BSR) mapped on the new seismic reflection sections from the northern part of the Labuan Basin may indicate the presence of gas hydrates.

1. INTRODUCTION

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

A preliminary analysis of the extent of Australia's "legal" Continental Shelf (LCS) under UNCLOS (Symonds and Willcox, 1989) indicated that it could be at least 14.8 million square kilometres in area - nearly twice the area of the continent and one of the world's largest. Nine areas of "extended" Continental Shelf, totalling an area of about 3.7 million km^2, extend beyond the 200 nautical mile Australian Exclusive Economic Zone (AEEZ). Geoscience Australia (former Australian Geological Survey Organisation or AGSO) has the responsibility for ensuring that Australia has the necessary technical information to fully define its LCS under UNCLOS. Geoscience Australia has adopted a 'safe minimum' approach to Continental Shelf definition in which bathymetric and seismic data are acquired to produce profiles spaced about 30 nautical miles apart over areas of margin extending beyond the AEEZ. Internal AGSO assessments indicated that further data collection and analysis was needed in about six of the nine areas extending beyond the AEEZ. One of the areas requiring such analysis was the Kerguelen Plateau, where Australia has potentially a very large LCS jurisdiction surrounding Heard and McDonald Islands (Fig. 1 and 2).

A comprehensive seismic and bathymetric database is being compiled for each of the potential extended Continental Shelf areas to substantiate the outer limit of Australia's jurisdiction. In addition, in the areas of complex morphology and ambiguous crustal structure, a detailed understanding of the continental margin geology is essential to optimise the extent of the LCS.

This report presents results of the geological framework study underpinning the Australian claim over the southern part of Kerguelen Plateau. Equivalent reports have been prepared for the other areas of extended Continental Shelf. The data and the interpretations based on that data, contained in this report are not necessarily indicative 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.

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

Technical data pertinent to definition of Australia's UNCLOS claim on the southern Kerguelen Plateau are contained in Parums, et al. (in prep.).

1.1 Limits of the Study Area

The AEEZ around Heard and McDonald Islands includes the central part of the Kerguelen Plateau and the northern part of William's Ridge (Fig. 2). The northern part of the AEEZ overlaps with the French EEZ around the Kerguelen Islands. This negotiated boundary between France and Australia has been defined in an agreement on maritime delimitation between Australia and France that came into force in 1983 (Department of Foreign Affairs and Trade, 1983). However, the boundary between the extended continental shelves of the two countries (i.e. LCS outside of the EEZ) has only been negotiated in the east (Figs. 2, 3) and is yet to be considered in the west. Extended Continental Shelf lying to the south of the AEEZ covers almost 1 million km^2 (Table 1) and comprises the southern part of the plateau, Elan Bank, most of the William's Ridge and the Labuan Basin (Fig. 2). Australian jurisdiction over the Labuan Basin depends mostly on sediment thickness and is described in detail in Parums, et al. (in prep.).

Zone	***Approximate Area (km^2)***
AEEZ adjacent to Heard and MacDonald Islands	412 000
Extended Continental Shelf off Heard and MacDonald Islands	949 000
Total (Legal Continental Shelf)	1 361 000

Table 1: Relevant areas of AEEZ and Extended Continental Shelf.

1.2 Data sets used in the study

1.2.1 Bathymetry

Bathymetric datasets used in the study include gridded predicted bathymetry based on satellite gravity data (Smith and Sandwell, 1997; Fig.2, Plate 1) and GEBCO (General Bathymetric Charts of the Oceans) digital contours (IOC, IHO, & BODC, 1994). There is a significant discrepancy between the two data sets. GEBCO contours lack detail in areas poorly covered by ship tracks and Kerguelen Plateau has a lot of areas with very poor coverage. Predicted bathymetry (Fig 2, Plate 1) reflects well the morphology of the plateau and it depicts seamounts and ridges sometimes absent on GEBCO. However comparison with depths recorded along individual ship tracks shows that predicted bathymetry is not always accurate. An attempt to integrate the predicted bathymetry grid with bathymetric soundings recorded during seismic Surveys 179 and 180 in order to produce an improved gridded data set failed because of these large discrepancies, particularly on Elan Bank.

The Australian claim over the southern part of the Kerguelen Plateau is based exclusively on the bathymeric ship track data (Parums et al., in prep.). For the purpose of this study, bathymetry has been used mostly for visualisation purposes (complementing seismic and gravity data).

1.2.2 Seismic Reflection

Most of the seismic data over the northern part of the Kerguelen Plateau have been acquired by French vessels. Seismic data in the southern "Australian" part of the plateau acquired since the 1970s include the following surveys:

Eltanin (1971-1972)
The Kerguelen was surveyed by in 1977 and 1978 by *Eltanin* cruises 47 and 54. The survey lines are distributed evenly across the plateau and provide good regional coverage at about 150 km spacing (Fig. 4). *Eltanin* surveys comprise single-channel monitor sections of reasonably good quality, although highly compressed. This data helped constrain interpretation of the structural provinces particularly in areas not covered by recent datasets.

Rig Seismic 47 (1985)
This survey was conducted in 1985 (Ramsay and Colwell, 1986) over the central part of the plateau and first described the Raggatt Basin (Fig. 4, Appendix 2). Most of the survey lines are oriented E-W, with only one line running N-S (RS47/013). In total 5500 km of multichannel seismic data (48 channels) was recorded. Digital seismic data from this survey were used as one of the principal datasets for the study.

Marion Dufresne 47 (1986) and 67 (1991)
Both surveys were planned to achieve a general regional understanding of the southern part of the plateau. The lines are broadly spaced across the whole area and more or less orthogonal to major structural elements (Fig. 4).

Due to delays in the data exchange, access to these lines was not obtained until the late stages of the project. Interpretation of selected lines from *Marion Dufresne* surveys helped to constrain interpretation in the Labuan Basin and to verify the structural map of the region.

Nella Dan (1981)

Only one seismic line (Line 70) was acquired during the *Nella Dan* Survey 33 (Fig. 4). It is oriented E-W across the southernmost part of the plateau, which is particularly poorly covered by the other surveys. Although data are of poor quality, they provided a tie to ODP Site 738. This line was used to constrain interpretation of the southernmost part of Kerguelen Plateau.

Rig Seismic 179 and 180 (1997)

Two multichannel seismic surveys, GA (AGSO) Surveys 179 and 180, were carried out by *RV Rig Seismic* in 1997 to support the Law of the Sea claim in the Kerguelen Plateau region (Borissova, 1997; Ramsay et al., 1999; Bernardel et al., 1999; Appendix 2). Some of the lines also served as site surveys for ODP Leg 183 (Fig. 4; 179/01; 179/06 and 180/02). The majority of lines are located in the Labuan Basin (AGSO Survey 180) and on the Elan Bank (AGSO Survey 179). In total, 4600 km of deep (16 sec) seismic were recorded. This includes line RS179/07, a regional transect from the Enderby Basin across the whole plateau to the Australian-Antarctic Basin. Seismic data from these two surveys were the primary datasets used for this study.

1.2.3 Geological Samples.

Geological samples within the study area consist of drillholes of the Ocean Drilling Project (ODP), seabed core, dredge and grab samples, and outcrops on Kerguelen, Heard and McDonald islands (Fig. 5, Plate 2).

The ODP holes were drilled by the R/V JOIDES *Resolution*, and are described in the Proceedings of the Ocean Drilling Program, Initial Reports, and Scientific Results, by Barron, Larsen et al., (1989, 1991), Schlich, Wise, et al., (1989), Wise, Schlich et al., (1992), and by Coffin, Frey, Wallace et al., (2000). The seabed samples were taken by the vessels *Eltanin* (E), *Marion Dufresne* (MD), and *Rig Seismic* (RS), (Schlich, Wise et al, 1989). Location of ODP drillholes in respect to seismic lines is tabulated in Appendix 3. Age and composition of the seabed samples are compiled in Appendices 4 and 5.

Ocean Drilling Project (ODP):

Three drilling campaigns (Legs) of the Ocean Drilling Project (ODP) have drilled sites that are relevant to this study. The locations of the sites are shown in Figures 4 and 5 and on Plates 2 and 3.

<u>Legs 119 and 120</u> were designed as a latitudinal traverse of the Kerguelen Plateau and areas to the south, from the Kerguelen Archipelago to Prydz Bay, Antarctica. The object was to study the origin, nature, age and

tectonostratigraphic history of the plateau and areas to the south, and the movement of water masses and boundaries such as the Antarctic Convergence (Polar Front) over time. Leg 119 drilled Sites 736 and 737 on the Central Kerguelen Plateau (CKP), 738 and 744 in the southwest of the Southern Kerguelen Plateau (SKP), and Sites 745 and 746 on the scarp that forms the eastern edge of the SKP, adjacent to the Labuan Basin. Leg 120 drilled Site 747 in the Central Kerguelen Plateau (CKP), and Sites 748, 749, 750 and 751 on the Southern Kerguelen Plateau (SKP). Nearly all of the holes achieved their objectives, although a few had to be terminated early because of interference from icebergs (Sites 745, 746) or inability to drill further because of hole loss or blockage (Site 751). ODP Site 736 found a thicker Quaternary-Pliocene succession than anticipated, and was abandoned and supplemented by ODP Site 737, which achieved the objectives.

The objectives of Leg 183 were to investigate the timing of Kerguelen Plateau magmatism and the mineralogy of the basement in order to better understand the composition and origin of the lithosphere. Holes were positioned so as to sample the basement in areas that had not been covered by previous drilling campaigns. Leg 183 drilled Sites 1135 and 1136 on the Southern Kerguelen Plateau (SKP), Site 1137 on the Elan Bank to the west, 1138 in the Central Kerguelen Plateau (CKP), 1139 on the Skiff Bank west-southwest of Kerguelen Island, and Site 1140 north of the island on the Northern Kerguelen Plateau (NKP) (Fig. 5, Plate 2). Leg 183 had a good measure of success in achieving its objectives.

Seabed samples from coring and dredging

Piston coring was carried out by USNS *Eltanin* on cruise 47 and cruise 54 (Colwell et al, 1988; Kennett and Watkins, 1976; Markl, 1973; Quilty, 1973; Houtz et al., 1977), by MS *Marion Dufresne* on cruise 35 'DRAKAR', (Fröhlich, 1983; Fröhlich and Wicquart, 1989; Wicquart and Fröhlich, 1986), and cruise 38 'ANTIPROD III', (Fontugne and Fiala, 1987). Dredge samples were taken by MS *Marion Dufresne* on cruise 35 'DRAKAR', 48 'NASKA/SUZAN 1'(Davies et al., 1989, Leclaire et al., 1987), cruise 67 'KERSIMAG' (Montigny et al., 1993) and cruise 109 'KERIMIS' (Weis, Damasceno et al., 1998). Five grab samples were taken by RS *Rig Seismic* on AGSO survey 47 (Ramsay et al., 1986). The seabed samples most significant for this study are listed in Appendix 4 and their locations shown on Figure 5 and Plate 2.

Of particular significance in terms of age of igneous basement were samples MD48 dredges 5 and 6 from a basement outcrop on the central part of the Southern province, and Eltanin Core E54-7 in the southeastern part of the Central province. For understanding depositional history in the Kerguelen Heard Basin, dredges and cores of MD cruise 35 to the east of ODP 737 (Fröhlich and Wicquart, 1989) were of particular importance. Results from shallow cores and grabs revealing present day sedimentation on the Kerguelen Plateau are summarized in Appendix 5. Sampling results are discussed in more detail in the relevant chapters on major tectonic provinces.

1.2.4 Velocity Data

Refraction data was acquired on all three AGSO surveys (47,179 and 180). Six sonobuoy stations were deployed during the AGSO Survey 47, however only one of these located on the western flank of the plateau, produced useable results (Ramsay et al., 1986).

Twenty two sonobuoys were successfully deployed during Surveys 179 and 180 (Fig. 5, Appendix 6). Sonobuoy stations were located along the longest line across the plateau (RS179/07) and on all lines in the Labuan Basin (RS180) (Plate 2). Refraction modelling was carried out for most sonobuoys. Out of six sonobuoys from survey 179, five have been modelled. Sonobuoy Site 179-5 (Appendix 6) was not modelled due to the small offset range of the refraction arrivals. Out of sixteen sonobuoys deployed during Survey 180 (Bernardel, 1999), eleven were successfully modelled. Modelling was not attempted for five sonobuoys where refraction arrivals had a small offset range. All refraction results are summarised in Appendix 8.

Refraction solutions from sonobuoys in the Labuan Basin have been used for groundtruthing sediment thickness calculations based on stacking velocities and for understanding the crustal structure of the basin.

1.2.5 Potential Field Data

Gravity and magnetic data have been used extensively to constrain the interpretation. Sources of potential field data include free-air gravity and magnetic intensity data calculated from shipboard recordings. Spatial correlations between structural elements were facilitated by a satellite gravity image derived from 2-minute satellite gravity dataset (Sandwell and Smith, 1997) (Fig. 6). This image has been particularly valuable for understanding the relationship between different geological structures in this remote frontier area, where shipboard data are both sparse and unevenly spaced.

1.3 Prevous work

The first geological studies of the Kerguelen Plateau started in 1960's. Since that time, it has been variously described as a fragment of Gondwanaland (Schlich et al., 1971), elevated oceanic crust (Udintsev, 1965), a product of a hotspot (Houtz et al., 1977) or an aborted mid-ocean ridge (Mutter and Cande, 1983). The Kerguelen-Heard basin (between Kerguelen and Heard Islands) was first investigated during cruises of *R.V. Gallieni* (Schlich et al., 1971, Schlich, 1975) and *R.V. Eltanin* (Houtz et al, 1977). Its seismic stratigraphy was further developed based on the data from cruise MD26 of the *R.V. Marion Dufresne,* as well as coring and dredging results from MD35 sampling program (Wicquart, 1983, Wicquart and Fröhlich, 1986, Munschy and Schlich, 1987). The age and depositional environment of the rocks from Heard and McDonald islands were described by Clarke et al. (1983), Quilty et al. (1983), and Hilton et al. (1995). Geology of the Kerguelen archipelago has been summarised by Giret & Lameyre (1983) and by Nougier et al (1983). Both islands are composed of volcanic rocks ranging in age from Late Eocene to Recent.

The southern part of the Kerguelen Plateau was first described by Houtz et al. (1977) based on geophysical and geological data collected by *Eltanin* in 1971-72, but very little was known about its structure and stratigraphy until mid-80s. 12500 km of seismic reflection data collected by *Marion Dufresne* (MD47) *and Rig Seismic* (AGSO survey 47) in 1985-86 and a sampling program carried out during *Marion Dufresne* cruise 48 (1986) provided the basis for a more detailed stratigraphic and structural interpretation of the region (Munchy and Schlich, 1987, Fröhlich and Wicquart, 1989; Ramsay et al., 1986). The Raggatt Basin was discussed in Ramsay et al. (1986) and Coffin et al. (1986). The volcanic nature of the plateau and widespread dipping basement reflectors were discussed by Schaming and Rotstein (1990). The sedimentary fill of the Labuan basin was first described by Rostein et al. (1991). The nature and age of the igneous basement based on dredging along the 77^{o} graben was first discussed by Leclaire et al. (1987). These data were also used to determine suitable ODP drilling sites for legs 119 and 120 (Barron, Larsen et al., 1989; Schlich, Wise et al., 1989; Peirce, Weissel et al., 1989). Interpretation and synthesis of the ODP drilling results with the seismic stratigraphy (Colwell et al., 1988; Coffin et al., 1990; Schlich and Wise, 1992; Fritsch et al., 1992: Munschy et al., 1992) improved understanding of the origin and tectonic history of the Kerguelen Plateau. It had become widely accepted that the Kerguelen Plateau formed in Early Cretaceous (120-115 Ma) as a large igneous province or LIP over the Kerguelen hotspot. Continental contamination of some basement rocks (Mahoney et al., 1995) has been explained by the close proximity of Gondwana continents at the time of the plateau formation. Large faults and rift systems on the plateau were attributed to a major tectonic event at the end of Maastrichtian (Munchy et al., 1992). The later stage of volcanism (from Oligocene to Recent) on the northern part of the plateau has been explained by plate movements over a fixed hotspot (Royer et al., 1991). After initial volcanism on Kerguelen Plateau the hotspot was transferred under the Indian

Plate and formed Ninetyeast Ridge (Frey, Jones, et al., 1991) then the hotspot returned to the Antarctic Plate initiating later volcanism on the Kerguelen Plateau.

The more recent studies of the Kerguelen Plateau include results of the MD67 cruise of *Marion Dufresne* (1991) in the southern part of the plateau (Angoulvant-Coulon and Schlich, 1994), which improved understanding of extensional structures. Gravity modelling of the Labuan basin based on preliminary results from AGSO surveys 179 and 180 (sonobuoys and reflection data) has been carried out by Gladczenko and Coffin (2001) indicating 4-8 km thick crust under this basin. Initial drilling results from the recent ODP Leg 183 (Coffin, Frey, Wallace et al., 2000) and first interpretations of these data (Nicolaysen et al., 2001; Duncan and Pringle, 2000; Coffin, Pringle et al., in press) have become available during the current framework study. The most significant results from this Leg of drilling include recovery of continental rocks on the Elan Bank (Weis et al., 2001) and more accurate age estimates for the igneous basement across the whole plateau (Coffin, Pringle et al., in press).

1.4 Regional setting

1.4.1 Physiography

The Kerguelen Plateau is a broad topographic high (~1.5 million km^2 in area) in the southern Indian Ocean surrounded by deep ocean basins: to the northeast by the Australian-Antarctic Basin; to the south by the 3500 m deep Princess Elizabeth Trough; to the west by the Enderby Basin (Fig. 2). The plateau extends approximately 2300 km between 46°S and 64°S in a southeast-trending direction toward the Antarctic continental margin. It is between 200 and 600 km wide and stands 2-4 km above the adjacent ocean basins, Figs. 3 and 7.

Earlier studies (Schlich, 1975; Houtz et al., 1977) divided the Kerguelen Plateau into morphologically different northern and southern parts. Coffin et al. (1986) and Könnecke et al. (1998) recognised six major provinces: Northern, Central, and Southern Kerguelen Plateau; William's Ridge, Elan Bank, and Labuan Basin (Fig. 8). The Northern Kerguelen Plateau (NKP), lies between about 46° to 50°S latitude in shallow water depths of less than1000 m. It is characterised by basement elevations of 3000-4000 m above adjacent seafloor, with maximum elevations forming the Kerguelen Archipelago. The Central Kerguelen Plateau (CKP) lies between about 50° to 55°S latitude in relatively shallow water depths (500-1500 m). It contains a major sedimentary basin (Kerguelen-Heard Basin) and includes the volcanically active Heard and McDonald Islands.

Relative to the Northern Kerguelen Plateau (NKP), the Southern Kerguelen Plateau (SKP) is characterised by greater water depths (1500 to 2500 m) and a more complex tectonic history. There are several large basement highs and evidence for multiple stages of normal faulting, graben formation, and strike-slip faulting (Houtz et al., 1977; Coffin et al., 1986; Fritsch et al., 1992; Rotstein et al., 1992; Royer and Coffin, 1992; Angoulvant-Coulon and Schlich, 1994; Könnecke et al., 1998; Gladczenko and Coffin, 2001). Elan Bank, a salient extending westward from the boundary between the CKP and SKP lies in water depths of 1000 to 2500 m. The Labuan Basin, which adjoins the CKP and SKP to the east, is a deep (>3500 m water depth), extensively faulted basin that contains a thick sedimentary succession (more than 2 sec TWT) (Rotstein et al., 1991).

1.4.2 Plate tectonic setting

Variable age oceanic crust abuts the Kerguelen Plateau (Fig. 9). As summarised by Schlich and Wise (1992), off the northeastern part of the plateau the age of adjoining oceanic crust ranges from Late Eocene to Oligocene (An18 - 40.1 Ma to An11 - 30.1 Ma) (we use the geomagnetic polarity time scale of Cande and Kent, 1995). Further south, the eastern flank of the Kerguelen Plateau is bounded by Labuan Basin, the age of which is unknown. There are no magnetic lineations recognised in the Labuan Basin and its basement has never been sampled. To the northeast of the Labuan Basin, the age of the crust is the same as along the northern part of the Kerguelen Plateau (Late Eocene, An18). No magnetic anomalies are identified in the area surrounding Kerguelen Plateau in the south (Fig. 9). Magnetic anomalies off Antarctic margin are not identified to the west past 100^{O} E. Magnetic anomaly sequences from An23 to An34 have been identified in the Crozet Basin (Fig. 9), but to the southwest, in the Enderby Basin (sometimes referred to as African-Antarctic Basin), no convincing anomalies have been mapped. Mesozoic anomalies have been suggested (Li, 1988; Nogi et al., 1996) for the southern Enderby Basin (equivalent to those of the Perth Bain), which appear to be consistent with new data collected on the Antarctic margin (Murakami et al., 2000).

The Kerguelen Plateau lies within the Antarctic Plate separated from the Indian Plate by the Southeast Indian Spreading Ridge (SEIR). The crust lying to the northeast of the Kerguelen Plateau and the Labuan basin was formed at this mid-ocean ridge. Areas lying to the south and west of the Kerguelen Plateau are interpreted (Royer and Coffin, 1992) to have formed during the breakup between India and Antarctica in the Early Cretaceous (Fig. 10). Much of the construction of the Kerguelen Plateau is due to the activity of the Kerguelen Hotspot (Fig. 10).

1.4.3 Regional geology

Difference in morphology and structure between the northern and southern parts of the plateau have been recognised since the early stages of the plateau's exploration (Schlich, 1975; Houtz et al., 1977). Structure and sediment distribution on the NKP were described by Schlich (1975); Houtz et al. (1977); Munschy and Schlich (1987); Fröhlich (1983); and Wicquart and Fröhlich, (1986). Results of geological sampling and drilling showed that there were two separate stages of volcanism in this province: an Early Cretaceous (Albian) phase, characterised by massive basaltic lava flows, and a later phase in Oligocene-Miocene. A large basin located between Kerguelen and Heard Islands, the Kerguelen-Heard Basin (Fig. 8), is filled with more than 2000 m of Cainozoic sediments (Fröhlich and Wicquart, 1989). Based on seismic reflection data from cruise MD 26, Munschy and Schlich (1987) and later Fröhlich and Wicquart (1989) described two major sequences in the basin (upper and lower) separated by a pronounced seismic boundary/unconformity. Based on the drilling results at ODP Site 737, this major unconformity has been interpreted to correspond to erosion or non-deposition between the end of Oligocene and the Middle of Miocene (Barron, Larson, et al., 1989). The age, structure and seismic stratigraphy of this basin remain poorly understood.

The NKP and the SKP are separated by a saddle with average depths ranging from 2500-3000 m. This area has been referred to as Central Kerguelen Plateau (CKP) (Fig 8). Geological and geophysical data on CKP was acquired by *Marion Dufresne* 26 and 35 (Fröhlich, 1983; Wicquart and Fröhlich, 1986; Munschy and Schlich, 1987) and later during ODP Legs 119, 120 and 183 (Schlich, Wise, et al., 1989; Wise, Schlich and Wise, 1992, Coffin, Frey, Wallace et al., 2000). Both Late Cretaceous and Oligocene-Miocene volcanics were recovered in this province. The oldest sediments of Albian age were sampled at ODP Site 1138.

The SKP lies higher than the CKP and features Banzare Bank in the west and a series of NW-SE oriented linear highs in the east and south. Munschy et al. (1993) and Angoulvant-Coulon and Schlich (1994) mapped in some detail prominent extensional structures on SKP, featuring north-south-trending grabens (77 Degree and 75 Degree Grabens of Houtz et al., 1977) and SE oriented rift zones (SKP Rift Zone) (Fig.8). Based on ODP drilling results at Site 747 it has been suggested (Munschy et al., 1993) that the 77 Degree Graben was formed at the end of Maaastrichtian. The age and origin of the other grabens and rift zones remain unknown.

The Raggatt Basin (Fig. 8) is a major sedimentary basin described on the SKP (Colwell et al., 1988; Coffin et al., 1990; Fritsch et al., 1992). It contains up to 2500m of Albian to Miocene sediments. Sequences mapped in previous interpretations (Colwell et al.,1988, Coffin et al., 1990) include pre-rift Lower and Upper Cretaceous sediments (K1 and K2), which fill in lows and onlap on the basement, and relatively thick (up to 2000 m) post-rift sequences of the latest Cretaceous to Quaternary age (K3 – PN1-NQ1) (Fig. 11). Unusual mounded structures were described within the sequence K3. Coffin et al. (1990) suggested that they could be carbonate mounds formed in shallow water. Throughout the Cretaceous, the Kerguelen Plateau remained a shallow marine feature subsiding to bathyal depths only during the Paleocene (Fritsch et al., 1992). The timing of tectonic events, which affected development of the Raggatt Basin, as well as the whole of the SKP, remain poorly constrained.

Elan Bank, extending to the west of the CKP (Figs. 2, 8), is characterised by shallow depths (up to 500 m) and E-W structural trends. It is 100 to 200 km wide and trends east-west for about 600 km. Until now it was considered to be part of the Kerguelen Large Igneous Province (Royer and Coffin, 1992) however locally sourced fluvial deposits containing clasts of garnet-biotite gneiss recovered during Leg 183 at Site 1137 (Nicolaysen, Pringle et al, 2000) indicate an at least partly continental origin for this structure. These new results still have to be explained and integrated with the exiting plate tectonic reconstructions.

The Labuan Basin (Ramsay et al., 1986) adjoining the Kerguelen Plateau in the east (Fig. 8) lies at about 4000 m water depth and is about 800 km long and 200 km wide. It's rough basement is concealed by thick sediments (up to 4500 m) although some basement ridges crop out on the seafloor (Fig. 8). The basin has never been drilled, and prior to AGSO Surveys 179 and 180 very limited seismic data were collected here. Rotstein et al. (1991) identified four major sequences in the Labuan Basin: pre-uplift, syn-tectonic, post-uplift and upper megasequences. They correlated these sequences to those on the SKP based on the seismic character, assuming they are the same age. Rotstein et al. (1991) suggested that the basin was formed at about the same time as the Southern Kerguelen Plateau, 130-100 Ma. Seismic lines and sonobuoy stations from AGSO Survey 180 provide the first regional coverage of the basin, allowing a more complete assessment of its structure and sediment distribution.

1.4.4. Present-day patterns of sedimentation

Present-day sedimentation and composition of surface sediments in the Kerguelen Plateau region are greatly affected by bottom-water circulation. This circulation was established in the Oligocene (33.6 Ma; Exon et al., 2000), when the Australian and Antarctic continents separated to the south of Tasmania. This allowed passage of water all around Antarctica and the Circum-Antarctic current was formed (Exon et al., 2000). This eventually caused the thermal isolation and cooling of the continent, and the Antarctic margin began to generate increasing amounts of cold bottom water. The changes in bottom water temperature have been described by Kennett and Shackleton (1976) including a large drop in the Late Eocene, at about 38 Ma. Strong bottom currents contributed to thermal isolation of Antarctic regions, including the Kerguelen Plateau, which resulted in profound changes in pelagic environment in the Neogene and Pleistocene. Calcareous oozes and chalks containing nannofossils and foraminifera were replaced with predominantly diatomaceous sediments. The transition from calcareous to biosiliceous sediments occurs today at about 45^{O} S, which corresponds to the position of the Antarctic Convergence or Polar Front (Fröhlich and Wicquart 1989). Diatom oozes become almost universal on the Kerguelen Plateau from the Late Miocene onward.

Deep-ocean basins surrounding the plateau are characterised by uniformly siliceous biogenic sedimentation - diatom ooze with some radiolaria (Plate 6,

Appendix 5) Over most of the plateau sediments are represented by a mixture of siliceous and calcareous (foraminifera) oozes with small amounts of mostly silty terrigenous material. Coring reveals that the carbonate content in the Early Quaternary and older sediments is significantly greater than in the Late Quaternary sediments. Older sediments outcrop on the uplifted parts of the plateau, particularly in its northern and northeastern parts. The amount of terrigenous and clastic material increases towards the eastern flank of the plateau and around some prominent basement highs in the south (Plate 6). Cores taken close to basement outcrops often contain fragments of basalt. Other rock types such as gneisses and granites also have been recovered in some cores, and are interpreted as ice-rafted debris rather than local material. Cores taken on the northeastern flank of the plateau around 50^{O} S contained fragments of Upper Cretaceous cherts and chalks (Plate 6).

In the northern part of the plateau close to volcanically active Kerguelen and Heard islands, sediments contain some volcanic ash and glass (Plate 6). Debris of volcanic rocks has been found on William's Ridge and on a large basement high in the southern part of the plateau. The latter is surprisingly far away from the known recent volcanic sources.

The southernmost part of the region is largely dominated by glacio-marine sedimentation, characterised by lack of microfossils, increase in terrigenous content, particularly towards the Prydz Bay, and commonly present ice-rafted debris.

2. CRUSTAL STRUCTURE

2.1 Introduction

A total of 21 sonobuoys were deployed during Geoscience Australia (AGSO) Surveys 179 and 180 mostly in the Labuan Basin, 16 of which were interpreted and successfully modelled (see Appendix 6). Sonobuoy data was modelled in house using the procedure described in Appendix 7. For several sonobuoy records a satisfactory model could not be generated, either because of a lack of data recorded or because a match could not be achieved probably due to significant lateral velocity variations in the sub-surface.

The information gained in the modelling was used to estimate sediment thickness and groundtruth geological interpretation based on seismic character only. Cretaceous and Early Tertiary sediments in the area are mostly shallow marine cherts and chalks characterised by velocities close to or over 3.0 km/s. In the Labuan Basin, where there is no well control, these velocities were considered to be indicative of Cretaceous sediments.

2.2 Previous work

Seismic velocity studies (Operto and Charvis, 1995, 1996) indicate that SKP crust is about 22 km thick and consists of three layers: an upper crustal layer (~5.3 km) with velocities ranging from 3.8 to 6.5 km/s; a lower crustal layer (~11 km) with velocities of 6.6 to 6.9 km/s; and 4 to 6 km thick, seismically reflective transition zone at the base of the crust characterised by velocities of 6.7 to 6.9 km/s. Such a transition zone at the crust-mantle interface has not been imaged on either the CKP or NKP, and forms the basis for the hypothesis that parts of the SKP contain fragments of continental crust (Operto and Charvis, 1995, 1996).

Könnecke et al. (1997) interpreted crustal thickness of at least 15 km for the Elan Bank. Wedges of seaward dipping reflectors indicate that the upper crust consists of mafic igneous material (Borissova, Coffin et al., 2000). A low velocity (~6.8 km/s) lower crust suggests that continental rocks may also comprise part of Elan Bank (Charvis et al., 1997).

Igneous crust of the CKP is 19 to 21 km thick, and consists of three layers (Charvis et al., 1995). The upper layer is 1.2 to 2.3 km thick, and velocities range from 3.8 to 4.9 km/s. The middle layer is 2.3 to 3.3 km thick, and velocities increase downward from 4.7 to 6.7 km/s. In the ~17 km thick lower crust, velocities increase from 6.6 km/s at about 8.0 km depth to 7.4 km/s at the base of the crust with no internal discontinuity (Charvis et al., 1995).

Wide-angle seismic data from the Kerguelen Archipelago on the NKP show an upper igneous crust, 8 to 9.5 km thick, with velocities of 4.6 to 6.2 km/s, and a lower crust, 6 to 9.5 km thick, with a velocity of 6.8 km/s (Recq et al., 1990, 1994; Charvis et al., 1995).

Gravity modeling based on preliminary results from AGSO sonobuoy stations in the Labuan Basin (Gladczenko and Coffin, 2001) suggested very thin (~5 km) crust, underlain by high-velocity crustal body (HVCB).

2.3 Refraction results

A detailed listing of results for each sonobuoy successfully deployed during Geoscience Australia (AGSO) Surveys 179 and 180 is given in Appendix 8. Interpretation of the data by region together with previous estimates of sediment thickness and velocity structure of the crust are summarised in Appendix 9. These previous estimates include: (1) Charvis and Operto (1999) for the Enderby and Kerguelen-Heard Basin and basement; (2) Gladczenko and Coffin (2001) for the Elan Bank and Labuan Basin; (3) Konnecke et al., (1998) for the Southern Kerguelen Plateau; (4) Operto and Charvis (1996) for the Raggatt Basin; (5) Charvis et al. (1993) for the Northern Kerguelen Plateau. Konnecke et al., (1998), Operto and Charvis (1996), Charvis et al. (1993) all propose a thick crust underlying the Kerguelen Plateau ranging from 18 to 25 km. Charvis and Operto (1999) suggest that the Enderby Basin crust thickens from 9.8 to 15.2 km towards the Kerguelen Plateau which would be consistent with excessively thick crust formed close to the Kerguelen Hotspot.

The present study shows that a typical velocity sonobuoy profile from Labuan Basin includes: an upper sedimentary layer with velocities of 1.7 to 2.0 km/s representing unconsolidated Cainozoic sediments; a lower sedimentary layer with velocities 2.6 to 3.1 km/s representing consolidated Mesozoic sediments; and an igneous crust with velocities ranging from 4.0 to 6.6 km/s and, in some areas of the Labuan Basin, up to 7.3 km/s. Crustal velocities under the Labuan Basin range from 4.3 to 7.8 km/s (north Labuan Basin), 4.0 to 6.6 km/s (central Labuan Basin), and 4.9 to 6.6 km/s (south Labuan Basin), whereas beneath the southern Kerguelen Plateau the range is 3.9-6.0 km/s. Igneous crust can be further broken down into extrusive volcanics with velocities from 4.0 to 5.5 km/s (oceanic layer 2) and middle crust (massive intrusives, oceanic layer 3) with velocities 5.6 to 6.6 km/s. Volcanics are about 3-4 km thick on the eastern margin of the Southern Kerguelen Plateau, but seem to be thinner, about 2 km, in the Labuan Basin. Their distribution and thickness are highly variable, especially in the south (sonobuoy stations 18005a and 18005b). Middle crust is about 2.5 km in the northern Labuan Basin and is up to 4.6 km in the southern Labuan basin (appendix 8).

For most sonobuoys in the Labuan Basin velocities have been resolved only for the upper 3-4 km, where they do not exceed 6.6 km/s and total crustal thickness is unknown. Gladczenko and Coffin (2001) used gravity modelling along seismic lines to estimate the Labuan Basin's crustal velocities. A variety of sources, including preliminary velocities from select sonobuoys from

Geoscience Australia (AGSO) Surveys 179 and 180, have been used to model the crustal structure, which then was tested against the gravity. Gladczenko and Coffin (2001) concluded that the basin is floored by 4-8 km thick crust, which thins southwards.

The Labuan Basin is characterised by a very prominent gravity low. The Gladczenko and Coffin (2001) model implies the presence of a high-velocity crustal body (HVCB) with characteristic velocities of 7.2–7.4 km/s under most of the Labuan Basin. The results presented here (Appendix 9) indicate the presence of thin igneous crust in the northern Labuan Basin (less than 5 km), which is in agreement with Gladczenko and Coffin (2001) model, however the proposed thinning to the south and the presence of HVCB beneath the central and southern Labuan Basin are not substantiated. Shallow depths of most sonobuoys and the lack of representative sonobuoy solutions in the eastern part of the basin may be responsible for the differences in the results. It is possible that thinning occurs mostly in the eastern part of the basin, structurally similar to the northern cross-sections, where high crustal velocities were registered, whereas the western and southern Labuan Basin may be underlain by a thicker crust.

2.4 Summary

For the southern Kerguelen Plateau, where the crust is thickest (22 km), Operto and Charvis (1995) described the crustal structure beneath the Raggatt Basin as being similar to the crustal structure of volcanic passive margins. This similarity led to the suggestion that the southern Kerguelen Plateau may be underlain by extended continental crust covered by basaltic flows (Operto and Charvis,1995).

Crustal structure of the northern Kerguelen Plateau with the lower crust velocities ranging from 6.8 to 7.3 km/s. is more consistent with an oceanic origin (Charvis, et al., 1993).

Results of Leg 183 drilling on the Elan Bank (Coffin, Frey, Wallace et al., 2000) indicate at least partly continental origin of its crust. These results are consistent with low velocity (~6.8 km/s) lower crust described by Charvis et al. (1997).

Geoscience Australia (AGSO) sonobuoy results in the Labuan Basin indicate that the middle crust and possibly the whole crust thickens to the south, and velocities typical for lower oceanic crust are not present in the south. This could be explained either by the presence of extended continental crust beneath the southern Labuan Basin, or unusual oceanic crust. Northern parts of the Labuan Basin are characterised by very thin crust, which could be either magmatic or highly extended continental.

3. AGE AND COMPOSITION OF IGNEOUS BASEMENT

3.1 Introduction

Most recent work indicates that the Kerguelen Plateau was formed primarily by emplacement of ocean-island type basalts (OIB) produced by the Kerguelen Hotspot in the period from about 117 Ma to present. In total the hotspot produced approximately 25 million km^3 of mafic crust since 130 Ma with rates of magma production varying significantly throughout geological history (Coffin, Pringle et al., in press). Most of the SKP and CKP were formed between 120 and 100 Ma at estimated rate of 0.9 m^3/yr (Coffin, Pringle et al., in press). Sampling results show that age and composition of the Kerguelen Plateau basement varies throughout the region indicating older basement in the south and younger in the north (Coffin, Frey, Wallace et al., 2000).

3.2 Geological evidence

Drilling results (Barron, Larsen, et al., 1989; Schlich, Wise, et al., 1989; Coffin, Frey, Wallace et al., 2000) and dredging (Leclaire et al., 1987; Davies et al., 1989; Duncan, 1991; Weis, Damasceno et al., 1998, Plates 2 and 3) have shown that igneous basement of the Kerguelen Plateau (and its conjugate Broken Ridge) is predominantly basaltic. Basement beneath the Central and Southern Kerguelen Plateau is silica-saturated transitional tholeiite that erupted in the Early to Late Cretaceous above, or just below, the sea surface. At ODP Site 1138, non-basaltic volatile-rich volcanics are preserved between the basalts (Moore, et al., 2000) and are indicative of the final, highly-evolved magmas erupted late in the constructional stage of the plateau. At least some of the plateau basalts were erupted above sea level, as shown by subaerially emplaced felsic pyroclastics, by inflated pahoehoe and by subaerial sediments in contact with the uppermost layers of the plateau basalts (Coffin, Frey, Wallace et al, 2000).

Cenozoic volcanism (~38 Ma to present) formed the Kerguelen Archipelago (Nicolaysen, Frey et al., 2000), Heard and McDonald Islands (Clarke et al., 1983; Quilty et al., 1983; Barling et al., 1994), and the bathymetric/gravity highs between the Kerguelen Archipelago and Heard Island (Weis, Frey et al., 1998). ODP Site 1140 on the northernmost part of the plateau, yielded basalts with an age of about 35 Ma (Duncan and Pringle, submitted).

Although tholeitic basalt is the dominant lava type forming the upper tens of meters of the igneous crust of the Kerguelen Plateau, other types of igneous and metamorphic rock are present. In contrast to basaltic lavas elsewhere on the plateau, basement lavas from Skiff Bank (Fig. 2, Plate 2) are alkaline (Coffin, Frey, Wallace et al., 2000). Basalts from the SKP (Site 738: Mahoney et al., 1995), Elan Bank (Site 1137: Coffin, Frey, Wallace et al., 2000; Frey et al., 2000), and CKP (Site 747: Storey et al., 1992) show geochemical evidence of contamination by continental lithosphere. On Elan Bank, clasts of garnet-biotite gneiss recovered from a fluvial conglomerate intercalated with basaltic basement are the only unequivocal continental basement rock recovered to date from the Kerguelen Plateau (Coffin, Frey, Wallace et al., 2000; Frey et al., 2000; Nicolaysen et al., 2001; Weis et al., 2001).

Highly-evolved felsic magma was erupted explosively on Elan Bank (Site 1137), the CKP (Site 1138), and Skiff Bank (Site 1139) (Coffin, Frey, Wallace, et al., 2000; Frey et al., 2000). The total volume of felsic volcanic rocks is still poorly constrained, but they probably account for a significant fraction of the volcanic deposits erupted during the final stages of magmatism at several locations on the Kerguelen Plateau.

The chronology of the plateau, based on dating of the sediments immediately overlying the basement, shows progressively younger sediments from about 110 Ma in the south to 38 Ma in the north (Coffin, Frey, Wallace et al, 2000), which has been tied to the movement of the Indian plate over the hotspot (Royer and Coffin, 1992). However, $^{40}Ar/^{39}Ar$ age dating of the basement from ODP leg 183 and revision of some previous results (Pringle and Duncan, 2000, and Pringle, Nicolaysen et al, 2000, Coffin, Pringle et al., in press) yielded basement ages of 109.9-117.2 Ma for the Southern Kerguelen Plateau, 109.3 Ma at Site 1137 on Elan Bank, and 102.8 Ma at Site 1138 on the Central Kerguelen Plateau, all of which fall within Barremian-Albian interval. Basement on the Skiff Bank (Fig.8) is younger; the oldest intersection is dated at 66 to 68 Ma (Maastrichtian) at ODP Site 1139 (Duncan and Pringle, 2000), but still much older than was previously assumed for the whole NKP. It is possible that Cretaceous basaltic basement is present beneath the NKP, but is buried out of range of the drill by a of layer of extrusives less than 40 Ma old.

3.3 Seismic characteristics

Multichannel seismic reflection data (Coffin et al., 1990; Schaming and Rotstein, 1990; Schlich et al., 1993) revealed numerous dipping intra-basement reflections on the Kerguelen Plateau interpreted as flood basalts. These dipping sequences have been identified in the crust of the CKP and SKP, and on Elan Bank (Könnecke et al., 1997; Borissova, Coffin et al., 2000). Large dipping reflector sequences have been mapped and are shown on Plates 3,4 and 5.

Seismic characteristics of the basement vary across the plateau. A detailed description and discussion of the observed features can be found in Chapter 5. Below we briefly describe identified basement types.

The **SKP basement** includes dipping reflector sequences (DR) under and to the east of the Raggatt Basin (Plates 4 and 5). An intra-basement horizon interpreted beneath volcanic flows (possibly pre-existing basement) has been mapped on some lines (lines 179-07, 47-14 and 34-70). The SKP basement is heavily faulted in places, particularly within the 59°S and 77°E Grabens (Plates 4 and 5), with several faulting episodes recognised.

The **CKP basement** is best displayed in the central and southern parts of the province where the seismic coverage is best. The basement does not appear to be faulted as much as the SKP basement. In the east and north of the CKP, there are a number of prominent volcanic intrusions, which extend above the level of basement and form bathymetric highs.

The **Elan Bank basement** underlies the main Elan Bank physiographic feature but also includes the terrace-like blocks of crust that step down into the Enderby Basin. The Elan Bank basement has a higher proportion of internal reflectivity than other part of the plateau. Dipping reflections can be seen underlying the western and southwestern flanks of the bank (Plate 4). Seismic section 179/06 (Plate 4) indicates a possible faulted basin underneath volcanic flows, which elsewhere on the Bank, form the top of the basement.

The **William's Ridge** basement itself has no internal character on its eastern flank but does have dipping reflector sequences on its western flank (Plate 4). Dipping reflector sequences intersected on line 179-07 (Plate 4, Line 179-07) are about 1.2 sec TWT thick and could be interpreted either as volcanic or sedimentary in origin. Results of this study suggest that they are more likely to be volcanic.

The Labuan Basin basement has been mapped immediately to the east of the escarpment bounding the Central and the Southern Kerguelen Plateau (Plate 5). Seismically, it is picked as the last coherent reflector prior to a featureless basement. The Labuan Basin basement has been subdivided into a Labuan Basin east and Labuan basement west based on differences in structure and in total magnetic intensity (TMI). The Labuan basement west is blocky and appears to be significantly faulted, while the basement in the east has a more rounded topography typical of intrusions and is relatively unfaulted. TMI values correlate well with the basement topography in the west, however in the east large basement ridges have no or very poor expression in the magnetic field.

The Enderby Basin basement is a fairly typical oceanic basement, however on lines 47-27 and 49-29 (Plate 5) we have mapped dipping reflector sequences adjacent to the western flank of the Kerguelen Plateau. These sequences are much smaller than dipping sequences on the plateau.

The Australian-Antarctic Basin basement is another example of oceanic basement. It has been mapped to the east of the William's Ridge and the Labuan Basin and is best represented on line 47/33 where basement shallows dramatically and displays typical abyssal hill morphology (Plate 5). Sediments overlying the basement are significantly thinner than those in the Labuan Basin reaching only a few hundred metres. Oceanic crust in this region has no internal seismic character.

3.4 Summary

Basement types encountered in the Kerguelen Plateau region can be broadly classified into magmatic (SKP and CKP, William's Ridge, Elan Bank), oceanic (Australian-Antarctic Basin and Enderby Basin) and Labuan Basin basement. The latter has unique characteristics and cannot be readily classified into magmatic, oceanic or continental type. Most of the dipping basement reflectors within the plateau itself occur on the flanks of seismically transparent basement highs. The location of prominent dipping reflector sequences is shown on the tectonic provinces map (Plate 3). The formation of these dipping sequences has been attributed to lava flows from multiple volcanic sources active during the plateau formation (Schaming and Rotstein, 1990). Subsequent erosion removed uplifted parts of these volcanic structures making it difficult to identify spatial distribution of volcanic sources. The only reliably mapped volcanic structure occurs on the eastern flank of the Raggatt basin (Plate 5, Lines 47-22, 47-24 and 47-27). This prominent basement ridge is characterised by reflectors dipping away from the crest of the ridge on both flanks, indicating direction of lava flows at the time of basement formation. Dipping reflectors have been also mapped on the western flank of the Raggatt Basin and the geometry of lava flows indicates that the western volcanic source existed longer than the eastern.

Banzare Bank (Fig. 2) has been described to have basement reflections dipping away from its central part in all directions (Schaming and Rotstein, 1990) and has been interpreted as a very large volcanic complex similar in scale to the one beneath the Kerguelen Islands. Dipping reflectors in Cretaceous basement of the Central Kerguelen Province (line 47-13) indicate that a large volcanic source may have been located in the northwestern part of the southern province.

On the Elan Bank, dipping sequences have similar origin to those on other parts of the Kerguelen Plateau. They probably reflect massive volcanism accompanying separation of this microcontinent from the major continental blocks (Antarctica and India).

4. STRATIGRAPHY AND SEISMIC SEQUENCES

4.1 Stratigraphy

4.1.1 Introduction

Knowledge of the stratigraphy of the Kerguelen Plateau and its surrounding area is based on ODP drillholes, seabed cores, dredges and outcrop geology as described in chapter 1.2.

The following sections provide a summary of basement and associated extrusives and volcanoclastics, and the sedimentary succession above. The summary is based largely on ODP reports by various authors, eg Barron, Larsen, et al., (1989, 1991), in Wise, Schlich et al., (1992) and in Coffin, Frey, Wallace et al., (2000). Details of stratigraphy at most representative Sites (747, 748, 750, 1135,1137 and 1138) and corresponding seismic with interpretation are shown in Figures 12–17. Stratigraphic units and lithologic columns of representative wells are shown on Plates 7 and 8, together with examples of representative logs, interpreted seismic sequences, and regional unconformities. Plate 9 summarises stratigraphy of the plateau including major tectonic and oceanic events and seismic horizons. More detailed description of drilling results is given in Chapter 5.

4.1.2 Basement

Basaltic basement of mid Cretaceous age has been intersected in the Central province (ODP 747, 1138), Southern province (ODP 738, 748, 750, 1136) and Elan Bank (ODP 1137). These provinces were formed by excessive hotspot volcanism during Early to mid-Cretaceous. Age-dating of the basement basalts varies from Barremian in ODP 1136 to Turonian in ODP 738. The extent of the Later Cretaceous volcanics in wells is restricted to ODP 1139 on Skiff Bank, where it is of Maastrichtian age. The most recent results on ages of the igneous basement are summarised in Coffin, Pringle et al. (in press). Variability in composition of the basement is discussed in chapter 3.

4.1.3 Sediments

Mesozoic sediments

Piston cores MD35-83503, 83505 and 83506, MD38-84554, MD48-701 and MD48-703 on the eastern flank of the plateau recovered Cretaceous carbonates from within or adjacent to basement volcanics (Appendix 4). ODP Sites 750, 1136 and 738, on the Southern Kerguelen Plateau recovered the oldest dated sediments, of Aptian to Albian age (Barron, Larson et al, 1989; Schlich, Wise et al, 1989; Schlich, Wise et al, 1992; Coffin, Frey, Wallace et al, 2000), while macrofossils of Cenomanian, Turonian and Campanian age were recovered from Sites 748 and 749 (Quilty, 1992). The oldest sediments are subaerial, fluvial or neritic, confirming that at the time of completion of volcanic plateau construction, the surface generally was at or above sea level, or at shallow marine depths (Fritsch et al., 1992). Volcaniclastics interbedded with the basalts at Site 1137 on the Elan Bank were deposited in braided stream environments. At Site 1138 in the Central province, a Late Cretaceous regolith was cored just above the volcanic basement (Coffin, Frey, Wallace et al, 2000) and the sandstones above it contain abundant wood debris. At Site 748 in the Southern province, Cretaceous glauconite indicates a shallow water environment, while at Site 750 in the eastern Raggatt Basin, basalt basement is overlain by Albian clay with charcoal and siderite, Turonian to Santonian chalk with clay layers containing pyritized wood fragments, and Santonian to Maastrichtian chalk and limestone deposited in neritic environments. There is widespread evidence for a rapid increase in water depth over the Plateau towards the end of the Mesozoic, and for differential subsidence that resulted in a high relief topography. For example, at Site 747 on the Central Kerguelen Plateau, Maastrichtian-lower Paleocene debris flows with breccias and cobbles were deposited during a major tectonic event that affected most of the plateau (Schlich, Wise et al, 1989). This event is variously dated at between 62 and 75 Ma, and resulted in an unconformity which is recorded on Plate 9 as the 'maas' seismic horizon.

Cainozoic sediments

Cainozoic sediments were intersected by ODP holes, as shown in Plates 7,8 and 9, and recovered in many dredges and piston cores (Appendices 4, 5). The Neogene succession is missing, truncated or absent in many holes on the Southern Plateau (Sites 749, 750, 1135, 1136) and on the Skiff Bank. Thicker and more complete Neogene successions were intersected at ODP Sites 736 and 737, and 745 to 748. The oldest seabed samples, of Paleocene and Eocene age, were recovered in cores MD48-698, -699, 701 and -704, and Elt54-3. ODP cores and seabed samples of Cainozoic age are almost universally deep ocean carbonates and tephra with very little terrigenous input, reflecting the oceanic setting of the plateau during this era. Palaeogene lithology is dominated by nannofossil chalk, whereas Neogene sediments consist mostly of nannofossil ooze. Volcanic glass and minerals occur within the general pelagic biogenic sediments throughout the Cainozoic succession, but distinct ash layers are few.

Kerguelen Plateau is located to the south of a major oceanographic boundary, the Antarctic Convergence, or Polar Front, which separates more temperate surface waters from polar waters. The boundary between these lies just north of ODP Site 1140. In the Pliocene to Pleistocene, an abrupt change in the diatom assemblage from species typical of temperate regions to species endemic to the Southern Ocean suggests that present-day oceanic water masses were established during the Late Miocene or Early Pliocene, as a result of climatic cooling.

Late Kerguelen Volcanics

The Heard and Kerguelen volcanic islands, and many submerged rises, consist of basalts, trachytes and rhyolites erupted from the latest Eocene to the present day (Giret and Lameyre, 1983). On Plate 9 these are classified as the Later Kerguelen Volcanics (LKV). They have been recognised on seismic data throughout the Northern province and part of the Central province.

Samples of alkali basalt of Miocene age have been recovered from submerged circular gravity and bathymetric features in the province (Weis, Damasceno et al., 1998). Two main plutonic episodes recognised by Giret and Lameyre (1983) are tholeiitic intrusions at about 40 Ma, and alkaline plutonism at about 28 Ma, that continued into the Pleistocene and the Quaternary.

4.2 Seismic sequences

4.2.1 Introduction

The first seismic stratigraphic scheme for the plateau was developed by Houtz et al., (1977). It was based on single channel seismic data, mainly from the Kerguelen-Heard Basin in the north of the Central Plateau. Three major bounding surfaces were recognised: A (prominent unconformity), B (top basement), and C (intra-basement reflector of unknown age or origin). Colwell et al., (1988) recognised six major units in the Raggatt Basin. No correlations were made with the sequences of the Kerguelen-Heard basin, though the correlation of Houtz's (1977) horizon B with Colwell's top of basement was noted. Coffin et al. (1990) added age-based names (K1, K2, K3, P1, P2, PN, and NQ) to the Colwell et al. (1988) sequences. Fritsch et al. (1992) in their interpretation of the plateau sequences (Fig. 11) used the same nomenclature. The correlation between these and seismic sequences defined in this study is shown in Appendix 10.

In a large area such as the Kerguelen Plateau, with probable diachronicity of major events, and basins isolated by areas of shallow basement, it is not always possible to correlate seismic events between individual depocentres. For this study major regional unconformities were indentified in ODP drillholes and correlated over very large areas, based on biostratigraphic data, supported by seismic correlation. The seismic horizons used in the interpretation of reflection seismic are shown on Plate 9 and on interpreted seismic sections (Plates 4 and 5). They are also shown on the well composites (Plates 7 and 8) and in Figures 12-17, which illustrate seismic ties for each ODP site. The time-depth picks for seismic horizons are tabulated in Appendices 11 to 13. The names used for horizons are descriptive of their age, eg *eoc* for the important regional Eocene unconformity, or in the case of basement picks descriptive of the region/province in which they occur.

ODP wells (738C, 747C, 748, 749, 750B, 751A, 1135, 1137 1138) located on and adjacent to seismic lines (Appendix 3) were used for correlating regional unconformities on the Kerguelen Plateau. No wells are available for the Labuan Basin region. Seismic packages/sequences were identified and mapped, but age interpretation of these is not constrained by coring or sampling and is based purely on regional context.

4.2.2 Basement

The seismic top of basement was named differently for each province, e.g, ***Ckpvb*** for Central Kerguelen Plateau volcanic basement, ***Skpvb*** for Southern Kerguelen Plateau basement, ***Ebb*** for Elan Bank basement, and ***Lbbe, Lbbw*** for Labuan Basin basement. Although basement character is often similar for different regions, this naming was used because of probable differences in age and composition of the basement. In some areas volcanic basement could be differentiated from deeper lying poorly imaged basement of unknown origin. The top of this deeper lying basement is shown on seismic sections by dashed lines (Plates 4 and 5) and was named ***Ckpb?*** in the Central province and ***Skpb?*** in the Southern province.

4.2.3 Sedimentary sequences

Sediment thickness over most of the Kerguelen Plateau doesn't exceed 1 sec TWT (Plates 4 and 5). Cretaceous sediments overlying the basement are commonly very thin and often display signs of erosion. Most of the sedimentary cover is represented by pelagic sediments of Palaeocene to Quaternary age. A Middle Eocene unconformity, corresponding to the breakup between the Broken Ridge and the NKP, is widespread in the younger section. This unconformity is less prominent over the SKP and the Labuan Basin, where the breakup took place earlier. Thick sections of Early to Late Cretaceous sediments (up to 1.5 sec TWT) are found in the Raggatt Basin, the 77° Graben and Labuan Basin. Cretaceous sediments in the Labuan Basin are up to 1.5 sec TWT thick, and they are restricted mostly to deep troughs between basement ridges (Fig. 18).

Broadly ten sedimentary sequences can be identified in the Kerguelen Plateau region ranging in age from pre-Albian to Recent.

Basement - pre-Albian (bment - pre-alb)
This is the oldest sequence overlying basement and bounded by a strong angular, pre-Albian unconformity *(**pre-alb**)* of possible Aptian age. It has been mapped only in the deepest part of the eastern Labuan Basin. There are very poor constraints on its age, which could be as old as Valanginian or as young as Aptian. On lines 180-06 and 180-07 this sequence appears to be at least partly volcanic and may represent a combination of lava flows, volcanoclastics and sediments.

Pre-Albian - Albian (pre-alb - alb)
This sequence has been mapped over large areas of the Labuan Basin and in the deepest part of the Raggatt Basin. It onlaps volcanigenic basement and is characterised by moderate to high amplitude reflectors. The top of the sequence is bound by erosional unconformity (***alb)*** (Plates 4 and 5). The sequence is significantly faulted in the Labuan Basin. Albian sediments recovered at the base of some ODP wells (see Chapter 4.1) have been deposited in subaerial, fluvial or neritic environment

***Albian - Campanian (alb-camp*)**
ODP wells 738, 748, 750 and 1135, all within the southern province, intersected Campanian-aged rocks whose top is represented seismically by the horizon ***camp*** (Appendices 11 -13). The distribution of these wells (Fig. 5) suggests that Campanian-aged rocks occur throughout the southern province.

This succession has been interpreted as extending into the Labuan and Enderby Basins, although there are no well data in these basins. The horizon ***camp*** is relatively conformable with adjacent reflectors. The Albian-Campanian sequence extends as a thin layer over most of the structural lows including the southern part of the central province. Seismically, it is relatively transparent in character with moderate to high amplitude reflectors in its upper section. Lithologies drilled on the plateau include chalks and limestones indicating neritic marine conditions.

Campanian - Maastrichtian (camp-maas)

Maastrichtian-age rocks have been intersected in several ODP holes in the southern and central provinces and on the Skiff Bank (Plates 4 and 5). This distribution together with seismic evidence suggests that the Maastrichtian is widespread across the Kerguelen Plateau.

The Campanian-Maastrichtian sequence is bounded by an unconformity (Appendices 11 -13) mapped as ***maas.*** Seismically, the sequence is characterised by higher amplitude reflections as compared with the underlying sequences. Overall it is concordant within the depocentres, but onlaps at the depocentre edges.

In the Central province the horizon ***maas*** is at near equivalent to the top of the K3 sequence (Appendix 10) of Coffin *et al*. (1990). The horizon is correlated by Coffin *et al.*(1990) with the faulting episode associated with the development of the grabens (77^0, 59^0 and SKP rift). It may also be equivalent to the major unconformity between Santonian and Eocene on the Broken Ridge (Leclaire *et al*., 1987).

Maastrichtian-Palaeocene (maas-pal)

In most wells on the Plateau the ***pal*** horizon (about 58 Ma) lies close to the slightly older unconformity delineated by horizon ***maas*** (Appendices 11 -13). The sequence is characterised by moderately to high amplitude reflectors. The horizon ***pal*** is best represented in the Raggatt Basin on the upthrown edge of the 77^0 Graben where it is correlated to the top of the mounded sequence (Plate 5, line 47-24). In most wells this sequence corresponds to nannofossil chalk (Plate 9) which supports an exlanation proposed by Coffin *et al*., (1990) that mounds in the Raggatt Basin represent shallow-water carbonate buildups.

Palaeocene - Mid-Eocene (pal-eoc)

This relatively thick sequence (up to 0.8 sec TWT) with parallel bedding is characterised by low amplitude high frequency reflectors. Both the base and the top of the sequence are well defined. The Mid-Eocene horizon at the top of the sequence represents a very widespread erosional unconformity (ODP 747, 738, 1137, Figs. 12, 16) at about 40 Ma (Fritsch et al., 1992). It is associated with the breakup between the Kerguelen Plateau/Labuan Basin and the Broken Ridge/Diamantina Zone in mid-Eocene time (Munschy & Schlich (1987).

In the Kerguelen-Heard Basin the Eocene unconformity lies very deep under a thick succession of Miocene sediments (up to 2 sec TWT) and was described by Fröhlich & Wicquart (1989) as Intermediate Reflector or IR. The base of the sequence cannot be defined on seismic and its thickness is unknown. Both in the Labuan Basin and in the Raggatt Basin, horizon ***eoc*** is identified by a relatively consistent onlap surface. The Palaeocene-Mid-Eocene sequence is composed entirely of pelagic sediment mostly of calcareous nature (e.g. nannofossil oozes).

Mid-Eocene - Oligocene (eoc-olig)

The Oligocene unconformity at the top of this sequence has been identified in ODP wells 737, 747, 748 and 1137 (Appendices 11 -13) and is mapped over wide areas of the Kerguelen Plateau. The sequence is characterised by weak low amplitude and high frequency reflectors. Well log interpretations and core data (Plates 7, 8) indicate that horizon ***olig*** occurs within a uniform succession of nannofossil ooze, which would result in very little acoustic inpedence.

In the western Labuan Basin, the ***eoc-olig*** sequence is characterised by parallel commonly undulating reflectors of moderate amplitide. Its thickness is noticeably variable (Line 180-07) which is likely to result from cut and fill processes caused by bottom currents. Channels and mounds created by bottom currents are best represented on lines 180-06 and 180-07. A dramatic increase in the ocean bottom circulation in the Oligocene (Breza and Wise, 1992) resulted in local erosional unconformities.

Olgocene - Lower Miocene (olig-miol)

This highly uniform sequence lies within the Cainozoic nannofossil succession. It has a similar seismic character to the underlying ***eoc-olig*** sequence. The Miocene hiatus (***miol)*** at the top of the sequence has been widely identified in ODP wells (Appendices 11 -13). The horizon ***miol*** generally occurrs about 0.5 seconds TWT below seafloor except for the Kerguelen-Heard Basin. In this basin it lies between 1 and 1.5 s TWT and forms the base of a highly-deformed section.

Horizon ***miol*** has been mapped in the northern part of the Labuan Basin. Further to the south, the post-Oligocene succession is fairly thin and only one Miocene horizon, which is correlated to Upper Miocene can be identified.

Lower –Upper Miocene (miol-miou)

This sequence occurs throughout the Kerguelen Plateau and the Labuan Basin. It is thickest in the Kerguelen-Heard Basin, where it is over 1 sec TWT and appears to be highly deformed. Over most of the plateau and in the Labuan Basin the sequence is characterised by low amplitude high frequency reflectors, whereas in the Kerguelen-Heard Basin the amplitude is higher and the frequency is lower.

The Late Miocene hiatus identified in ODP wells 748, 1138 and 1139 (Figs 13 and 17, Appendices 11 -13) ranges from about 5 to 7 Ma. Lithologies corresponding to this sequence are mostly calcareous nannofossil oozes.

Horizon ***miou*** marks the base of Pliocene diatom oozes, which indicate a change to polar water environments. The horizon occurs generally less than 0.3 seconds below sea bottom and shows little relief In the Labuan Basin it has been interpreted as the first sequence boundary below the seafloor at about 0.2 s TWT, which correlates well with thicknesses recorded in ODP holes 745 and 746 (250m).

Pliocene-Pleistocene (miou-wb)

This sequence is bounded by ***miol*** or ***miou*** unconformities and ***wb.*** Its thickness typically does not exceed 200 m, and it is often absent on uplifted parts of the plateau. In seismic character it is very similar to the Miocene sediments underneath, which reflects similar lithologies.

5. STRATIGRAPHY, STRUCTURE & DEPOSITIONAL HISTORY OF THE MAJOR TECTONIC PROVINCES

5.1 Introduction

The Northern, Central and Southern Kerguelen Plateau as well as Elan Bank, William's Ridge and the Labuan Basin represent morphologically and structurally distinct provinces of the Kerguelen Plateau region. They are characterised by significant differences in crustal structure, basement age and geological evolution (Borissova, Moore et al., 2000). New evidence from ODP drilling and interpretation of a large seismic dataset confirmed these differences and provided new insights into the origin of the different parts of the plateau.

The provinces are illustrated in a structural elements map of the region (Plate 3 and Fig. 19). This map results from the compilation undertaken for this study, integrated with published interpretations from previous studies (Angoulvant-Coulon and Schlich, 1994; Rotstein et al., 1991; Munschy et al., 1993). The provinces have been further subdivided to reflect differences in the age or origin of the basement. The northern Kerguelen Plateau (NKP) has been split up into a Western Banks Province, which is bathymetrically lower and has Late Cretaceous basement (Duncan and Pringle, 2000) and a Kerguelen Northern Province including Kerguelen Archipelago with much younger Oligocene-Miocene basement (Nicolaysen, Frey et al., 2000; Duncan and Pringle, 2000). The Labuan Basin has been subdivided into three provinces: Eastern, Western and Southern Labuan, with potentially different crustal structures.

More detailed descriptions of each province are provided in the following sections with the particular emphasis on new results. As no seismic data were available for NKP and Western Banks provinces, their descriptions are based on published materials (Munschy and Schlich, 1987; Gladczenko and Coffin 2001; Duncan and Pringle, 2000). Structural elements in these provinces were defined using satellite gravity and interpretation of single-channel Eltanin sections (USNS Eltanin, cruises 46-50, 1977; USNS Eltanin, cruises 51-55A, 1978).

5.2 Northern Kerguelen Province (NKP)

The Northern Kerguelen Province (NKP) as defined in this study, is a distinctive bathymetric and gravity high located almost entirely to the north of 50 degrees South latitude (Fig. 19, Plate 3). It includes the Kerguelen Archipelago. ODP drilling and dredging results indicate that Northern Kerguelen Plateau basement is composed of Oligocene-Miocene basalts (less than 40 Ma) (Coffin, Frey, Wallace et al., 2000; Duncan and Pringle, 2000).

Refraction studies in the Northern Kerguelen Province (Charvis, et al., 1993) showed considerable differences in the crustal structure between the Kerguelen Archipelago and the Kerguelen-Heard Basin located further to the south on the Central Kerguelen Plateau. The Kerguelen-Heard Basin is characterised by a deep crustal root, which suggests that the crust has been emplaced in the Late Cretaceous. In contrast, beneath the Kerguelen Islands, layer 2 is thick (10 km) and layer 3 is relatively thin (4-10 km), which may be explained either by entirely Cainozoic age crust or significant reworking and/or underplating of the pre-existing Cretaceous crust during the Oligocene-Miocene volcanic phase.

5.2.1 Stratigraphy

Until the recent ODP Leg 183, the Northern Kerguelen Plateau had not been drilled. Geological interpretations of this province were based on observations of the geology of the Kerguelen Islands, and samples taken during MD cruise 109 (Appendix 4), which recovered Miocene basalts. Tholeiitic rocks described from the Kerguelen Islands are 'at least' 40 Ma old (Giret and Lameyre, 1983), and the alkaline flood basalts are dated at 26 Ma. Analysis of peridotite xenoliths (Hassler and Shimizu, 1998) from the Kerguelen Archipelago indicates the presence of ancient Gondwana continental lower-lithospheric elements in the crust underneath the islands. Based on these data it was considered that most of the Northern Kerguelen Plateau was formed in Oligocene-Miocene following the breakup of the Kerguelen Plateau and Broken Ridge in Late Eocene–Oligocene.

ODP Site 1140 (Coffin, Frey, Wallace et al., 2000, Plates 7 and 9), located on the northern margin of the plateau, encountered submarine pillow basalts at 235 mbsf, with minor dolomitized nannofossil chalk beds dated as latest Eocene to Early Oligocene. The lavas were extruded on top of the sediments, in deep water. The basalts are overlain by pelagic oozes and chalks of Early Oligocene to Middle Miocene age.

Very little sediment older than Oligocene has been intersected in the Northern Province, although some of the chalks interbedded with the basalts intersected at ODP Site 1140 might be of latest Eocene age. They were deposited in bathyal water depths, and pelagic deposition accompanied extrusion of the lava flows (Coffin, Frey, Wallace et al, 2000). These conditions continued through the Middle Miocene. The increased number of diatoms in the overlying sediments indicates the onset of cold water conditions.

5.3 Western Banks Province (WBP)

The Western Banks Province lies between 47° and 52° S (Fig.19) to the west of the Northern Kergeuel Plateau (NKP). This part of the plateau is located in water depths of 1500-2500 m. It is characterised by a gravity signature more typical of the central and southern parts of the plateau, rather than the NKP, which stands out as a prominent gravity high (Fig. 6). Several basement highs are recognised in the southwestern part of the province. Some of these have an E-W orientation, others trend NW-SE.

5.3.1 Stratigraphy

The largest bathymetric and gravity high of the Western Banks Province, Skiff Bank, was drilled during ODP leg 183. Skiff Bank lies some 350 km west-southwest of the Kerguelen Archipelago, separated from the NKP by a bathymetric and gravity low (Figures 2, 6). Prior to ODP Leg 183, only the western flank of the feature had been sampled (MD cruise 35) recovering Miocene and Pleistocene sediments (Fröhlich, 1983). ODP Site 1139 was drilled on the south-facing bathymetric margin of the feature (Coffin, Frey, Wallace et al., 2000). The well encountered altered volcaniclastics, basalt and multiple flows of mainly trachitic basement, 461 m below seafloor (Plate 7). Basement is overlain by Late Eocene to Early Oligocene carbonates, comprising mainly grainstone with rudstone and packstone. This succession is overlain by nannofossil-bearing clay and claystone, ooze and chalk of Oligocene to Middle Miocene age and Pleistocene nannofossil oozes with diatoms and foraminifers.

Recent Argon dating of minerals in a basement core from ODP Site 1139 (Duncan and Pringle, submitted) yielded an age estimate for the basement of 66-68 Ma. This unexpectedly old age of the basement requires a considerable change in our concepts of age progression on the Kerguelen Plateau. Discovery of the Cretaceous basement on Skiff Bank also has serious implications for understanding the plate tectonic history of the region. Until now it has been postulated (Royer and Coffin, 1992) that overlap in reconstructions between Northern part of the Kerguelen Plateau and Broken Ridge prior to Anomaly 18 could be explained by the fact that most of the NKP formed during the Oligocene to Miocene (Fig. 10). Another generally accepted idea is that the hotspot, which created the Kerguelen Plateau was transferred to the Indian Plate at about 85 Ma, and is responsible for the formation of the Ninetyeast Ridge (Royer and Coffin, 1992). The presence of Latest Cretaceous basement in the northern province challenges these ideas and requires some revision of existing plate tectonic concepts for this area.

5.4 Central Kerguelen Province (CKP)

The Central Kerguelen Province (50°-55°S) lies between the bathymetric and gravity high of the NKP, and the bathymetric saddle on the northern side of the Southern Kerguelen Plateau. The Central Kerguelen Plateau includes the volcanically active Heard and McDonald Islands and contains a major sedimentary basin (the Kerguelen-Heard Basin).

5.4.1 Stratigraphy

The province has been drilled by ODP holes 736, 737, 747 and 1138 (Plates 7 and 8), and numerous samples have been taken during *Marion Dufresne* cruises 35, 38, 48 and 109, and *Eltanin* 54 (Appendix 4).

Basement

Basement rocks of the CKP were first recovered during a major geological sampling cruise, *Marion Dufresne* 48 (Leclaire et al., 1987). A dredge (DR8, Appendix 4) located on the scarp bounding the eastern margin of the plateau recovered a Miocene saprolitic basalt. Cretaceous basement in the province has been intersected by ODP wells 747 and 1138 (Plate 7 and 8). The Kerguelen-Heard Basin, which occupies the northern part of the CKP, was partially drilled by two wells, ODP 736 and 737, neither of which reached basement or Cretaceous sequences.

Basement rocks recovered from Site 747 (Fig. 12, Plate 7) located in the southern part of the province on a prominent basement high consist of basalts erupted at about 85-88 Ma (Cenomanian) (Munschy et al., 1992). ODP Site 1138 is located about 150 km to the SE of Heard Island and reached basement (Fig. 17) recovering dacitic lavas and pyroclastic flow deposits of trachyte.

The felsic composition of the basement has been interpreted as characteristic of the highly-evolved magmas erupted during the final stages of plateau construction. Ar/Ar step heating experiments (Coffin, Pringle et al., in press) showed that basalts from the top of volcanic basement are of Albian age (102.8 Ma), which is about 15 Ma older than at Site 747.

Mesozoic sediments

Eltanin core E54-7 on the southeastern extremity of the CKP, recovered Cenomanian/Turonian chalk (Quilty, 1973). At ODP Site 1138 glauconitic sandstones and claystones of Cenomanian to Turonian age overlie dacitic volcanoclastics and multiple basalt flows (Coffin, Frey, Wallace et al., 2000; Plate 7). The basal Cretaceous (?Late Albian) sediments contain wood fragments, leaves and fern fronds indicative of regolith formation. Shallow neritic conditions were established by the Cenomanian/Turonian (~99-89 Ma). Black organic rich claystone at 660-662 mbsf may represent the change from the neritic to the pelagic environment that followed soon after and continued to the present-day (Coffin and Frey, Wallace et al., 2000).

Mesozoic sediments recovered at Site 747 are younger. They are represented by Late Maastrichtian - Early Paleocene debris flows with breccias, which according to Schlich, Wise et al. (1989) represent a major tectonic event.

Cainozoic sediments

ODP Site 736 (Plate 7) was designed to investigate the thick Neogene succession expected at the site, and also to shed light on the movement over time of the Antarctic Convergence (the Polar Front). The rig drilled 366 m of diatom oozes of Quaternary and Late Pliocene age with minor nannofossil ooze and volcanic debris.

ODP Site 737 (Plate 7) intersected calcareous claystones of Late Oligocene to Middle Eocene age interbedded with clayey limestone overlain by sandy siltstones and calcareous nannofossil ooze with volcanic sand of Middle Miocene age, followed by diatom and nannofossil oozes of Miocene age. ODP Site 1138 (Coffin, Frey, Wallace et al., 2000) intersected chalks and nannofossil oozes of Late Cretaceous to Late Oligocene age overlain by 150 m of Late Miocene to Pleistocene diatom oozes. Evidence from this well suggests that from the Late Miocene onwards, there is an increase of terrigenous materials, clay and ash. Palaeocene and Cretaceous sediments were also cored by the *Marion Dufresne* during cruise 35 (Appendix 4, Fröhlich, 1983).

Cainozoic volcanics

The Cainozoic volcanics are represented in the CKP by the basalts of Heard and McDonald islands. Quilty et al (1983) reported a diverse discoaster flora of Early to Middle Eocene age' (about 47 to 49 Ma) in clasts of lithified ooze within phonolite flows.

5.4.2 Structure

Only a few seismic lines were available to the project from the CKP: 47/010, 47/011 and 47/012 (Plate 2). Line RS47/010 (Plate 4) gives a good example of the basement character in the northern part of the province. It appears that Miocene basalts sampled on the eastern flank of the plateau represent young intrusions in much older basement (Fig. 20). The basement cannot be identified reliably under the Kerguelen-Heard Basin, but it shallows both to the east and to the west forming two broad highs. From basin stratigraphy and piston core results it was postulated that the Central Kerguelen Plateau formed in the Late Cretaceous (Munchy and Schlich, 1987); this has been later confirmed by ODP drilling results.

5.4.3 Kerguelen-Heard Basin

The Kerguelen-Heard Basin (Fig. 19, Plates 3 and 4) is a 'sag' basin in the northern CKP. It covers an area of more than 40,000 km^2 and contains in excess of 2000m of Cainozoic sediments.

Seismic stratigraphy

The basement underneath a large part of the Kerguelen-Heard Basin cannot be identified on seismic. The basin-fill is highly reflective and the basement can only be reliably mapped in the outer parts of the basin (Plate 4).

Based on seismic reflection data from cruise MD 26, Fröhlich and Wicquart (1989) estimated that the sedimentary fill in the central part of the basin reaches 2000-2500 m. However, seismic refraction results from OBS data collected on *Marion Dufresne* cruise 66 (MD66) indicate a sediment thickness up to 2.9 km (Charvis, et al.,1993).

Two major successions have been identified in the basin: an "upper" and a "lower" megasequence (Munchy and Schlich, 1987), separated by a distinctive seismic reflector, termed "Acoustic Discordance" or AD (Fröhlich and Wicquart, 1989).

Upper megasequence

The "upper" megasequence is typically about 1 km thick and is characterised by numerous undulating reflections. The reflections are high amplitude, medium to high frequency and are fairly uniform across the basin. The major unconformity at the base of this sequence (seismic horizon *miol*) is prominent on lines across the Kerguelen-Heard Basin (Plate 4, lines 47/10 and 47/12). Current-generated sedimentary structures are observed in the succession immediately above horizon *miol* (Fig. 21). They have been attributed to vigorous bottom current activity during the Neogene (Fröhlich and Wicquart, 1989).

Acoustic Discordance

Seismic horizon *AD* has been intersected at ODP Site 737. Middle Eocene to Upper Oligocene calcareous claystone was recovered from below it and Middle Miocene calcareous diatom oozes from above it. A major hiatus extends from the top of the Oligocene to Mid Miocene (23 to 15 Ma; Barron, Larson, et al., 1989). According to Schlich, Wise et al (1989) the AD in other parts of the basin spans a longer period of time, from the Middle Eocene to the base of the Miocene (43 to 23.5 Ma), and is caused by the Eocene breakup of the Kerguelen Plateau and the Broken Ridge. Munschy, Fritsch et al (1994) noted that along the eastern margin of the Kerguelen-Heard Basin the hiatus extends from middle Eocene to middle Miocene, but it is of somewhat shorter duration toward the west.

The interpretation of this project supports the view that the AD results primarily from a change in the activity of ocean bottom currents beginning in the Oligocene (e.g. Colwell et al, 1988; Rotstein et al, 1992) following the establishment of the Antarctic Circumpolar Current. We suggest that the tectonically induced hiatus and unconformity resulting from the Eocene breakup was prolonged by the current activity. The two events are joined in one unconformity, but they are not identical. At ODP 737 there is a deposit of nannofossil ooze between them (Plate 8). We note also large changes in seismic reflectivity near, but not exactly at, the unconformity, and attribute them to some form of diagenesis.

Lower megasequence

In areas where the basement is visible on seismic the "lower" megasequence is 800 m to 1 km thick, however in central parts of the Kerguelen-Heard Basin it could be significantly thicker. The sequence is charactrised by medium to high amplitude medium frequency reflectors (Plate 4, Lines 47-10 and 12). Generally parallel bedding is disrupted in the eastern part of the basin above and close to Miocene intrusions.

According to Munschy and Schlich (1987) the "lower" megasequence was deposited from the Coniacian to Middle Eocene. The magasequence appears to consist mainly of chalks with some "interbedded" cherts (Fröhlich and Wicquart, 1989). A prominent seismic reflector within the sequence has been designated by Fröhlich and Wicquart (1989) as "Intermediate Reflector (IR)". This reflector is recognisible in outer parts of the basin, but is not present in its central part (Plate 4). The reflector was not quite reached by ODP 737, but was sampled by MD 35 on a scarp northwest of William's Ridge. Dredging (MD35Dr01) recovered chert flag of Paleocene/Eocene boundary age. Based on these results, the IR horizon has been mapped as horizon ***eoc*** in this study.

5.4.4 West Heard Mound

A thick slope deposit occurs to the west of Heard Island (Plate 4, Lines 47-11 and 12), along the south-western side of a basement ridge trending northwestward from Heard Island (Plate 3). This deposit is here named the "West Heard Mound". Its sediment thickness reaches 800 m.

Although it is possible that the West Heard Mound partly represents a slump deposit, there is evidence that this is not the case. The absence of distorted bedding and toe thrusts and the presence of well-defined layering, as well as position of the deposit next to the steep topography of the Heard Ridge, suggest that this feature was formed by contour currents. An important role played by contour currents in sedimentary processes of the region has been highlighted by Kennett (1982). The material of the mound is not necessarily derived from the adjacent basement ridge, and may have come from elsewhere on the southwestern side of the NKP or western CKP, or even from the Skiff Bank. Its location appears to be governed by an embayment in the western slope of the Kerguelen Plateau. The embayment may have provided an environment sheltered from faster currents, so that suspended materials were deposited. Similar to contourite deposits observed elsewhere (e.g. Youbin et al., 1999) the West Heard Mound has a moat or channel on its eastern side (Plate 4, line 47/11). It is likely that the West Heard Mound consists entirely of Neogene sediments, and was formed as a result of changed circulation pattern after establishment of the Circum-Polar current.

5.4.5 Synthesis

The CKP was formed in Early Cretaceous contemporaneously (Albian) with, or a few million years later than the SKP. Cretaceous volcanic activity ceased by Cenomanian (Munchy et al., 1992). The CKP remained sub-aerial or shallow-water until about the beginning of the Turonian (Coffin, Frey, Wallace et al., 2000). A major tectonic event resulting in faulting of the eastern flank of the CKP took place in Maastrichtian (Schlich, Wise et al., 1989).

From the Late Cretaceous to Eocene, the CKP remained a shallow-marine feature dominated by pelagic sedimentation (pelagic chalks). Paleogene deposits indicate deeper waters, however during the Eocene there was another shallowing and possible subaerial erosion (Fröhlich and Wicquart 1989). This uplift preceded the breakup between Broken Ridge and William's Ridge and the second phase of volcanism on the plateau (Oligocene to Recent). It also resulted in a major gap in sedimentation – between the Middle Eocene and Late Oligocene - Early Miocene (Colwell et al, 1988). The Kerguelen-Heard platform was formed mostly during the Middle Eocene immediately prior to the breakup, whereas intrusive magmatism appears to peak in the Miocene (Leclaire et al., 1987). Current volcanic activity is restricted to Heard and McDonald Islands.

During the later part of Oligocene and Miocene, the CKP gradually subsided and the plateau was covered by calcareous chalks and oozes with some clastic component derived mostly from Kerguelen Island (Fröhlich, 1983). Sedimentation was significantly affected by bottom currents established since the Oligocene (Kennett, 1982), while the transition from calcareous chalks and nanno-oozes to diatomaceous sediments occurred in the Miocene in response to dropping water temperatures associated with the movement of the Polar Front. Both water temperature and depositional environment are closely linked to the opening of the continental bridge between Australia (Tasmania) and Antarctica and establishment of the Circum-Polar Current.

5.5 Southern Kerguelen Province (SKP)

The Southern Kerguelen Province (south of 55°S) is a tectonically complex area. The basement lies bathymetrically higher than in the CKP and often shows signs of subaerial erosion. Numerous dipping basement reflectors, representing volcanic flows can be seen on seismic data, particularly on the slopes of prominent basement highs (Plate 5). The province is characterised by several large NW-trending basement ridges and it was affected by several stages of normal faulting resulting in a complex of NW and NE-SW trending grabens (77 Degree Graben, SKP Rift Zone) (Rotstein et al., 1992; Royer & Coffin, 1992). A large sedimentary basin, the Raggatt Basin, is located in the northern part of the province, bounded by faults in the west and south and by an eroded basement ridge in the east (Plate 5).

5.5.1 Stratigraphy

ODP Leg 119 drilled Sites 738 and 744 in the far southwest of the Southern Kerguelen Plateau (SKP), and Sites 745 and 746 on the bathymetric ridge that forms the eastern edge of the province, adjacent to the Labuan Basin. Leg 120 drilled Sites 748, 749, 750 and 751 along an east-west traverse across the Raggatt Basin. Leg 183 drilled Sites 1135 and 1136 on basement highs near the eastern flank. The successions encountered by these wells are illustrated in Plate 8, and the stratigraphy is summarised on Plate 9.

Basement

SKP basement was sampled at ODP Sites 738, 747, 748, 749, 750, and 1136 and in a number of dredges along the 77 Degree Graben (Leclaire et al., 1987). All wells recovered altered tholeiitic basalt. At Site 1136, seismic data (Line 180/02) show that the top of the basement consists of a series of lava flows. Basalt from the uppermost flow (6.2 m recovered from about 10-m-thick flow) varies downward from moderately altered, to a massive interior, to a fine-grained, vesicle-rich and oxidised base. Its petrographic characteristics indicate that it formed as an inflated pahoehoe flow (Coffin, Frey, Wallace et al., 2000). The absence of features typical of submarine volcanism (e.g., pillows and quenched glassy margins) suggest subaerial eruption. The age of the top volcanic flows in most wells has been estimated to be Aptian-Albian. Pringle and Duncan (2000) conducted Ar/Ar step-heating experiments on basalts from several ODP sites. The oldest ages (117+-0.8 Ma) have been obtained for phenocrystic plagioclase from Site 1136. Plagioclase from Site 750 in the northern part of the province showed a slightly younger age (112+-0.4 Ma). The K-Ar age of basalts recovered within the 77 Degree Graben is about 114 Ma (Appendix 4).

Mesozoic sediments

ODP Site 748 (Schlich, Wise et al., 1989) was drilled on a basement high on the western margin of the Raggatt Basin. It recovered weathered Albian sediments, siderite, and wood fragments above alkaline basalt flows with interbedded sediments (Plate 8). Glauconite and carbonates in the Cretaceous succession indicate a shallow-water environment, deepening sharply near the close of the Mesozoic.

ODP Site 750 was drilled on a basement high on the eastern flank of the Raggatt Basin. It recovered 29 m of Albian claystone with coal overlying extruded depleted (tholeiitic) basalt. The upper part of the volcanics were weathered to kaolinitic clays, and the charcoal found in the basal sedimentary layer, together with the high organic content (up to 7%) indicate a warm, high rainfall, swampy onshore environment (Schlich, Wise et al., 1989). Santonian and younger carbonates above the Albian claystones (Plate 8) display the onset of open marine conditions, and an upper-slope environment in the late Campanian. The environment of deposition is consistently deeper than that at Site 748 on the western side of the province, and was bathyal by the close of the Cretaceous.

ODP site 751 located in the central part of the Raggatt basin was intended to recover Neogene and Paleogene stratigraphic section, but terminated in Miocene oozes at 166 m.

ODP hole 1136 (Plate 8) recovered nannofossil and calcareous oozes of Late Cretaceous age with calcareous volcanic clayey sand and 38 m of silty clays of Albian age above basalt of Barremian (119 Ma) age (Pringle and Duncan, 2000).

ODP Site 738 was the most southerly hole drilled on the Kerguelen Plateau. The well recovered 77 m of limestone of early Maastrichtian to early Turonian age overlying basaltic basement followed by Early Maastrichtian oozes and chalks with foraminifera, nannofossils and cherts (Plate 8). The sedimentary succession records a history beginning with neritic deposition in the early Turonian, and pelagic (but not deepwater) conditions in the remaining upper Cretaceous. Late Maastrichtian planktonic foraminifera are of subtropical transitional types, not the cool-water genera of temperate regions (Barron, Larsen et al., 1989).

Cainozoic sediments

ODP Site 748 on the western margin of the Raggatt Basin drilled one of the most complete successions encountered on the Kerguelen Plateau. The well drilled 898 m of Albian to Pleistocene sediments. The Cainozoic succession consists mainly of nannofossil ooze and chalk. Ice-rafted debris occurs first in the Oligocene succession. Diatom oozes typical of the polar waters dominate in the Plio-Pleistocene. ODP Site 750 on the eastern margin of the Raggatt Basin intersected 450 m of Maastrichtian to Middle Eocene nannofossil ooze and chalk with cherts.

ODP holes 1135 and 1136 were drilled on the uplifted and eroded eastern rim of the Southern Kerguelen Plateau. Site 1135 passed through 222 m of calcareous chalks of Paleocene to Santonian age followed by 304 m of pelagic nannofossil ooze and chalk of Middle Eocene to late Paleocene age and 9 m of Pliocene diatom ooze with sand and pebbles. ODP Site 1136 drilled through 76 m of nannofossil and calcareous oozes of Late Cretaceous to Middle Eocene age.

ODP Site 738 is located north of the present Antarctic Divergence and near the southern limit of the Antarctic Circumpolar Current (Barron, Larsen et al., 1989). The hole intersected 402 m of Early Maastrichtian to early Oligocene oozes and chalks with foraminifera, nannofossils and followed by 17 m of Late Miocene to Quaternary diatom oozes. Climatic alteration is apparent in the upper Miocene and lower Pliocene with the change from nannofossil to diatom ooze, and the arrival of ice-rafted gneiss and granite components of Antarctic origin.

5.5.2 Rift zones

The most striking feature of the SKP is an complex system of rift zones. Three separate rift systems intersect the plateau in several directions. The best studied rift zone, the 77 Degree Graben (Houtz et al., 1977; Munschy et al., 1992; Rotstein et al., 1992; Munschy et al., 1993), extends in a N-S direction for more than 500 km. The 59 Degree Graben extends roughly E-W to the south of the 77 Degree Graben, and the Southern Kerguelen Plateau (SKP) Rift Zone trends in a NW-SE direction to the south of the 59 Degree Graben (Plate 3).

77 Degree graben

The 77 Degree Graben is a north-south trending rift zone extending from 54° to 58° S. Most of the 77 Degree Graben, except its northernmost part, is clearly expressed on the satellite gravity (Fig. 6). Gravity lows usually correspond to the rift axis, and gravity highs to the uplifted flanks of the rift. The 77 Degree Graben is generally 10-30 km wide within a 100 to 150 km zone of uplift (Fig. 22). Sediment thickness in the graben varies from 0.8 to 2.5 sec TWT.

Our analysis of "*Rig Seismic"* Lines RS47/014 to RS47/029 and RS179/07 confirms most of the earlier observations (Plate 5, 10 and 11). On most crossings, the 77 Degree Graben looks like a half-graben with up to 2.5 sec TWT throw on a major bounding fault and tilted blocks on both sides of the axial zone (Fig. 22, Plate 10). Most faults terminate at Paleocene level, however, some faults displace Eocene and Oligocene horizons (Plate 5) and some (Line 47-27) form major scarps on the seafloor.

Munschy et al. (1993) analysed the morphology and structure of 77 Degree Graben in some detail on the basis of both *"Rig Seismic"* and *"Marion Dufresne"* data. They noted changes in asymmetry of the rift zone along strike and identified six segments, each 50-100 km long, with alternating polarity within the graben.

One of the most noticeable features of the graben is that its flanks are increasingly uplifted towards the south. It appears that the whole southern part of this rift system including the western part of the Raggatt Basin experienced Neogene tectonic uplift with differential movements along the faults. The timing of this tectonic event is uncertain, but judging from the geometry of the Lower Miocene horizon mapped in the Raggatt basin the fault movement could be as young as Miocene (Plate 5).

The age and origin of the 77 Degree Graben remain poorly constrained. Interpretation of seismic data indicates that it probably formed in the Maastrichtian-Paleocene, which correlates with ODP drilling results (Site 747). This suggests a major tectonic event at the end of Maaastrichtian followed by by several phases of tectonism, resulting in selective fault reactivation. Some faults were reactivated during the Eocene-Oligocene in response to the breakup between the Kerguelen Plateau and the Broken Ridge, while the most recent reactivation may have been caused by intraplate stress associated with the formation of the Kerguelen-Heard volcanic complex.

59 Degree Graben

The 59 Degree Graben is located immediately to the south of 77 Degree Graben (Plate 3). E-W trending structures on Kerguelen Plateau were first described and mapped by Angoulvant & Schlich (1994). They suggested that the E-W trend may reflect the Late Cretaceous to Early Tertiary post-emplacement deformation of the Broken Ridge/KP volcanic province. Munschy et al. (1993) suggested that the 59 Degree Graben could be explained by the interaction of the 77 Degree Graben and the Southern Kerguelen Rift Zone.

Only two seismic lines (47-027 and 47-29) were available to the present study to investigate the 59 Degree Graben (Plates 5 and 11). They show closely spaced steep normal faults in the area of uplifted and partly eroded basement that forms the southern boundary of the 77 Degree Graben. The width of the 59 Degree Graben varies from 60 to 85 km and it is about 500 km long. Sediment fill is generally less than 1000 m. Analysis of the satellite gravity indicates that the western part of the graben has a WNW-ESE orientation and consists of en-echelon segments.

The geometry of the 59 Degree Graben in relation to 77 Degree Graben and the SKP Rift Zone (Plate 3), suggests that the 59 Degree Graben may be a strike-slip fault zone linking the N-S trending grabens. Seismic data across the 59 Degree Graben are oriented along strike rather than dip, therefore no clear conclusions can be drawn about its origin. Sediments have been eroded from structural highs and correlation across fault boundaries can be only tentative (Fig. 23). Based on seismic character correlation, the age of the syn-rift section is interpreted as Late Cretaceous to Eocene suggesting that this rift zone may be slightly younger than the 77 Degree Graben.

Southern Kerguelen Rift Zone

None of the seismic data available for this study intersected the Southern Kerguelen Rift Zone. The rift zone was mapped by Rotstein et al. (1992) as trending in a NW-SE direction, between 59° and 62° S. It lies in the central part of the Central SKP Uplift, which is about 1000 km long and 50 to 70 km wide. The rift zone is generally symmetric, with different amounts of throw on its flanks. Faults with over 1 km throw mapped by Rotstein et al. (1992) have been incorporated into our structural map (Plate 3). There is good correlation between the mapped faults and the gravity image, which has been used to extrapolate major faults beyond seismic coverage.

The sediment fill has been described by Rotstein et al. (1992) based on interpretation of MD47 lines. He defines three megasequences across the whole SKP: pre-uplift, post-uplift and upper. A major unconformity separating pre-uplift and post-uplift corresponds to 68 to 64 Ma interval, when according to Rotstein et al. (1992) the central part of the SKP was uplifted. Correlation with the seismic data in the Raggatt Basin indicated that pre-uplift sequence may consist of Lower Turonian to Campanian limestone deposited in a shelf environment, whereas the post-uplift sequence correlates with Campanian to lower Oligocene nannofossil ooze and chalk. The post-uplift megasequence in the SKP rift is about 1 km thick.

Rift structures in the southernmost part of the Plateau

In the southernmost part of the province *Nella Dan* Line 34-70 (Plate 5) shows another prominent rift (Fig. 24). It was first mentioned by Rotstein et al. (1992). The rift appears to lie on the continuation of a hinge zone mapped from the Eltanin data on the western flank of a wide basement high (Plate 3). The rift is asymmetric with a steep bounding major fault on its eastern flank and a minor fault on its western flank. The displacement along this fault is close to 2 km. The central part of the rift is narrow (2 km) with almost no sediment. Uplifted flanks of the rift are covered by sediments up to 0.8 sec TWT thick. Correlation with stratigraphic units in ODP well 738 show that Campanian and possibly Paleocene horizons onlap on the rift flanks. Neogene sediments are partly eroded from the most uplifted parts of the rift zone.

Based on the satellite gravity image, this graben trends NW-SE similar to SKP Rift Zone. Bathymetric and gravity data indicate that there may be more rifts in the southern part of the plateau, however the low density of seismic coverage does not allow mapping of these features.

Age and origin of the rift zones

According to Munschy et al. (1993), all rift systems on the KP were formed between 72 and 60 Ma during a major extensional phase associated with the initial stage of spreading at the Southeast Indian Mid-ocean Ridge (SEIR). This extension resulted in the formation of NW-SE trending rifts in the eastern and southern parts of the plateau, and N-S oriented rifts in the central part. They suggest that N-S trending rift zones were initiated along pre-existing fracture zones with a minor strike-slip motion. Our analysis of seismic data shows normal faulting within the 77 Degree Graben (Plates 4, 5), which supports Munschy's conclusion about a predominantly extensional mechanism for the formation of this rift system.

Tikku and Cande (2000) suggested that the Kerguelen Plateau rift system may have been a plate boundary between the Australian and Antarctic plates between 75 and 63 Ma. The amount of predicted extension on this boundary does not contradict seismic reflection results. Evidence for fault reactivation in the Eocene, Oligocene, and possibly the Miocene suggests that the rifts were affected by later tectonic events, which were caused by adjustments to a changing stress field. The 59 Degree Graben may represent an accommodation zone between the two major rifts.

5.5.3 Raggatt Basin

The NW trending Raggatt Basin is a major sedimentary basin in the southern province (Fig. 19, Plate 6). The basin (Plate 3) covers about 38,000 km^2 in area and contains up to 2500 m of sediments. It is at least 500 km long and is up to 250 km wide. In the south, it is bounded by 77 Degree and 59 Degree grabens and extends to about 81° E. The northern boundary of the basin is not well defined. Previous interpretations (Colwell et al., 1988; Coffin et al., 1990) mapped the northern extent of the Raggatt basin to about 56°S, however Eltanin records (USNS Eltanin, Cruises 46-50, 1977) indicate significant sediment accumulations further north, possibly to the west of the 77 Degree graben (Fig. 18). This northern basin (Plate 3) is about 20,000 km^2 in area.

Seismic sections across the Raggatt Basin (Plate 5) show the presence of NW-SE trending a 300 km long and about 100 km wide linear volcanic centre within basement on the eastern side of the basin (Lines 47-22, 24, 27 and 33). This volcanic centre is characterised by dipping reflector sequences with a visible thickness up to 2 sec TWT. At the point of convergence between west-dipping and east-dipping reflectors there is a graben, which may have formed due to subsidence over an exhausted magma source. This volcanic centre has been mapped continuously between 56° and 59° S trending in NW-SE direction. Dipping reflectors under the Raggatt Basin (e.g. Line 47-24, Plate 5) indicate that depression existed on the southeastern part of the Kerguelen Plateau into which lavas flowed from volcanic centres.

Seismic sequences

Stratigraphy of the basin is based on the results from ODP Sites 748 and 750, indicating that Raggatt basin contains Albian to Recent sediments.

Albian (or older) to Campanian sediments occur in the central part of the basin, where they fill in lows and onlap on to basement. They are characterised by low to medium amplitude reflections and moderate continuity. Maximum thickness of this succession is about 1 sec TWT. A well-defined erosional unconformity within the sequence has been mapped as a possible Albian horizon (*alb*).

The overlying Campanian to Palaeocene sediments are characterised by bright discontinuous reflections. The uppermost Palaeocene part of the succcession contains a number of mounded features (Fig. 25, Plate 5). These mounds usually have relief of 200-300 m and display clear signs of growth. Most likely they represent carbonate mounds formed in shallow water (Munchy et al., 1993; Coffin et al., 1990). Paleocene to Eocene sediments usually drape the mounds and fill in lows n the faulted basement of the eastern part of the basin.

The uppermost sequence is of Palaeocene to Recent age and is characterised by continuous medium amplitude reflections. Unconformities within this sequence (*eoc, olig* and *miol*) have been tied to ODP wells. The Eocene to Oligocene succession is partly eroded in the east and is displaced on some faults in the vicinity of the 77 Degree Graben. It is similar in seismic character to the underlying sequence. Miocene and younger sediments are thickest (300 msec) about 100-150 km to the east of the 77 Degree Graben and thin out to the east and west. This sequence is easily identified by its high amplitude and continuous reflections.

Tectonic and depositional history

The basement of the Raggat Basin formed at about 112-110 Ma by subaerial eruption of massive lava flows (Coffin, Pringle et al., in press). The volcanic ridge mapped beneath the eastern border of the basin may have been one of the major sources of the lava flows.

ODP wells 748 and 750 drilled on opposite sides of the Raggatt Basin reveal differences in depositional histories of its eastern and western parts (Fritsch et al., (1992). Deposition at Site 750 in the east remained close to sea level until about the end of the Coniacian, when the eastern margin of the central Plateau was uplifted. After this event, subsidence was rapid and the depositional environment was bathyal by the end of the Cretaceous (Plate 9). At Site 748 in the west, the uppermost Cretaceous is characterised by shallow-water carbonates. Regional uplift of the SKP around 66 Ma led to the development of mounds in the western part of the basin. (Schlich, Wise et al., 1989, Coffin et al., 1990, Fritsch et al., 1992).

Slow thermal subsidence of the entire Southern Kerguelen Plateau continued until about 40 Ma (Late Eocene). Sedimentation during this period was dominated by pelagic nannofossil ooze and chalk. Thereafter, sedimentation continued in the western Raggatt Basin, but ceased in the east. Deposition, or the lack of it, was controlled not by accommodation or subsidence, but probably by currents. These north-flowing currents prevented any deposition on the eastern part of the Southern Kerguelen Plateau and the sediments were deposited further west in the Raggatt Basin. Sediments of Oligocene to Quaternary age are represented mostly by nannofossil and diatom ooze.

5.5.4 East Kerguelen Sedimentary Ridge (EKSR)

The largest structure attributable to non-tectonic, non-volcanic processes is the East Kerguelen Sedimentary Ridge described by Houtz et al., (1977) and Ramsay, Colwell et al.(1986) and shown on Plate 3. It lies in water depths of about 4000m, is more than 820 km in length, around 85 km wide, and its maximum thickness is about 800 m (Plate 5, lines 180-05, 180-06, 180-07, 180-01 and 47-33). It therefore contains about 20000 km^3 of sediments. It is overall younger than mapped horizon *eoc* mapped throughout the Labuan Basin (Fig. 26), and it is therefore Eocene to Quaternary in age. During uppermost Miocene, the currents that created the ridge slowed, and pelagic drape is indicated by parallel seismic reflections.

The EKSR is a current-deposited feature containing material that may have been transported from a considerable distance, rather than being sourced from adjacent parts of the Kerguelen Plateau. There is a current-created channel or moat between the EKSR and the Plateau along most of its length. Currents moving along this channel would have prevented the transport of sediment from the Plateau directly to the adjacent areas of the EKSR, particularly if the currents come from the southeast.

ODP holes 745 and 746 were drilled on the EKSR. They each encountered more than 200 m of uppermost Miocene to Quaternary diatomaceous ooze and clay, of mixed pelagic and terrigenous origin. The terrigenous component is dominated by material from a metamorphic terrain (Ehrmann et al., 1991). It is probably derived from Antarctica and carried to the site by ice rafting or melt-water plumes. The biogenic component is derived locally, from the water column. Although seismic profiles in the area show a lot of channels, erosional surfaces were not observed in the cores (Barron, Larson et al., 1989). The lack of erosional features in cores can be explained by the fact that they were taken from the crest of the ridge, which is the site of greatest deposition.

Development of this sedimentary structure is directly related to the opening of the Southern Ocean accompanied by a dramatic change in bottom ocean circulation. Prior to the Eocene breakup, the Labuan Basin was almost enclosed and characterised by restricted bottom water circulation. Following the Eocene breakup and development of the Circum-Antarctic Current in the upper part of the water column, bottom circulation changed too, featuring a strong current entering Labuan Basin from the south and following the eastern flank of the Kerguelen Plateau. Current measurements by MV *Eltanin* (Eittreim et al., 1972) confirmed existence of this north-flowing current. Towards the north the current slows down, which results in less carrying power and sediment deposition. The smaller size of the sedimentary ridge towards the north is documented by our seismic data, which supports the above interpretation.

5.5.5 Discussion

The key to the complex tectonic history of the Southern Kerguelen Province may lie in its crustal structure.

Refraction results indicate up to 22 km thick crust with low velocities (6.6 - 7.3 km/s) in the lower crust. Operto and Charvis (1995) described the velocity-depth structure beneath the Raggatt Basin as being different from other hotspot-related oceanic plateaus and more consistent with a thinned continental crust overlain by basalt flows. In contrast, Gladczenko and Coffin (2001) interpreted the low velocity crustal body underneath the Southern Kerguelen Plateau as a possible product of metamorphism associated with reheating of the oceanic plateau crust at about 85 Ma. Although basalts recovered in the Southern province are best described as ocean island basalts, their isotopic characteristics (Mahoney et al., 1995) show geochemical evidence of contamination by continental lithosphere, which may indicate the presence of continental crust beneath the Southern Kerguelen

Plateau. Alternatively continent-like isotopic and chemical signatures may be explained by incorporation of continental lithospheric material into the mantle plume (Mahoney et al., 1995). However, neither geophysical nor geochemical evidence rule out the possibility that some continental crust left from early rifting stages form part of the Southern Kerguelen Plateau (Coffin and Eldholm, 1994). We suggest that crust thickened through the presence of continental fragments and cemented by Late Cretaceous basalts caused heterogeneity of the crust in the Southern province. This pre-existing heterogeneity may be responsible for the complex pattern of extensional structures.

5.6 Elan Bank

Elan Bank extends westward from the boundary between the central and southern Kerguelen Plateau (Fig. 19, Plate 3). Bathymetry and gravity images (Figs.2 and 6) and seismic data indicate that it consists of two large basement highs displaced along a NW-SE trending feature in the central part of the bank. The western high is very shallow, rising up to 500 m below sea level, whereas the eastern part is about 1000 m deep. Elan Bank's predominant east-west structural trend differs from the trends observed from the Central and Southern provinces. Angoulvant and Schlich (1994) suggested that its structural trend may reflect the Late-Cretaceous to Early Tertiary deformation of the Broken Ridge/KP volcanic province.

5.6.1 Stratigraphy

Until recently the stratigraphy of Elan Bank was unknown. It was first drilled during ODP Leg 183. Site 1137 (Fig. 4, Plate 2) is located on high in the central part of the bank. The hole reached basement recovering 153 m of mainly brecciated and massive basalts. These rocks have been dated 109.3 Ma (Coffin, Pringle et al., in press). The basement is overlain by Campanian glauconitic sandy packstone and nannofossil pelagic oozes of Late Eocene to Pleistocene age (Fig. 16). Basal volcaniclastics and conglomerates interbedded with the basalts contain evidence of fluvial deposition. In the bottom unit, the volcaniclastic conglomerate contains clasts of garnet-biotite gneiss (Nicolaysen, Pringle et al, 2000) indicating a continental component of the bank. The conglomerate was sourced locally in a sub-aerial environment and deposited in a braided river environment. Zircons and monazites in individual clasts have been dated as between 675 and 938 Ma, whereas biotite grains yield an age of ~550 Ma (Nicolaysen, Bowring et al., 2001). These predominantly Cambrian dates together with a low velocity layer at the base of the crust (see chapter 2.2) provide good evidence for the presence of old continental crust within the mafics of the Kerguelen Plateau.

Sedimentary cover over most of Elan Bank doesn't exceed 1 sec TWT. On uplifted parts of the bank basement shows clear signs of wave-based erosion. Sequences extrapolated from Site 1137 include a very thin (0.1 sec TWT) Cretaceous sequence characterised by continuous bright reflections and a thicker (0.5-0.8 sec TWT) Tertiary to Pleistocene succession with medium amplitude, generally continuous reflectors. The most prominent unconformity in the upper sequence has been dated as Eocene (ODP Site 1137, Coffin, Frey, Wallace et al., 2000).

5.6.2 Structure

During AGSO survey 179 five lines were acquired on the western and southern flanks of the bank (Fig. 4, Plate 4). All lines show the complex seismic character of the basement. It contains thick dipping reflector sequences (Fig. 27, Plate 4), non-reflective buildups, and faulted intra-basement reflector sequences similar to those mapped on volcanic passive margins, particularly on marginal plateaus such as Wallaby and Exmouth Plateaus off Western Australia (Symonds, Planke et al., 1998; Planke, Symonds et al., 2000). In these areas, dipping reflector sequences have been interpreted as massive lava flows formed in subaerial environments above a hotspot. On some lines across the Elan Bank the dipping refrlector sequences terminate against a surface (Plate 4, 179-03, 179-04) that could correspond to a large landward dipping fault or pre-existing basement. At the base of the slope, thick lava flow sequences (about 500 m) extend up to 50 km seaward (Plate 4, Line 179-05). A smooth surface and very bright reflector at the top of this succession usually indicate shallow marine, rather than subaerial depositional environments (Eldholm et al., 1995).

South of Elan Bank a very strong reflection (*Endb*) at about 7.5 sec TWT (Plate 4, Line 179-05) overlies well-layered crust. This reflective and layered crust could represent a transitional continental-ocean zone underlain by highly-extended continental crust with sedimentary sequences capped by basalt flows, or alternating volcanoclastics and basalts. Further seaward this transitional crust adjoins thickened oceanic crust of the Enderby Basin interpreted from sonobuoy data (Charvis and Operto, 1999), which is consistent with the structure of volcanic rifted continental margins (Symonds, Planke, et al., 1998; Planke, Symonds et al., 2000).

The basement low separating the western and eastern segments of Elan Bank has been partly intersected by line 179/06 (Fig. 28, Plate 4). Tilted blocks with possible syn-rift sequences of unknown age have been tentatively mapped under the top volcanic sequence (which corresponds to the last basement forming volcanic accumulations in the region). Total sediment thickness in this basin reaches about 2 sec TWT with up to 1 sec of probable Early Cretaceous sediments. This small rift basin could be a pull-apart basin formed along the strike-slip fault separating eastern and western parts of the bank. Seismic data indicates that the basin was formed and filled prior to the final stage of volcanism, which is dated from ODP Site 1137 as Albian (109.3 Ma) (Coffin, Pringle et al. In press).

Observed volcanostratigraphy as well as results from drilling and refraction data indicate that Elan Bank is a complex feature composed of continental fragments modified and covered by volcanics. We suggest that volcanic sequences on Elan Bank may have formed either during the Valanginian(?)

breakup of India/Elan Bank and Antarctica, or during later Albian breakup of India and Elan Bank, when the bank was transferred from the Indian to the Antarctic plate via a ridge jump. In either case, massive Albian volcanism has overprinted and radically altered the continental sliver forming the core of the Elan Bank.

5.7 William's Ridge

William's Ridge extends in a NNW-SSE direction as a continuation of a prominent basement ridge mapped in the eastern part of the Central province (Fig. 19, Plate 4). William's Ridge is underlain by 12-15 km thick crust (Gladczenko and Coffin, 2001), which is significantly thicker than the adjacent Labuan Basin crust, but similar to that of the Kerguelen Plateau. It rises to only 500 m below sea level and appears to consist of two blocks separated by a narrow fault-bounded valley.

Williams Ridge has never been drilled and its stratigraphy and the nature of basement are unknown. A basement high, which lies on the structural continuation of William's Ridge to the north, has been sampled in a few locations (Appendix 4, Plate 2). As mentioned earlier (chapter 5.4), MD48 dredge 8 recovered Miocene saprolitic basalt, and MD35 cores sampled Late Cretaceous sediments, interpreted as Cretaceous basement intruded by Miocene volcanics. In the Central Province, Miocene volcanics are apparent on seismic data, however on the William's Ridge there is no clear seismic evidence of younger volcanism.

Futher evidence about possible age and crustal structure of William's Ridge comes from the conjugate margin, Broken Ridge. Prior to breakup in the Eocene, William's Ridge and Broken Ridge belonged to one structural province (Fig. 10). We therefore suggest that William's Ridge basement is of similar age and composition. Igneous basement of Broken Ridge was first sampled during ODP Leg 183 recovering mostly alkaline basalts with the top units represented by subaerial lava flows. The age of these basalts was estimated as 94 Ma (Duncan and Pringle, 2000).

A dipping reflector sequence has been interpreted on Line 179-07 on the western flank of the ridge (Fig. 29, Plate 4). It is 50 km long and about 1.2 sec TWT thick. In the western part of the ridge the top of the sequence is faulted. Massive lava flows normally have a strong magnetic signature, however the dipping sequence on the William's Ridge displays no magnetic anomaly. This may indicate the presence of significant amounts of sediment interbedded with volcanics or a non-volcanic sedimentary origin for the entire sequence.

Results of ODP drilling on Broken Ridge showed the presence of a thick (about 1sec TWT) carbonate section dipping to the north and characterised by strong continuous reflectors. Driscoll et al. (1991) described prograding clinoforms, comprising lower Maastrichtian to Eocene limestones and chalks, indicating shallow-water deposition during this period. A very strong erosional unconformity of Middle Eocene age truncates this dipping sequence (Driscoll et al., 1991).

Although superficially the dipping sequence on William's Ridge is similar to the sedimentary sequence on the Broken Ridge their seismic characteristics are quite different. Seismic character of the dipping sequence on the William's Ridge is more consistent with volcanic-dominated sequences mapped in other parts of the plateau. Sediments overlying the dipping sequence appear to comprise an onlapping Albian (Pre-Albian) to Campanian sequence and Campanian to Oligocene succession which are broadly concordant with the top of the dipping sequence (Fig. 29). The section interpreted as pre-Eocene in age is characterised by continuous medium-amplitude reflectors and may correspond in age and composition to the carbonates of Broken Ridge.

ODP drilling results from Broken Ridge indicate that Kerguelen/Broken Platform formed in the Cenomanian. By the Santonian, the depositional environment was bathyal to outer neritic (Driscoll et al., 1991). However, during the Maastrichtian to Eocene, shallow-water carbonates dominated most of the region. In the Eocene between 50-47 Ma, the platform has undergone uplift and subaerial erosion, followed by breakup at about 40 Ma. At the same time, Broken Ridge was tilted to the north, which resulted in further erosion and redeposition of eroded material northwards. Sediments on the western flank of William's Ridge are tilted in the opposite direction, i.e to the south. Since the Middle Eocene both features were continuously subsiding.

5.8 Labuan Basin

The Labuan Basin is located along the eastern margin of the Kerguelen Plateau (Fig. 19) and generally contains 2.5 to 4 km of sediment above basement. In the north it is separated from the Australian-Antarctic Basin by William's Ridge. Its eastern (and particularly southeastern boundary) are delineated by a deep (9 sec TWT) trough in basement containing up to 5 km of sediments which separates it from the oceanic crust of the Australian-Antarctic Basin (Plate 3).

The nature of the crust underlying the Labuan Basin and the age of its sedimentary fill are very poorly constrained. Most of the evidence is derived from the adjacent Kerguelen Plateau and our understanding of the regional tectonic history. There is a remarkable similarity in the gravity signature between the Labuan Basin and its conjugate on the Australian margin, the Diamantina Zone. Plate tectonic reconstructions of the Southern ocean (Royer and Coffin, 1992, Gladczenko and Coffin, 2001; Tikku and Cande, 2000; Fig. 30) show that prior to the start of the fast spreading between Australia and Antarctica in the Eocene, the Labuan Basin lay against the Diamantina Zone. Therefore, both features are likely to have a similar origin.

5.8.1 Stratigraphy

Only two wells have been drilled in the Labuan Basin, both sampling the uppermost part of the sedimentary section, whereas the stratigraphy of the Mesozoic and Early Cainozoic section remains unknown. ODP Sites 745 and 746 were drilled on the western margin of the Labuan Basin (Barron, Larson et al., 1989) near the crest of the East Kerguelen Sedimentary Ridge (Plate 3). The drill results are summarised in section 5.5.4.

5.8.2 Structure

The Labuan Basin is separated from the Kerguelen Plateau by a high escarpment, which appears to be a surface manifestation of a fundamental crustal-scale fault zone at the western edge of the Labuan Basin. The escarpment trends NNW along most of its western margin and dips typically 8 to 22 degrees. In the central and northern parts of the Labuan Basin it breaks up into a number of narrow terraces defined by a series of large faults. The transition to Australian-Antarctic Basin on the eastern side of the basin is marked by a deep trough bordered by prominent basement highs. A dramatic change in depth to basement occurs across this boundary (Plate 12). In the Labuan Basin, basement typically lies at 7.5 to 8.0 sec TWT, whereas in the adjacent parts of the Australian-Antarctic Basin it lies at 6.5 - 7 sec TWT, which is consistent with its much younger age. The satellite gravity image (Fig. 6) shows the Labuan Basin as a distinct gravity low containing a number of prominent highs generally parallel to the strike of the basin. Analysis of the seismic reflection data shows that all gravity highs correspond to basement highs and ridges. The deep trough along the eastern boundary of the Labuan Basin is marked by a continuous linear gravity low that extends from the William's Ridge to the southernmost part of the basin at about 95^{o} E. It is shown as a depocentre in Fig. 19 and on Plate 3.

Labuan Basin basement is extensively faulted and intruded (Plates 4 and 5). Analysis of seismic data shows significant differences in basement character between the eastern, western and southern parts of the basin. The ***western part of the basin*** is 130-150 km wide and is extensively faulted. The dominant fault-style is extensional, with planar normal faults typically dipping to the SW (Fig. 31, Plates 4, 5 and 12) and resulting in a series of tilted fault blocks. On most lines these faults offset interpreted Albian and Campanian sediments. Eocene sediments are offset only on some faults, mostly in the area close to the eastern boundary. Oligocene and younger sediments are generally not affected, but show differential compaction and drape over the basement faults.

In the central part of the Labuan Basin the faults typically dip to the SW, however, some NE dipping faults are present on lines 180/08 and 180/01 (Plate 5). These two lines cross the eastern trough bounding the Labuan Basin where it splits into two branches (Plate 3). NE facing basement faults were mapped in between these two depocentres.

Although timing of faulting cannot be constrained reliably due to the lack of good stratigraphic data, growth of interpreted pre-Albian sediments into faults suggests that structuring first occurred in the Albian or earlier (Fig. 31). However on some lines from the northern Labuan Basin (Fig. 31) the interpreted Albian and older succession does not show syn-rift characteristics. This may indicate that rifting commenced later in some areas. Maastrichian and younger sediments show clear sag phase characteristics, although some reactivation occurred, particularly in the Eocene. The faulted basement of the western Labuan Basin is separated from the less faulted basement of the eastern Labuan Basin by a large basement high (Fig. 32).

The ***eastern part of the Labuan Basin*** is about 120 km wide and is characterised by large NNW trending basement highs (Plates 4, 5 and 12). The appearance of these blocks is different from the faulted blocks of the western part of the basin. They are usually larger and dome-shaped. Analysis of magnetic anomalies over these basement blocks shows that most of them do not have a magnetic signature typical of intrusions. One of these blocks in the northern part of the basin was dredged in 1991 (Montigny et al., 1993) and yielded one and a half ton of metamorphic and granitic rocks interpreted as ice rafted debris. However, if these rocks are representative of Labuan Basin basement, as opposed to being ice-rafted, then the absence of a magnetic signature can be easily explained. The issue of possible origin of the crust in the Labuan Basin will be discussed later (Chapter 6.8.4).

Basement in the eastern Labuan Basin lies generally deeper (8.0–9.0 sec TWT) than in the western Labuan Basin and the sedimentary sequences are generally less faulted. In the easternmost part, the basement appears to be structured, featuring tilted blocks partly covered probably by volcanics or volcaniclastics. These volcanics obliterate the seismic signature of the faults, making the definition of the structural style difficult. Faulting in this part of the basin took place earlier than in the western part of the basin.

The ***southern part of the Labuan Basin*** is crossed by lines 180/03, 04 and 05, as well as by *Marion Dufresne* lines MD47/08 and MD47/10 (Fig. 4). Basement character on these lines is significantly different from the rest of the Labuan Basin. There is no clear boundary fault with the Southern Kerguelen Plateau. Distinct dipping reflector sequences extending from the slope into a transitional zone (Plate 5, line 180-05) indicate that formation of the Labuan basin crust was accompanied by extensive volcanism. The basement and overlying sediments are generally unfaulted. Survey 180 lines extend only 200 km off the margin, however '*Marion Dufresne'* lines (8 and 10) cross the entire southern zone. Both lines show consistently smooth flat basement lying at 7.5 – 8.0 s TWT. The eastern bounding trough has a similar appearance and sedimentary fill as elsewhere in the eastern part of the basin (Fig. 33). We classified this part of the Labuan Basin as its southern sub-province (Plate 3, Fig. 19). A very different basement character in this province indicates that it may be underlain by crust of a different origin or has a different tectonic history.

Crustal structure

Sixteen sonobuoys were deployed in the Labuan Basin during the AGSO surveys 179 and 180. Velocities for the upper part of the crust have been calculated using the ray-tracing method for 10 sonobuoys (Appendix 8). A detailed description of data processing methods are given in Appendix 7. Only one sonobuoy in the northern part of the basin (179/07c) appears to have reached Moho, yielding a crustal thickness of about 7.5 km, consisting of 3 km of sediments and 4.5 km of igneous crust. Sonobuoy 179/07d on the same line showed the presence of a high velocity layer (7.8 km/s) at about the same depth, while all layers above had similar thicknesses and distribution of velocities.

Most sonobuoys in the Labuan Basin did not resolve crustal thickness. The typical velocity profile includes an upper sedimentary layer with velocities of 1.7-2.0 km/s (unconsolidated Cainozoic sediments), a lower sedimentary layer with velocities of 2.6 - 3.1 km/s (consolidated Mesozoic sediments) and an upper igneous crust (or middle crust) with velocities of 4.0 to 6.6 km/s. Igneous crust can be further broken down into extrusive volcanics with velocities of 4.0 to 5.5 km/s and massive intrusives with velocities of 5.6 to 6.6 km/s. The extrusive successions are about 3 - 4 km thick on the eastern margin of the Southern Kerguelen Plateau, and about 2 km thick in the Labuan Basin. On the southern lines (sonobuoys 18005a and 18005b), spatial distribution and thickness of the volcanics are highly variable, while the middle crust appears to thicken southwards. It is about 2.5 km thick in the northern Labuan Basin and up to 4.6 km in the southern Labuan Basin (Appendix 8).

Our results indicating thin igneous crust beneath the northern Labuan Basin (less than 5 km) are in agreement with the estimates made by Gladczenko and Coffin (2001) based on gravity modelling. However, the proposed crustal thinning to the south and the presence of high velocity crustal body (HVCB) beneath the central and southern Labuan Basin are not substantiated by our calculations. Our interpretation of the sonobuoy data shows that, in the northern part of the Labuan Basin the crustal thickness is 7–8 km. In its southern part the crustal thickness is unknown, but there is a noticeable increase in thickness of the middle crust. This does not support the inferred thinning of the crust to the south. However, the modeling results may also indicate that the thinning occurs mostly in the eastern part of the basin where we lack sonobuoy solutions. Velocities corresponding to the HVCB under the Labuan Basin have been retrieved only from one sonobuoy from the northern part of the basin, which is not representative enough to confirm or disprove the assumptions of the model.

Due to insufficient resolution at depth for most sonobuoys the crustal structure of the Labuan Basin remains unclear. Low middle crust velocities in the central and southern parts of the Labuan Basin may indicate that these areas are underlain by highly extended continental crust, whereas crustal structure of the northern Labuan Basin is more consistent with extended magmatic crust.

5.8.3 Seismic sequences

Rotstein et al. (1991) identified four major seismic sequences in the Labuan Basin: a pre-uplift megasequence formed prior to the uplift of the eastern Kerguelen Plateau in the Late Cretaceous, a syn-tectonic sequence deposited during this event, a post-uplift megasequence and upper megasequence. Rotstein et al. (1991) noted that these major sequences could be correlated to those on the Southern Kerguelen Plateau. He concluded that the basin formed at about the same time as the Southern Kerguelen Plateau in the Early Cretaceous and may represent downfaulted plateau crust. Our interpretation of the sedimentary sequences generally agrees with that of Rotstein, however a much better seismic coverage of the basin and new high quality seismic data allowed more detailed mapping.

The bedding in the oldest sediments (pre-uplift sequence of Rotstein) is parallel to the surface of the tilted blocks and there is a prominent unconformity with overlying sediments, clearly showing hanging wall onlap. Sediments of this age are throughout the Labuan Basin, missing only from basement highs, however their thickness is highly variable. Three units have been identified within this megasequence. The oldest unit occurs only in the eastern bounding trough and in the southernmost part of the basin (Plate 5 lines 180-06, 180-07). It is often seismically transparent and may represent volcanoclastic deposits or volcanic flows. The age of this sequence is unconstrained but is thought to be pre-Albian based on regional inference. The two overlying sequences are strongly laminated and, in seismic character, resemble Albian-Campanian sediments of the Kerguelen Plateau (Plate 5). The Albian-Campanian sequence (alb-camp) shows basement-parallel bedding in the northern part of the Labuan Basin, however in the southern part it shows growth into faults. Together with the absence of the oldest (pre-alb) sequence in the north, these relationships indicate that rifting progressed from south to north.

Campanian age of the upper boundary of the syn-tectonic sequence has been inferred from analysis of line MD47-08 (Fig. 33). On all lines intersecting the boundary with the younger oceanic crust created at the Southeast Indian mid-ocean Ridge (SEIR) the transition is marked by a prominent basement high, which doesn’t allow correlation of sequences in the Labuan Basin with those in the Australian-Antarctic Basin (e.g. line 47-33). Line MD47-08 (Fig 33) is the only line, which shows an unbroken record of seismic sequences across both basins, thus helping to constrain the age of the oldest sediments in the Labuan Basin. The transition from the Labuan to the Australian-Antarctic Basin on this line is clearly marked by a rise of the basement from 9.5 sec to 7.5 sec TWT. Sequences, which extend onto the younger crust progressively onlap onto the younger basement within an 80 km wide zone. Towards the eastern end of the line the age of basement is dated from linear magnetic anomalies as Middle Eocene (Chron 18, 43 Ma), therefore a distinct unconformity close to the basement has been interpreted as Eocene. The zone with onlapping sequences has been interpreted as a zone of slow seafloor spreading, which took place between the Campanian (80 Ma) and Eocene. Thick sediments beneath the Campanian unconformity have been interpreted as Albian-Campanian in age with the possibility of older sediments in the deepest parts of the basin.

Campanian to Eocene (camp-eoc) sag-phase sediments in the Labuan Basin are represented by a flat lying succession about 500 m thick, filling in depressions between the tilt blocks. The unconformity at the top of this sequence (eoc) is a prominent onlap surface (Fig. 31, Plates 4,5) throughout the entire Labuan Basin. The geometry of the onlap surface in the Labuan Basin is similar to that interpreted for the Great Australian Bight (Sayers, Berbardel *et al.*, in prep), where it is dated as Mid-Eocene. During the Late Cretaceous to Early Tertiary sedimentation on the Kerguelen Plateau was predominantly shallow marine, with some local erosion, whereas in the Labuan Basin deposition was bathyal and continuous.

Post-Eocene sediments are characterised by parallel bedding with some compactional drape over basement blocks (Lines 180-01, 47-15 and 179-07; Plates 4,5). Two regional unconformities were mapped within this succession: Oligocene (olig) and Upper Miocene (miou). Sediments overlying the Oligocene unconformity are characterised by relatively high amplitude and low continuity reflectors and the presence of channels, especially in the western part of the basin. Local unconformities present in post-Oligocene sediments are probably caused by bottom currents. Sedimentary structures produced by currents include mounds, cut and fill structures and channels (Fig. 34). Post-Eocene sediments are thickest in the northern and western parts of the basin, where they are about 800 m thick. This can be attributed to bottom currents, which enter the Labuan Basin from the south depositing sediments on the eastern flank of the Kerguelen Plateau/Western Labuan Basin (East Kerguelen Sedimentary Ridge) and slow down in the northern part of the basin before turning back to the south.

Although most of the post-Campanian sediments are unstructured, some lines in the northern and central parts of the Labuan Basin (179-07, 180-01, 180-07) show evidence of tectonic deformation as young as Miocene. This tectonism could be associated with readjustment along major faults in response to uplift of areas affected by the Neogene volcanism (northern part of CKP).

In the northernmost part of the Labuan Basin (line 179-07), a prominent bottom-simulating reflector (BSR) extending across the whole width of the basin has been identified (Fig. 35). It lies about 0.6 sec TWT below the seafloor mimicking its topography and cutting through the sediments, which are gently draped over the basement highs. Anomalous seismic reflectors that are parallel to seafloor and cut through geology usually indicate the presence of natural gas hydrates, where the position of the reflector coincides with the transition boundary at the base of the gas hydrate zone.

BSRs mark the interface between higher sonic velocity in hydrate-cemented sediment above and lower sonic velocity in uncemented sediment below. The seismic reflection from the base of the gas hydrate zone is generally characterised by a negative impedance contrast and large reflection coefficients.

Similar bright reflectors sub-parallel to the seafloor have been observed on several other seismic lines (47-15, 180-06), but due to the horizontal bedding of the sediments and flat seafloor morphology it is very difficult to be sure whether these reflectors are BSRs or just a change in lithology.

5.8.4 Discussion

Interpretation of the seismic data has shown that Labuan Basin is at least as old as the Kerguelen Plateau itself. However the absence of drill holes, the tenuous correlation with the plateau sequences, inadequate sample coverage and inconclusive sonobuoy results leave a lot of questions unanswered. The main questions are:

- The age and origin of the Labuan Basin crust.
- Timing of extensional faulting in the basin.
- Origin of non-magnetic ridges in the eastern Labuan Basin.
- Timing and cause of fault reactivation in the central/northern Labuan Basin
- Correlation of tectonic events between the Labuan Basin and the conjugate Diamantina Zone.

Below we discuss possible scenarios for evolution of the Labuan Basin taking into account results of recent sampling in the Diamantina Zone (Chatin et al., 1998) and on the Antarctic margin adjacent to the Kerguelen Plateau (Murakami et al., 2000).

Age and origin of the crust in the Labuan Basin

Rotstein et al. (1991) noted that the tilt-block morphology of the Labuan Basin extends onto the Kerguelen Plateau and that there is a reasonably good correlation between sequences on the plateau and in the basin. They suggested that the Labuan Basin was formed by crustal extension at about the same time as the plateau itself (130-95 Ma). On the contrary, based on plate tectonic considerations Gladczenko and Coffin (2001) suggested that Labuan Basin basement formed at about 95 Ma ago as a combination of extended Kerguelen Plateau crust and oceanic crust. In terms of basin age, our interpretation is more consistent with Rotstein's view. Extension in the Labuan Basin occurred progressively from south to north and by Campanian (80 Ma) the sediment fill in some parts of the basin was close to 2 sec TWT. Correlation of seismic sequences suggests that the basin may have existed by Albian.

Considering the heterogeneous appearance of the Labuan Basin basement, it is possible that the basin is floored by aggregation of different crustal types including extended continental and/or magmatic crust and fragments of re-rifted Early Cretaceous oceanic crust. Recent results from a geological and geophysical survey in the Princess Elizabeth Trough (Mukarumi et al., 2000) indicate possible presence of Mesozoic magnetic anomalies in the southernmost part of the Labuan Basin.

Comparison to Diamantina Zone and origin of the basement ridges

Based on the data from *Marion Dufresne* survey 80 (1994), Munschy (1998) showed that the Diamantina Zone consists of two structurally different basement provinces: tilted blocks separated by south-dipping faults in the northern part, and elongated highs and lows, interpreted as volcanic intrusions, in the southern part. A deep trough similar to the Labuan Basin's eastern trough has been mapped along the boundary with the oceanic crust of the SEIR. The volcanic and tectonic zones mapped within the Diamantina Zone are similar to the western and eastern Labuan Basin described earlier. Conjugate position of the Diamantina Zone and the Labuan Basin and their structural similarities suggest Labuan Basin-Diamantina Zone formed as one extensional terrane with an extrusive zone in its central part. The total width of this zone prior to the breakup was about 600 km.

A satellite gravity pre-breakup reconstruction of the Kerguelen-Broken Ridge region (Fig. 36) shows continuity of basement topography between the Labuan Basin and the Diamantina Zone. Some of these basement ridges could be correlated from the northern Labuan Basin into the southern Diamantina Zone. Recent dredging in the Diamantina Zone recovered alkaline basalts in the tilt-block zone and highly altered peridotites in the 'volcanic' zone (Chatin et al., 1998). Alkaline basalts recovered from the top of a large tilted block are similar in composition to some basalts drilled on the Kerguelen Plateau and, particularly, to the basalts from Kerguelen Islands. Because alkaline basalts never occur at mid-ocean ridges, Chatin et al. (1998) concluded that Diamantina Zone/Labuan Basin are not underlain by typical oceanic crust. Peridotites were recovered at four sites (Chatin et al., 1998; Royer and Beslier, 1998) on the basement ridges, which continue into the eastern province of the Labuan Basin (Fig 36). To the west of the Naturaliste Fracture Zone (110^0 E) their geochemical signature reflects very small degrees of partial melting, indicating rapid mantle exhumation typical for continental rifts (Chatin et al., 1998). Further to the east, peridotites exhibit even more similarity with peridotites from continental margins.

The new sampling results support the idea of extreme crustal thinning of the Labuan Basin/Diamantina Zone region. This resulted in formation of peridotite ridges within a broad extensional zone. The primitive character of peridotites is consistent with significant crustal thinning. Peridotite ridges can form as a result of extreme extension when there is a lack of magmatic material. This leads to unroofing the upper layers of the mantle and the formation of "peridotite intrusions" (Sibuet, 1992). A peridotite composition of the basement ridges in the Eastern Labuan Basin would explain the absence of a magnetic signature over these ridges. Beslier et al., 2001 estimated that emplacement of the peridotites in the Diamantina Zone took place between 90 and 84 Ma. Labuan Basin peridotites ridges would have formed at the same time.

5.8.5 Tectonic and depositional history: a synthesis

The Labuan Basin started to form in the Early Cretaceous before the major pulse of hotspot-related volcanism on the Kerguelen Plateau. If SKP is underlain (partly or wholly) by continental crust, then both the Diamantina Zone and Labuan Basin may be floored by highly extended continental crust formed during separation of India and SKP. If SKP is wholly oceanic, then the Labuan Basin is underlain by Early Cretaceous oceanic crust formed during separation of India from Australia/Antarctica. Its western part in this scenario may be floored by downfaulted plateau crust (Gladczenko and Coffin, 2001).

The earliest deposition in the Labuan Basin occurred in the southern part of the basin adjacent to the Princess Elizabeth Trough and the sediments could be as old as Valanginian (Mukarumi et al., 2000). Further to the north the deposition started in Albian or earlier. The earliest sediments may have been terrestrial with significant input of volcanic and volcaniclastic material.

The early Cretaceous Labuan Basin was faulted and rerifted during a major tectonic event, which occurred sometime between 90 and 84 Ma (Rotstein et al., 1991; Fritsch et al., 1992). This tectonism was associated with initiation of spreading between Australia and Antarctica. A significant amount of extension in the Labuan Basin/Diamantina Zone may have eventually led to mantle exhumation resulting in a zone of peridotite ridges and rapid subsidence. Extensional structures of this period are preserved in the parts of western Labuan Basin and the northern Diamantina Zone.

Uplift of the Eastern part of the Kerguelen Plateau followed by rapid deepening of the Labuan Basin in Turonian has been documented from the ODP drilling results (Fritsch et al., 1992). According to our interpretation pre-Albian section is present in the eastern and southern parts of the Labuan Basin. This suggests that Turonian-Santonian extension was preceeded by an earlier extensional episode. Fault movements and syn-rift deposition continued at least until the Campanian. Depositional environments during this time gradually changed from shallow-marine to bathyal.

In the Maastrichtian (75-68 Ma) another uplift occurred on the Kerguelen Plateau (Rotstein, 1991), accompanied by a major extensional episode (formation of the 77 Degree Graben and posssibly SKP Rift). However, the Labuan Basin was relatively unaffected by these events. Some fault reactivation, restricted to the northern Labuan Basin, has been documented. Deposition in the Labuan Basin continued to be characterised by deep-water environments.

Breakup of the Labuan Basin-Diamantina Zone extensional terrane occurred in the Eocene prior to the breakup between William's Ridge and the Broken

Ridge further to the north. A prominent erosional unconformity corresponds to this event both in the Labuan Basin and in the Diamantina Zone (Munchy et al., 1998). Some fault reactivation occurred in the northern part of the basin, but generally sedimentation in the Labuan Basin was undisturbed.

First signs of vigorous bottom current activity are observed in Eocene sediments. Bottom currents intensified with the full opening of the Southern Ocean in the Oligocene. This led to the establishment of the Antarctic Circum-Polar current and a new pattern of strong bottom currents around the Kerguelen Plateau. Currents affected sediment deposition mostly in the western part of the basin where they created deep channels and mounds and deposited the thick East Kerguelen Sedimentary Ridge. Since Late Miocene significant climate cooling led to a change from predominantly calcareous to siliceous biogenic sedimentation.

6. RESOURCE POTENTIAL

6.1 Introduction

Due to the remote location of the Kerguelen Plateau, and the currently held view that the plateau is predominantly igneous in origin, there has not been a lot of interest in its petroleum prospectivity. Symonds and Willcox (1989) were first to estimate petroleum potential of its sedimentary basins located in the area of Australia's Exclusive Economic Zone around Heard and MacDonald Islands and the potential Legal Continental Shelf to the south. The reserve calculations were based on the assumption that the southern Kerguelen Plateau is continental in origin. The sediment volume calculated by Symonds and Willcox (1989) was 174, 800 km^3 with reserves ranging from 0.27 (min.) < 6.23 (best) < 39.14 (max.) billion barrels. It is still not clear whether any substantial parts of the Southern Kerguelen Plateau are underlain by continental crust and their reserve figures should be treated with extreme caution.

Kerguelen Plateau sedimentary basins developed on "basement" include the Raggatt, Kerguelen-Heard and Labuan Basins (Plate 3). All of these have sufficient thickness of sediment for hydrocarbon generation. However, the thickest sedimentary accumulations lie in deep water, often in excess of 3 km. The structural and stratigraphic complexity of the Kerguelen Plateau is likely to result in significant number of traps within the basins. ODP drilling results showed the presence of organic rich rocks, but the lack of terrigenous input is likely to result in poor reservoir quality. The following summary addresses the petroleum prospectivity of these basins and is primarily based on the recently completed petroleum prospectivity review (Bradshaw et al., in prep.).

6.2 Major depocentres

The **Raggatt Basin** covers about 38,000 km^2 in area (Fig. 19, Plate 3) and contains up to 2500 m of sediments. More than half of the sediment fill (Early Cretaceous to Palaeocene) is represented by terrestrial and shallow marine deposits.

The **Kerguelen-Heard Basin** (Fig. 19, Plate 3) lies in water depths 1500 to 2000 m. It is about 500 km long and is up to 250 km wide and contains in excess of 2000 m of post-Oligocene sediments. The presence of Late Cretaceous to Eocene sediments has been suggested (Munchy and Schlich, 1987) in the central part of the basin with the possible thickness up to 1.5 km.

The **Labuan Basin** is about 500 km wide and more than 1000 km long (Fig. 19, Plate 3). It is characterised by extremely rough basement (Fig. 37) and variable sediment distribution. Between the basement ridges, sediment thickness is usually 2.5 to 3.5 km, including up to 1.5 km of shallow marine Cretaceous sediments.

6.3 Potential source rocks

In the best studied area, the **Raggatt Basin,** there are several possible source facies (Bradshaw et al., in prep.):

1.Early Cretaceous terrestrial coaly sediments intersected in ODP Site 750 over the interval 623.5 to 675.5 m (Fritsch et al., 1992). These sediments are represented by red-brown silty claystone with reworked coal fragments with total organic carbon (TOC) contents in excess of 10% and HI values up to a maximum of 401 (Schlich, Wise et al., 1989).

2. Mid Cretaceous marine and marginal marine shales. There are indications of organic rich intervals within Early to Late Cretaceous sediments (Coffin et al., 1990), which may relate to oceanic anoxic events. In ODP hole 748 a peak of marine kerogen was noted in the Turonian (Watkins et al., 1992). At ODP Site 1138 a Cenomanian/Turonian organic rich layer is described as a black, laminated claystone with a TOC content of 2.22% (Coffin, Frey, Wallace, et al., 2000). Phosphatic chert in dredge samples (Coffin et al., 1990) could also be consistent with an ocean with high organic productivity. Drilling results suggest that facies across the Raggatt Basin become more marine to the east in the Cretaceous, hence better source-rock quality in this facies may be developed in this direction.

3. There is a remote possibility of sources from underlying Pre-Cretaceous section. Permian rifts, similar to those in Perth Basin that produce hydrocarbons (Gondwana petroleum supersystem; Bradshaw, 1993), may underlie parts of the Kerguelen Plateau that are founded on continental fragments. Currently there is no known pre-Cretaceous sedimentary section on the Kerguelen Plateau.

Possible source facies the **Kerguelen-Heard basin** by analogy with the Raggatt Basin may include Mid-Cretaceous marine and marginal marine shales.

In the **Labuan Basin** the only possible source rock include Cretaceous marine shales. The overlying sediments are most unlikely to either contain significant amounts of organic carbon or to have reached maturity.

6.4 Potential reservoir and seal

Possible reservoir rocks in the **Raggatt Basin** include:

1. Cretaceous fluvial and shallow marine sandstones within pre-Albian-Albian and Albian-Campanian sequences. The discontinuous character of these sequences on seismic, and the drilling information (Coffin et al.,1990), suggests that they are variable, becoming more marine to the east, with better reservoir development to the west. At ODP Site 750 the basal clastic section

was interpreted by Watkins et al., (1992) as the Albian-aged weathering products of basaltic islands deposited in a fluvial environment. ODP Site 748 intersected a basal basaltic conglomerate overlain by 188m of glauconitic sandstones, siltstones and claystones. Cross-bedding occurred in the Turonian shallow marine/marginal marine section.

2. Cretaceous bioclastic limestones forming mounds within the Maastrichtian-Paleocene sequence (Chapter 5.5.3). Watkins et al. (1992) interpreted that bioclastic limestones intersected at ODP Site 748 have been deposited in shallow (less than 20 m) water, in a benthic bank complex. Recorded porosities range between 4 and 47%.

3. Late Cretaceous-Palaeogene fractured chalks (Coffin et al.,1990). The fracturing may have been produced by the differential behaviour of carbonates and chert to burial.

Potential seal in the **Raggatt Basin** could be formed by:

1. Cretaceous intra-formational claystones in fluvial and shallow marine facies may provide intra-formational seals to sandstone reservoirs in the pre-Campanian sediments.

2. Cretaceous fine-grained carbonates, overlying the clastic sequences, would provide a regional seal to reservoirs within the pre-Campanian sediments.

3. Palaeogene drape of pelagic sediments would provide a regional seal for reservoirs within the Maastrichtian to Palaocene sequence. Most faults do not extend through this sequence.

By analogy with the Raggatt Basin possible reservoir facies in the **Kerguelen-Heard Basin** may include Cretaceous fluvial and shallow marine sandstones, if present. Cretaceous intra-formational claystones or Cretaceous fine-grained carbonates may also represent potential seal. Cainozoic pelagic sediments intersected at ODP Sites 736 and 737 may also form a regional seal in this basin.

In the **Labuan Basin** possible **reservoir facies** include:

1. Basal and near-basal Cretaceous sandstones within the pre-Albian-Albian and Albian-Campanian sequences. These would be deeper water equivalents of the shallow marine sandstones of the Raggatt Basin. Reservoir quality of these may not be very high, as they would represent weathering products of basaltic volcanic islands. These potential reservoirs would be predominantly in the west of the basin, close to the Kerguelen Plateau proper.

2. Turbidites within the Cretaceous part of the section might provide suitable reservoir facies, again predominantly in the west of the basin. The younger

the sequence, however, the poorer turbidite reservoir quality is likely to be, as they are more likely to be composed mainly of ooze and clay than coarser clastic material. Younger turbidites could also in places provide potential reservoir facies.

Potential seal in the Labuan Basin may be represented by:

1. Pelagic limestone and/or shale may provide a regional seal. The limestone will have its best sealing properties where it includes a large component of siliceous remains, but will be a problematical seal where it grades towards chalk. The uppermost oozes and clays in the basin will be insufficiently indurated to provide seal, but this should not be a problem at the level of possible reservoir facies.

2. Lateral seal for reservoirs within tilted fault blocks may be provided by igneous basement.

6.5 Potential plays and exploration risks

Bradshaw et al. (in prep.) identified the following potential plays for the Kerguelen Plateau basins:

1. Early Cretaceous fault block clastic play (Raggat Basin and Labuan Basin). The primary reservoir targets are Early to Late Cretaceous sandstones. Seal facies include intra-formational claystone seals and the regional seal of Cretaceous fine-grained carbonates. Possible source rocks include terrestrial and marine Cretaceous facies Trap types include fault block and stratigraphic closures. The major risks are reservoir quality, and the existence of a mature source. Similar plays potentially can exist in the Kerguelen-Heard Basin. Potential plays in the Labuan Basin all rely upon the presence of a marine Cretaceous source rock at or near the base of the sequence. Although this is unproven, the presence of BSR in the Labuan Basin may be an encouraging sign. Suitable reservoirs and traps are likely to be present for any hydrocarbons that may have been generated.

2. Late Cretaceous carbonate play (Raggatt Basin). Carbonate biogenic mounds in the Raggatt Basin provide the reservoir and trap. Secondary reservoirs may occur in fractured chalks and lag deposits overlying and surrounding the mounds. Mid Cretaceous marine shales are a potential source, with possible migration from deeper early Cretaceous source facies. The drape of Palaeogene pelagic sediments provides a regional seal. The major risks are maturity of source and migration.

Depth of burial sufficient to produce hydrocarbon generation is difficult to assess using currently available data. Uncertainties include the actual sediment thickness, especially in the Kerguelen–Heard basin, and the heat flow history. In the Early Cretaceous due to young volcanic basement the heat flow was high, but there is no late thermal loading, as the Kerguelen-Heard basin was almost completely filled by Oligocene time. However, Oligocene-Miocene volcanism in the NKP may have provided some late stage heating episodes. Faults provide a possible migration path from potential Early Cretaceous source units up into reservoirs in the Late Cretaceous.

Exploration risks for all of the basins present on the Kerguelen Plateau are very high. There is no established petroleum exploration or production infrastructure within many thousands of kilometres of this remote location. Severe to extreme weather conditions and distance to world markets adds to the difficulties of potential exploration. The Kerguelen Plateau is located close to Antarctica and its exploration may represent a threat to the unique marine life that it hosts.

7. DISCUSSION

A number of scientifically important questions have been raised in this study. Some of these have been debated in the literature for decades, others are related to results of the ODP legs and the current study.

One of the least understood questions is the extent of the continental crust beneath the Kerguelen Plateau and possibly the Labuan Basin. Size and location of continental fragments prior to the start of extensive volcanism in the Early Cretaceous are unknown and therefore plate tectonic reconstructions are incomplete and may be erroneous. There is a lack of understanding of plate geometries at the Australia/India/Antarctica triple junction.

The other widely debated issue is the age of the igneous basement, which has been used to model movement and evolution of the Kerguelen hotspot through time. New age estimates from ODP Leg 183 add new complexities to the story.

Timing of tectonic events in the region still remains problematic due to the sparsity of the seismic coverage and great variability of structural settings.

The Kerguelen Plateau is an area of very strong bottom currents. Current-related structures did not receive a lot of discussion in the literature, although current activity dominated deposition on and around the plateau since Late Eocene.

In the following sections of this chapter we discuss some of these issues in detail.

7.1 Continental crust in the Kerguelen Plateau region

The unusual crustal structure of the Southern Kerguelen Plateau (Operto and Charvis, 1995, 1996) together with geochemical indications of continental contamination of basement basalts (Storey et al., 1992; Alibert, 1991; Mahoney et al., 1995) led to an ongoing discussion in the literature about the origin of the plateau crust. Three possibilities have been proposed for its origin: (1) it is a continental fragment left over from the breakup of India and Antarctica (Houtz et al., 1977); (2) it is a product of excessive on- or off-axis hot-spot-related oceanic volcanism (Coffin and Edholm, 1994); or (3) it a combination of different crustal blocks, including continental fragments and trapped oceanic crust (Coffin et al., 1986). In the first two ODP drilling legs (119 and 120), all wells that reached basement recovered only volcaniclastic rocks and altered basalts. These results supported the prevailing viewpoint of an oceanic origin of the plateau (Coffin and Edholm, 1994, Gladczenko and Coffin, 2001).

However, more recent results provide evidence for possible continental origin of some parts of the plateau. Based on a refraction study, Operto and Charvis (1995) concluded that velocity-depth structure beneath the Raggatt Basin is different from other hotspot-related oceanic plateaus and more consistent with a thinned continental crust overlain by basalt flows. A low velocity reflective zone mapped beneath the Raggatt Basin is similar to reflective lower crust commonly observed under extended continental areas, including volcanic passive margins (Operto and Charvis, 1995). Basement basalts from ODP Site 747 on the CKP, and from Site 738 from the SKP, show geochemical evidence of contamination of originating magma by elements derived from continental lithosphere (Coffin, Frey, Wallace et al., 2000). This infers that the basaltic magma came into contact with continental crust during its ascent through the crust of the Kerguelen Plateau. Peridotite xenoliths from the Kerguelen Archipelago show unradiogenic osmium and old rhenium-depletion ages (833-1360 Ma) which indicates a lower continental lithospheric origin of these xenoliths (Hassler and Shimizu, 1998).

Continental material recovered at ODP Site 1137 on Elan Bank provided the first direct evidence for the presence of continental blocks within the Kerguelen Plateau. However, because Elan Bank is morphologically and structurally different from other parts of the plateau it may represent the only large-scale continental block within the plateau. Seismic data from Elan Bank show that volcanic flows overlying basement completely obliterate seismic character of the underlying continental rocks. Therefore the use of seismic character in mapping continental crust is very limited. In some instances, we have mapped intra-basement reflectors underneath the volcanic basement (Plate 4, Line 179-07), which look like buried tilted blocks and may indicate the presence of continental crust, but seismic evidence alone is insufficient to infer continental origin.

On the basis of the data available to this study we suggest that a large part of the SKP and Labuan Basin may be underlain by extended continental crust. On the SKP these fragments are buried by massive lava flows and it would be difficult, if not impossible, to sample. Recovery of continental rocks from the Elan Bank was possible only because it stands bathymetrically higher than most of the plateau and has been significantly eroded. Uncertainties about the crustal origin of the Labuan Basin could possibly be resolved by sampling its basement ridges and sequences overlying basement.

7.2 Characteristics of volcanic basement

Seismic data from Kerguelen Plateau show a range of volcanic features, including dipping reflector sequences, multiple lava flows, volcaniclastic debris accumulations and sills. Numerous dipping reflectors have been mapped (Plates 3, 4 and 5) on the plateau and its margins. The most prominent and continuous dipping reflector sequences are in the eastern part of the plateau, particularly beneath the Raggatt Basin (Plate5), and on Elan Bank (Plate 4).

Dipping basement reflector sequences have received a lot of publicity in the literature (Eldholm et al., 1995, Planke, 1994; Schaming and Rotstein, 1990) because of their association with volcanic margins. In many cases, margins have been classified as volcanic based on the presence of dipping reflector wedges only. These volcanic features have been studied in detail during the Ocean Drilling Program on the Voring Plateau (Eldholm et al., 1995, Planke, 1994). Since then, dipping reflectors and other volcanic sequences have been described on Australian marginal plateaus (Symonds, Planke et al., 1998; Planke et el., 1999; Sayers, Borissova et al, *in prep*., Stagg et al., *in prep*) not all of which fall into categories originally identified by Planke (1994). The same is true for the Kerguelen Plateau. Only some of the dipping reflector sequences may be described as seaward dipping reflector sequences (SDRS) typical of rifted volcanic margins and associated with continental breakup. The other dipping sequences appear to be unrelated to the breakup and often form in areas of excessive volcanism, such as hotspot volcanism.

Locations of prominent dipping reflector sequences within the study area are shown on the tectonic provinces map (Plate 3). Volcanic sequences which are directly comparable to those of typical volcanic margins have been identified on the southern margin of the Elan Bank (Plate 4, Lines 179-02, 179-03, 179-04, 179-05), the western margin of Banzare Bank (Plate 5, Lines 47-27, 47-29) and on the southeastern margin of the Kerguelen Plateau (Plate 5, Line 180-05). On Elan Bank, very thick (up to 5 km) wedge-shaped dipping sequences were mapped in the lower part of the slope (Fig.27), while lava flows and highly reflective crust can be seen at the base of the slope (Plate 4, Line 179-05). On Banzare Bank, SDRS units are smaller and located at the foot of the slope (Plate 5, Lines 47-27, 47-29). A succession of at least two SDRS units separated by transparent buildups could be identified on these seismic data.

On Elan Bank dipping reflector sequences could have formed either during the continental breakup between India and Australia/Antarctica in the Valanginian (130 Ma), or in the Albian, when a ridge jump separated Elan Bank from India. It is also possible that both breakup events were accompanied by extensive volcanism and formation of SDRS.

Current seismic coverage doesn’t allow an assessment of whether other SDRS on the Kerguelen Plateau margin are restricted to particular terrains or occur throughout the transitional zone between the plateau and deep ocean basins. Depending on the crustal origin of the SKP these dipping sequences may be either related to continental breakup, or represent another manifestation of hotspot-related volcanism.

Most of dipping intra-basement reflectors within the plateau itself occur on the flanks of seismically transparent basement highs. Formation of these dipping sequences has been attributed to lava flows from multiple volcanic sources active during plateau formation (Schaming and Rotstein, 1990). Subsequent erosion removed uplifted parts of these volcanic structures making it difficult to identify spatial distribution of volcanic sources. The only reliably mapped basement volcanic structure occurs on the eastern flank of the Raggatt Basin (Plate 3). This prominent basement ridge is characterised by reflectors dipping away from the crest of the ridge on both flanks (see Chapter 5.5.3). Banzare Bank has been described to have basement reflections dipping away from its central part in all directions (Schaming and Rotstein, 1990) and has been interpreted as a very large volcanic complex similar in scale to the one beneath the Kerguelen Islands. Dipping reflectors in Cretaceous basement of the Central Kerguelen Province (Line 47-13) indicate that another large volcanic source may have been located in the northwestern part of the southern province.

7.3 Plate tectonic history of the region

Tectonic events of the Kerguelen Plateau are closely linked to the breakup history of the region and to movement of plates above the Kerguelen Hotspot. The Kerguelen Plateau formed in a close proximity to the triple junction between the Indian, Australian and Antarctic Plates (Fig. 10).

On the West Australian margin (Australian/Indian boundary) rifting and extension first started in Permian. Rifted basins along this margin (e.g. the Perth Basin) were formed in a highly oblique extensional setting. Studies of this margin (Marshall et al., 1989, Song and Cawood, 2000) identified three main stages of extension: in Early Permian, Late Permian, and Late Jurassic-Early Cretaceous with progressively younger basins to the south. At this time, the Western Australian margin was joined to and continued onto the Antarctic margin, which presently lies to the south of the Kerguelen Plateau. Magnetic anomalies in the Perth and Gascoyne Abyssal Plains (Markl, 1974, 1978) indicate that breakup along this part of the Western Australian margin occurred in the Valanginian. After the breakup, in the Early Cretaceous, India was moving northwestward in respect to Australia/Antarctica (Fig. 10).

Breakup on the West Australian and Antarctic margins was preceded and accompanied by formation of several volcanic provinces. The Bunbury Basalt (BB) of SW Australia is formed by two different types of basalt: Casuarina (128-132 Ma) and Gosselin (123 Ma), which may represent magmatism associated with the initial stages of breakup between Australia and Antarctica (Coffin, Pringle et al., in press). Rajmahal rocks of northeast India post-date the breakup of India and Australia by about 15 Ma (115-118 Ma; Baksi, 1995, Coffin, Pringle et al., in press). Indian and Antarctic lamprophyres also post-date major breakup events (114 Ma, Coffin, Pringle et al., in press).

The recent discovery of continental rocks within the Elan Bank the complexity of the early spreading history between India and Australia/Antarctica. Following this discovery it has been suggested (Weis et al., 2001) that Elan Bank belonged to the Indian Plate and via a rift jump in the Albian it was transferred to the Antarctic Plate, however it is not clear what plate interactions could have caused this rift jump. We suggest that widespread ages of volcanic rocks on the margins, some postdating the Valanginian breakup, could be explained by the second stage of rifting in the Albian.

The first major pulse of magmatism associated with the Kerguelen hotspot occurred in the Albian (117-109 Ma). As the Indian Ocean lithosphere migrated SE relative to the Kerguelen hotspot first SKP and then CKP were formed (Fig. 10).

Extension between Australia and Antarctica and formation of rifted basins along their margins occurred in the Late Jurassic-Early Cretaceous. Interpretation of seafloor spreading anomalies adjacent to the continental margins of Australia and Antarctica by Cande and Mutter (1982) suggested that breakup along the southern margin occurred in the Cenomanian followed by a period of very slow spreading. Veevers (1986) reinterpreted the magnetic lineations and estimated breakup at about 95 Ma. However based on the seismic stratigraphy of the southern Australian margin, Stagg and Willcox (1992) suggested that initiation of sea-floor spreading between Australia and Antarctica could have occurred earlier, in Hauterivian (125 Ma). In a more recent work based on re-examination of magnetic data, Tikku and Cande (1999) suggest that the period of very slow spreading occurred on the southern margin between An31 and An24 (68.7-53.3 Ma), while prior to that the region experienced amagmatic extension (Tikku and Cande, 2000). The latest work (Sayers, Symonds et al., 2001) suggests that seafloor spreading in the Great Australian Bight region was initiated in the Early Campanian (~ 83 Ma).

Pre-breakup reconstructions of Australia and Antarctica (Royer and Coffin, 1992; Royer and Sandwell, 1989) always encountered a problem with a gap in the Great Australian Bight (GAB) area and overlap between the NKP and Broken Ridge. Although recent plate reconstructions (Tikku and Cande, 2000) mostly overcame the problem, a good fit magnetic anomalies in the Australian-Antarctic Basin still requires a large-scale deformation of oceanic or continental crust.

The slow-spreading concept was initially used to explain the unusually wide continent-ocean transitional zone and rough topography of the Diamantina Zone (Cande and Mutter, 1982). Results of our study confirm Tikku and Cande (2000) conclusion that this area experienced amagmatic extension, rather than spreading. The exact timing and mechanism of this extension remain problematic. Recent sampling of Diamantina Zone and Naturaliste Plateau (Chatin et al., 1998, Beslier et al., 2001) showed the presence of continental material, which extends continental margin setting to about 98^{O}E. To the west of the Naturaliste Plateau the origin of Diamantina Zone crust is unknown, however satellite gravity and limited seismic data available for this area indicate that there is no significant change in its structure. Diamantina Zone and Labuan Basin appear to form a continuous extensional terrane extending seamlessly from about 80^{O}E to the continent-ocean transitional zone between Naturaliste Plateau and Bruce Bank (Fig.36). There is mounting evidence of possible continental origin of some parts of the

Kerguelen Plateau, particularly SKP. Results of our study indicate that structurally the Labuan Basin is similar to a continent-ocean transition zone. Based on these observations we suggest that Labuan Basin/Diamantina Zone formed initially as a result of continental extension between India and the SKP and was rerifted in the Late Cretaceous just prior to the breakup along the Southern margin. The problems associated with this interpretation include the unproven continental origin of the SKP and possible presence of M-series magnetic anomalies off Antarctic margin (Murakami et al., 2000) to the southeast of the Kerguelen Plateau.

The other possible scenario for the formation of the Labuan Basin/Diamantina Zone (Tikku and Cande, 2000; Gladczenko and Coffin, 2001) is that both areas are underlain by old (Valanginian-Hauterivian) oceanic crust rerifted during the long period of extension and slow accretion between Australia and Antarctica (95 to 40 Ma). The Labuan Basin in this interpretation could be partly floored floored by downfaulted eastern flank of the Kerguelen Plateau. There are several problems associated with this scenario. There is no apparent major structural boundary between postulated oceanic crust to the west of the Naturaliste Plateau/Bruce Bank and continental crust to the east. Analysis of seismic sequences in the Labuan Basin suggests that this basin started to form before the Albian, rather than in Cenomanian. There is no apparent age progression in the sedimentary sequences overlying Labuan Basin basement, which would be associated with accretion. It is difficult to explain the continental signature of peridotites recovered in the Diamantina Zone. Overall, the continental extension scenario appears to fit the observations better than rerifting of oceanic/magmatic crust.

Although plate reconstructions of the southern Indian Ocean region (e.g. Royer and Coffin, 1992; Royer and Sandwell, 1989) are not well-constrained prior to about 84 Ma, a model has been developed using a hotspot reference frame (Müller et al., 1993) and keeping Antarctica fixed that is self-consistent back to about 130 Ma (Coffin, Frey, Wallace et al., 2000; Frey et al., 2000). According to this model (Fig.10, Coffin, Pringle et al., in press) between 130.9 and 118.7 Ma, Antarctica migrated to the southeast relative to the Kerguelen hotspot. SKP formed between 118 and 100 Ma, followed by formation of CKP and Broken Ridge between 103 and 96 Ma. From about 83 to 63.6Ma, India continued its drift northward relative to Antarctica, and the Kerguelen hotspot is predicted to have remained close to the NE edge of the CKP and Broken Ridge (Fig. 10). Subsequently (82 to 36 Ma), the hotspot generated the Ninetyeast Ridge (Duncan and Storey, 1992). At about 40 Ma, seafloor spreading commenced between the CKP and Broken Ridge. At the same time the hotspot generated the NKP (Fig. 10). From 40 Ma onwards, as Broken Ridge and the Kerguelen Plateau continued to separate, the Kerguelen, Heard and McDonald islands and a chain of volcanoes between them was formed (Fig. 10).

In the model outlined above, formation of the Ninetyeast Ridge started at about 82 Ma and the age progression of its basement (from 82 to 36 Ma) from north to south is explained by the hotspot lying underneath the Indian

Plate as it moved northwards. This model was developed (Royer and Coffin, 1992) when the age of the basement sampled on the CKP was dated no younger than about 85 Ma. Since the discovery of Maastrichtian (68-66 Ma) basement on Skiff Bank (Coffin, Frey, Wallace et al., 2000) it becomes more difficult to explain how these rocks were formed with the Kerguelen Hotspot being under the Ninetyeast Ridge several hundred kilometres away. The original idea (Luyendyk and Rennick, 1977) of the two hotspots, Kerguelen and Amsterdam-St. Paul, involved in the formation of Kerguelen Plateau and Ninetyeast Ridge may still be worth considering.

From the above discussion it is evident that plate tectonic history of the region is not fully understood. The lack of mapped Mesozoic anomalies on the Antarctic margin, large areas of oceanic crust formed during Magnetic Quiet Period (118 - 85 Ma) and unknown extent of continental crust beneath the Kerguelen Plateau and possibly the Labuan Basin make Early-Late Cretaceous reconstructions poorly constrained. Results of ODP leg 183 and interpretation presented in this study highlighted the need to update plate tectonic reconstructions of the region, particularly for the Cretaceous.

8. CONCLUSIONS

Analysis of diverse datasets available to this study (seismic data, sonobuoys, drilling and sampling information) resulted in:

- New compilation of tectonic elements for the region (Plate 3)
- Updated stratigraphic compilation (Plates 7, 8 and 9)
- Interpretation of seismic stratigraphy for the main sedimentary basins: Kerguelen-Heard, Raggatt and Labuan (Plates 4, 5, 10, 11 and12).
- Interpretation of volcanic sequences on the Elan Bank (see chapter 5.6)
- New interpretation of the Labuan basin origin and crustal structure (chapter 5.8)
- Improved understanding of the tectonic history of the region

Below we present a summary of the tectonic history of the Kerguelen Plateau derived from a variety of evidence including the results of this study.

8.1 Geological evolution of the region

The history of the Kerguelen Plateau region is intimately linked with the breakup of India, Australia and Antarctica, which commenced about 160 Ma ago. Main tectonic and depositional events are summarised in Appendix 14.

8.1.1 Oxfordian to Valanginian (160-131 Ma)

The end of Jurassic beginning of Cretaceous was marked by rifting along the incipient plate boundary between Greater India and Australia/Antarctica. The first breakup between the two continents occurred off Western Australia. In the Valanginian (An M13), spreading started in the Perth, Gascoyne and Cuvier abyssal plains as well as in parts of the seafloor adjacent to Antarctica (Muller et al, 1993, Murakami et al., 2000). Our interpretation suggests that the Labuan Basin and Diamantina zone may have formed at the end of this period as part of the extensional terrane between India and Australia/Antarctica. An alternative hypothesis that the basin is floored by oceanic crust formed during the slow spreading between Australia and Antarctica (from 95 to 53 Ma) is not yet supported by seismic stratigraphy (Rotstein et al.,1991 and this study) and sampling results in the Diamantina Zone (Beslier et al., 2001). The Labuan Basin could be underlain by a combination of extended continental and/or old (Early Cretaceous) oceanic crust.

8.1.2 Hauterivian to Albian (131- 97 Ma)

The earliest known volcanism associated with the Kerguelen hotspot began about 130 million years ago. Several volcanic provinces developed close to the locus of the breakup; the Bunbury Basalts in southwest Australia between 132 and 122 Ma (Frey et al., 1996), the Rajmahal traps in Northeastern India between 118 and 115 Ma (Kent et al., 1997), and lamprophyres in the Prince Charles Mountains in Antarctica at about 114 Ma (Coffin, Pringle et al, in press). The Barremian-Albian corresponds to the major constructional phase of the Kerguelen Plateau. Massive volcanism affected first SKP and then Elan Bank and CKP. Although the SKP and CKP volcanic complexes formed in a young oceanic basin (Royer and Coffin, 1992; Munschy et al., 1994), evidence is equivocal as to whether they were constructed at a spreading centre, like Iceland, or off-ridge, like Hawaii (Coffin and Gahagan, 1995). Most of the newly formed plateau was subaerial. As indicated by seismic data volcanic basement was exposed over wide areas and eroded during the Mid- to Late Cretaceous. In the Aptian to Albian the SKP was significantly eroded and started to subside, while the CKP and Elan bank remained subaerial. The Raggatt Basin started to develop in the central part of the plateau as a sag basin of NW-SE orientation following completion of the plateau construction. The first sediments were deposited in the Raggatt Basin during the Albian, shortly after cessation of the volcanic activity in this part of the plateau. Several igneous bodies in the deepest part of the basin intruding Albian sediments indicate that isolated volcanic sources were still active at that stage.

Since the original breakup, Elan Bank was part of eastern margin of India. In the Albian a new mid-ocean ridge separated Elan Bank from India, while the old one became extinct. This resulted in a transfer of the Elan Bank to the Antarctic Plate (Frey et al., 2000). Being in close proximity to the Kerguelen Hotspot, this continental fragment became part of the Kerguelen Plateau. We documented very thick volcanic sequences on the Elan Bank, which we suggest formed during the Albian breakup as part of the volcanic margin complex. Similar sequences might be expected on the conjugate Indian margin.

Growth sections against basement involved faults indicate extensional regime in the Labuan Basin in the Early Cretaceous. The absence of extensional structures in the southern part of the Labuan Basin (apart from the boundary trough) indicates that, this area was mostly unaffected by extension. Our interpretation suggests that age of the southern Labuan Basin is the same as of the Eastern Labuan Basin. There are two possible explanations for its origin. It may represent part of the continent-oceanic transition zone off Antarctica with tilted blocks buried beneath early (Valanginian-Hauterivian) volcanic accumulations. Alternatively it may represent a remnant of oceanic crust formed between India and Antarctica prior to the Albian rift jump.

8.1.3 Cenomanian to Santonian (97- 83 Ma)

Seafloor spreading between India and Australia/Antarctica continued unchanged to about 85 Ma. The Kerguelen Plateau continued to grow in the north with Broken Ridge forming by the Cenomanian (95 Ma) and becoming the northern margin of the Kerguelen Large Igneous Province. In the Santonian (85 Ma), a significant plate reorganisation took place. India, which since the Valanginian breakup moved to the northwest, stated to move very fast to the north. This change seems to have affected all the plates involved. Australia/Antarctica started to breakup along the southern margin of Australia. The Diamantina Zone/Labuan Basin experienced extension during this period resulting in formation of peridotite ridges in the central part of the zone. In the Turonian (about 88 Ma) the eastern margin of the plateau was uplifted and downfaulted (Munschy et al, 1992) followed by a rapid deepening of the Labuan Basin (Munschy, Fritsch et al, 1994).

Towards the end of this period, volcanic activity ceased over most of the Kerguelen Plateau. Discovery of Maastrichtian volcanics on the Skiff Bank, however, may indicate some restricted volcanic activity on NKP. Since the Santonian major volcanism was associated with the Ninetyeast Ridge. The question of whether it was formed by the Kerguelen Hotspot or another hotspot, remains open.

With the cessation of volcanic activity on the Kerguelen Plateau it subsided below sea level and shallow marine carbonate sedimentation became widespread. Since the Cenomanian the Labuan Basin became a major depocentre. It was deeper than the Raggatt Basin and characterised predominantly by pelagic sediments. Up to 1.5 sec TWT of sediment accumulated in the depressions of its rough basement during this period.

8.1.4 Campanian to Middle Eocene (83-45 Ma)

In the Campanian seafloor spreading commenced in the Great Australian Bight (GAB) between Australia and Antarctica (Sayers, Symonds et al*.,* 2001). Magnetic lineations along the Australian and Antarctic margins (Cande and Mutter, 1982; Tikku and Cande, 1999), as well as plate tectonic reconstructions, indicate that the spreading was very slow. Towards the west, in the Diamantina Zone, it could have been accommodated by further extension (Tikku and Cande, 2000). By the end of Campanian – Early Maastrichtian the locus of extension suddenly shifted from the Labuan Basin/Diamantina Zone to the central part of the Kerguelen Plateau. Extensive areas of the CKP and SKP were affected by extensional faulting and differential uplift and erosion. Large rift zones formed across most of the plateau (77^{o}E Graben, SKP rift zone and possibly other rifts). According to Tikku and Cande (2000), the Kerguelen Plateau rift system may have been a plate boundary between the Australian and Antarctic Plates between 75 and 63 Ma.

Basement adjacent to the 77 Degree Graben was uplifted by more than 1 km, and intensely faulted in the Maastrichtian. The main depocentre of the Raggatt Basin shifted about 50 km to the east to accommodate this uplift. ODP data suggests that during the Palaeocene the Raggatt Basin subsided to about 1 km water depth. Slow thermal subsidence of the basin and its surroundings on the SKP continued until about 40 Ma in the Late Eocene. Although the major rifting phase on the plateau finished in Maastrichtian, seismic data indicates that differential movements on some faults may have continued much longer, up to Oligocene. In Paleocene to Early Eocene times, the Kerguelen Plateau and Labuan Basin continued subsiding. It appears that while Kerguelen Plateau still remained fairly shallow (less than 1 km water depth), the Labuan Basin was in much deeper waters.

8.1.5 Middle Eocene to present (45 - 0 Ma)

The next major tectonic event in the region was the breakup of Kerguelen Plateau and Broken Ridge at about 43 Ma (Anomaly 20) in the Middle Eocene. This breakup was precipitated by the start of fast spreading in the central part of the southern margin of Australia. Prior to the breakup, some parts of the plateau, in particular areas adjacent to the Broken Ridge (William's Ridge and northeastern margin of the plateau), were uplifted. Basement faults were reactivated on the plateau and in the northern part of the Labuan Basin. Since the breakup, the plateau has been continuously subsiding.

The uplift and breakup between Kerguelen Plateau and Broken Ridge was associated with the last major phase of volcanism on the plateau. It affected only its northern part and led to creation of the Kerguelen Archipelago, at about 40 Ma. This recent volcanism is restricted to Kerguelen-Heard Platform of the NKP, and intrusions along the northeastern margin. Eocene-Oligocene volcanism is characterised by a change from predominantly tholeitic basalts to trachytes and rhyolites and plutonic alkaline basalts. The subsidence on the NKP remains fairly slow because of the thermal effect of the hotspot presently located beneath the Kerguelen Island. The area around Kerguelen and Heard Islands remains shallow (less than 500 m) as it is still building up through volcanic extrusion, although the volume appears to be small.

Prior to the Eocene breakup, Kerguelen Plateau sedimentation was dominated by pelagic nannofossil ooze and chalk. Breakup between Australia and Antarctica led to profound changes in the global circulation pattern. Both water temperature and depositional environment are closely linked to the opening of the continental bridge between Australia and Antarctica in the Oligocene and establishment of the Circum-polar current (Kennett, 1982). This current led to the thermal isolation of Antarctica and water temperatures started to drop. Transition from calcareous chalks and nanno-oozes to diatomaceous sediments is indicative of dropping water temperatures associated with the movement of the Polar Front. Deposition, or the lack of it in many areas were controlled by currents. Numerous channels and turbidite structures in Oligocene and younger sediments observed on seismic data provide evidence of vigorous bottom water activity.

Prior to the breakup, the Labuan Basin was almost enclosed and characterised by restricted bottom water circulation, but after opening of the Southern Ocean and development of the Circum-polar Current, a strong bottom current started to flow into the Labuan Basin from the south. This north-flowing current gradually dropped of suspended material on the eastern flank of the Kerguelen Plateau forming one of the largest known current-constructed feature – an 800km long sedimentary ridge (EKSR). The north-flowing currents also prevented any deposition on the eastern part of the SKP and the sediments were deposited further west in the Raggatt Basin. Sediments of Oligocene to Quaternary age over the Kerguelen Plateau and Labuan Basin are represented mostly by nannofossil and diatom ooze. A major change from calcareous to diatomaceous sediments occurred in the Miocene due thermal isolation of Antarctica and progressive cooling of the Southern Ocean.

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APPENDICES

Appendix 1: 1982 United Nations Convention on the Law of the Sea (UNCLOS)

Article 76 : Definition of the continental shelf

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

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

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

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

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

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

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

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

6. Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from 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 Geoscience Australia (former AGSO) Seismic Surveys

Survey	47
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1985
Streamer length (m)	1200 and 2400
Seismic channels	54
Sample rate / rec. length (ms)	2/7000
Group length/interval (m)	25 (2x25)
Shot interval (m)	50
Cable depth (m)	10
Source type / power or volume	3 bolt 1500C air guns/500 cu in
Nominal vessel speed (nm)	5
Primary navigation	Dead reckoning tied to transit satellite fixes
Secondary navigation	the same
Tertiary navigation	Magnavox sonar doppler
Primary echo-sounder	12 KHz
Secondary echo-sounder	3.5 KHz
Magnetic data	yes
Gravity data	yes

Survey	179
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1997
Streamer length (m)	3000
Seismic channels	240
Sample rate / rec. length (ms)	2 / 16000
Group length/interval (m)	12.5 / 12.5
Shot interval (m)	50
Cable depth (m)	12-14
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (nm)	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	180
Contractor	AGSO
Vessel	*Rig Seismic*
Year	1997
Streamer length (m)	3000
Seismic channels	240
Sample rate / rec. length (ms)	2, 4 / 16000
Group length/interval (m)	12.5 / 12.5
Shot interval (m)	50
Cable depth (m)	12-14
Source type / power or volume	20 x sleeve airguns / 49.2 litres
Nominal vessel speed (nm)	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: Well ties

Marion Dufresne 47

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
737	MD21	?	35	16:15 (3 km NE)	715.5	567
738	MD7	3870	20	2:55 (4.6 km W)	750.9	2274
751	MD5	5580	17	5:10 (2km E)	166.2	1651
747	MD14	?	15	16:05 (1.6 km N)	656.8	1725
749	MD13	5680	28	19:40 (1.3 km E)	382.8	1096
744	MD7	610	19	12:26 (16.4 km W)	280.6	2236
745	MD10	8120	25	23:03 (7.6 km S)	225	4053
746	MD10	8080	25	22:55 (7.6 km S)	280	4098
1135	MD10	9800	26	7:00 (6.4 N)	526.0	1626
1136	MD10	9200	26	4:20	161.4	1963

Rig Seismic, 1985, AGSO survey 47

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
750	RS24		97	21:25	1170.2	2059
751	RS24		97	13:40	166.2	1674
748	RS27		100	23.30 (4 km N)	1170.3	1333
749	RS27		101	14:17 (17.4 km N)	382.8	1038

Rig Seismic, 1997, AGSO survey 179

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
1138	01	1228	26	3:57	842.7	1177
1137	06	2024	39	7:02	371.2	1029

Rig Seismic, 1997, AGSO survey 180

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
1135	02	1585	75	21:00	526	1594

Marion Dufresne 26

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
736	10	2300	-	-	371	629

Eltanin 47

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
736	-	-	85	23.00 (14.5 km S)	371	629
736	-	-	46	1:00 (9.6 kmN)	371	629

Gallieni 3 & 5

Site	Seismic line	Shotpoint	Day	Time	TD	Water depth
1139	GA5-16	-	-	-	694.2	1427
1140	GA3-17	-	-	-	321.9	2406

Appendix 4: Details of Geological Sample Stations

Cruise-Type index	Ref	Sample No.	Latitude	Longitude	Depth (m)	Greatest Age	Lithology and environment
ELTANIN 54-Co3	1	core 3	57° 26'S	77° 50'E	1890	Late Eocene	
ELTANIN54-Co7	4, 6	core 7	55° 53'S	81° 07'E	4021	Upper Cenomanian	chalk. Late Cenomanian sample is at 212 cm. Warm surface waters
MD48 NASKA							
MD48-Dr1	4	dredge 1	51° 58'S	77° 46'E	2300-1600	13.2+/- 0.1 Ma	propyl-altered basalt and phlogopite melagabbro
MD48-Dr2	4	dredge 2	57° 18'S	77° 36'E	2400-1970	Pre-Cenoman.	saprolitic basalt, pink limestone, pre-Cenomanian
MD48-Dr3	4	dredge 3	57° 18'S	77° 35'E	2000	N/A	chert, erratics
MD48-Dr4	4	dredge 4	57°17'S	77° 37'E	2600-2000	?Late K	chert with Late K radiolaria, interbeds dolomite
MD48-Dr5	4	dredge 5	58° 06'S	76o 55'E	2200-1620	114+/-1 Ma	saprolitic basalt w/ coarse plagioclase, lava breccia w/ K lst, conglom.
MD48-Dr6	4	dredge 6	58° 17'S	76° 55'E	1550-1250	13.2+/- 0.1 Ma	saprolitic basalt , lava breccia w/ K lst, conglom.
MD48-Dr7	4	dredge 7	55° 18'S	77° 28'E	2265-1865	?pre-Santonian	conglom. of saprolitic, amygd'l basalt, boulders of basalt
MD48-Dr8	4	dredge 8	50° 19'S	74° 49'E	2175	13.2+/- 0.1 Ma	saprolitic basalt, conglom. Of basalt & lst cobbles in tuff, forams not older than Mioc. Boulders olivine basalt
MD48 Grabs	4	grabs	58° 19'S	77° 01'E	1750-1810	mixed	saprolitic basalt, granite and metasediments
MD48-Co697	4	core 697	57° 23'S	79° 39'E	1680	Pleistocene, NN21	ooze
MD48-Co698	4	core 698	57° 15'S	80° 10'E	1980	Late Eocene, NP19	calc. ooze
MD48-Co699	4	core 699	57° 08'S	80° 57'E	2625	Late Eocene, NP19	calc. ooze
MD48-Co700	4	core 700	57° 06'S	81° 11'E	3130	Pleistocene, NN21	ooze

MD48-Co701	4	core 701	57° 04'S	81° 23'E	3850	Maastr. & Pal'cene	Mixed Maastrichtian and Paleocene calc. ooze, NP6, under Mid-Late Eocene calc. ooze, NP17-19
MD48-Co702	4	core 702	57° 06'S	81° 13'E	3115	Pleistocene, NN21	ooze, and older undated ooze
MD48-Co703	4	core 703	57° 04'S	81° 24'E	3800	Cretaceous, undiff.	partly recrystallised calc. ooze,
MD48-Co704	4	core 704	57° 17'S	77° 48'E	1890	uppermost Eocene	calc. Ooze, NP20/21
MD48-Co705	4	core 705	57° 17'S	77° 31'E	2272	Pleistocene, NN21	siliceous ooze
MD67 KERSIMAG							
MD67-Dr	5	dredge	55° 18'S	83° 04'E	3000	500 Ma - 1 Ga	1.5 tons of metamorphic and granitic blocks, may be dropstones from Antarctica. Basalt fragments resemble drilled KP basalts.
MD38 ANTIPRODIII							
MD38 Antiprod III	2	core 84544	60° 41.5'S	78° 16.5'E	3107	Miocene	siliceous and carbonate ooze
MD38 Antiprod III	2	core 84554	54° 57.6'S	77° 06.2'E	2357	Cretaceous	clay, gravel, pebbles and carbonate ooze
MD38 Antiprod III	2	core 84555	53° 34'S	79° 23.5'E	4235	Miocene	siliceous clay
MD35 DRAKAR							
MD35-Co503	3	core 83503	50° 19.6'S	74° 47.3'E	1358	Cretaceous	nanofossil ooze, chalk pebbles
MD35 -Co505	3	core 83505	50° 19.0'S	74° 47.5'E	1823	U. Cretaceous	nanofossil chalk, pebbles. Zone m.mura
MD35-Co506	3	core 83506	50° 19.9'S	74° 47.1'E	1259	U. Cretaceous	nanofossil chalk, pebbles. Zone m.mura
MD35-Co510	4	core 510	50° 20'S	74° 48'E	1358	Santonian	four cores, 83-503, 505, 506, 510, bottomed in U. Cret. Ooze. Oldest is core 510.
MD109 KERIMIS							
MD109-Dr	7	Dredges between Kerguelen and Heard Islands					
MD109-1		dredge 1	50°21.2'S	63°47.9'E		14 - 19 Ma	picritic pillow basalts, columnar basalt
MD109-4		dredge 4	51°31.2' S	71°08.8'E		14 - 19 Ma	picritic pillow basalts, columnar basalt
MD109-5		dredge 5	51°31.1' S	71°08.6'E		14 - 19 Ma	picritic pillow basalts, columnar basalt
MD109-6		dredge 6	51°01.3' S	71°03.9'E		14 - 19 Ma	picritic pillow basalts, columnar basalt

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Appendix 5: Surface sediments from Geological Sample Stations

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_depth	Penetration (m)	Surface_sediments	SS_code	Source
1987	ODP	736	-49.4030	71.6610	well	-629.00	371.0000	Diatom ooze with minor volcanic debris	ODV	1
1987	ODP	737	-50.2280	73.0320	well	-564.00	715.5000	Mixed glauconitic sand and diatom ooze	SOD	1
1988	ODP	738	-62.7090	82.7880	well	-2253.00	533.8000	Calcareous diatom ooze	OD	1
1988	ODP	739	-67.2850	75.0820	well	-412.00	486.8000	Diamicton and sand-silt-clay with up to 10% gravel	DSG	1
1988	ODP	740	-68.7640	76.6820	well	-807.00	225.5000	Diatom ooze (75-95%) with minor radiolarians	ODR	1
1988	ODP	741	-68.3870	76.3830	well	-551.00	128.1000	Diatom ooze with quartz silt	ODSi	1
1988	ODP	742	-67.5530	75.4090	well	-416.00	316.0000	Diatomaceous sand-silt overlies pebbly diamicton	SDSi	1
1988	ODP	743	-66.9160	74.6910	well	-989.00	98.1000	Diatom rich sandy silt	SiD	1
1988	ODP	744	-61.5790	80.5950	well	-2307.00	176.1000	Diatom ooze with 5-15% radialarians	ODR	1
1988	ODP	745	-59.5950	85.8540	well	-4082.00	215.0000	Diatom ooze with minor silt and radiolarians	ODR	1
1988	ODP	746	-59.5690	85.8680	well	-4059.00	280.8000	Diatomaceous ooze alternating with silty clay	ODSi	1
1998	ODP	747	-54.8110	76.7940	well	-1695.00	350.5000	Foraminifera diatom ooze	OFD	2
1988	ODP	748	-58.4410	78.9980	well	-1287.00	935.0000	Diatom ooze with rare ice-rafted debris	OD	2
1988	ODP	749	-58.7170	76.4070	well	-1071.00	249.5000	Diatom ooze with foraminifera and ice-rafted debris	ODF	2
1988	ODP	750	-57.5920	81.2400	well	-2030.00	709.7000	Diatom ooze and lag deposits	OD	2
1988	ODP	751	-57.7260	79.8150	well	-1634.00	166.2000	Diatom ooze with foraminifera	ODF	2
1998	ODP	1135	-59.7000	84.2730	well	-1578.00	526.0000	Sand, granules, pebbles and minor amounts of pelagic ooze	SGrP	3
1998	ODP	1136	-59.6520	84.8350	well	-1931.00	128.0000	Mixed clastic sediment and ooze	CO	3
1998	ODP	1137	-56.8330	68.0930	well	-1004.00	370.2000	Foraminifera-bearing diatom ooze	ODF	3
1999	ODP	1138	-53.5520	75.9750	well	-1141.00	842.7000	Foraminifera-bearing diatom clay and ooze	ClODF	3
1999	ODP	1139	-50.1850	63.9370	well	-1415.00	694.2000	Calcareous diatom ooze	OD	3
1999	ODP	1140	-46.2770	68.4920	well	-2394.00	321.2000	Foraminifera-bearing nannofosil ooze	ONF	4
1985	RS/2	1	-58.3380	77.0300	free-fall grab	-1810.00	0.0000	Saprolitic volcanic rocks (lavas)	V	4
1985	RS/2	3	-58.3150	77.0100	free-fall grab	-1750.00	0.0000	Granite and granodiorite, quartz sandstone	Granite	4
1985	RS/2	4	-58.2660	76.9080	free-fall grab	-1500.00	0.0000	Volcanoclastic sandstone	SV	5
1995	AA/149	24	-66.0100	71.5350	gravity core	2535.00	2.5000	Nannofossil ooze	ON	5
1995	AA/149	47	-58.5160	81.7300	gravity core	1500.00	4.8900	Nannofossil ooze with diatoms	OND	5
1995	AA/149	48	-57.6030	78.3020	gravity core	1720.00	3.8200	Nannofissil ooze with forams	ONF	5
1995	AA/149	49	-57.7510	77.5350	gravity core	2050.00	4.4800	Foraminifera-bearing nannofossil ooze and silt	ONFSi	5
1995	AA/149	50	-57.1170	78.4530	gravity core	1710.00	4.7300	Foraminifera-bearing nannofossil ooze	ONF	5
1995	AA/149	51	-55.7530	76.5030	gravity core	2210.00	5.3000	Foraminifera-bearing nannofosil ooze	ONF	5
1971	Elt/47	1	-51.5800	78.9680	piston core	3626.00	6.0900	Diatom ooze and mud with radiolarians	OMDR	6
1971	Elt/47	2	-59.6960	80.8160	piston core	1818.00	5.6700	Foraminifera ooze with diatoms and radiolarians	OFDR	6
1971	Elt/47	3	-62.3850	80.7880	piston core	2812.00	3.8200	Foraminifera ooze with spicules	OFSp	6
1971	Elt/47	4	-64.1180	80.3980	piston core	3638.00	3.3500	Sand and mud with forams	SMF	6
1971	Elt/47	5	-65.5430	80.4250	piston core	2960.00	5.7300	Sand and mud with diatoms and radiolarians	SMDR	6
1971	Elt/47	6	-66.1120	78.4350	piston core	2969.00	12.1600	Mud and sand	MS	6

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1971	Elt/47	7	-66.6550	77.9000	piston core	1443.00	3.6900	Mud, gravel and sand with radiolarians	MGSR	6
1971	Elt/47	8	-66.8260	77.8750	piston core	296.00	2.4500	Diatom ooze with volcanoc ash	ODA	6
1971	Elt/47	9	-66.3800	78.0200	piston core	2460.00	11.7700	Mud and sand with diatoms and radiolarians	MSDR	6
1971	Elt/47	10	-63.9580	83.9910	piston core	3648.00	5.2900	Mud and sand with forams	MSF	6
1971	Elt/47	11	-62.9800	84.1930	piston core	2623.00	5.5100	Foraminifera ooze with radiolarians	OFR	6
1971	Elt/47	12	-61.9450	84.0410	piston core	2797.00	5.3700	Ooze, gravel and foraminifera sand	OGFS	6
1971	Elt/47	13	-58.7830	84.2330	piston core	2923.00	5.7700	Foraminifera ooze with radiolarians	OFR	6
1971	Elt/47	14	-61.1180	71.2730	piston core	4218.00	1.3300	Diatom ooze	OD	6
1971	Elt/47	15	-51.2880	78.8080	piston core	1648.00	5.2500	Foraminifera ooze with radiolarians and diatoms	OFRD	6
1971	Elt/47	16	-54.8500	82.8410	piston core	4541.00	12.0300	Ooze and mud with diatoms and radiolarians	OMDR	6
1971	Elt/47	17	-53.3510	72.1820	piston core	973.00	5.8500	Diatom ooze wit foraminifera and radiolarians	ODFR	6
1971	Elt/47	18	-52.9650	72.8510	piston core	404.00	0.9400	Volcanic ash, gravel and sand with diatoms	AGSD	6
1971	Elt/47	19	-51.3810	73.1510	piston core	277.00	0.7300	Volcanic ash, gravel and sand with foraminifera	AGSF	6
1971	Elt/47	20	-49.1910	72.1450	piston core	958.00	4.1900	Volcanic ash and sand	AGS	6
1971	Elt/47	22	-47.4800	73.9260	piston core	2701.00	1.7000	Mud and sand with volcanic ash	MSA	6
1972	Elt/54	1	-48.1170	86.1920	piston core	3907.00	11.7600	Diatom mud with radiolarians	MDR	6
1972	Elt/54	2	-52.0830	84.5460	piston core	4281.00	8.1400	Diatom ooze and mud with radiolarians	OMDR	6
1972	Elt/54	3	-57.4280	77.8300	piston core	1942.00	0.2700	Nannofissil ooze with foraminifera and radiolarians	ONFR	6
1972	Elt/54	4	-57.4420	77.8800	piston core	1879.00	2.4400	Nannofissil ooze with foraminifera and radiolarians	ONFR	6
1972	Elt/54	5	-56.8760	74.5550	piston core	2971.00	5.5400	Foraminifera ooze with diatoms and radiolarians	OFDR	6
1972	Elt/54	6	-55.4680	76.0160	piston core	2179.00	5.9700	Diatom ooze with foraminifera and radiolarians	ODFR	6
1972	Elt/54	7	-55.8800	81.1180	piston core	4132.00	5.2700	Diatom ooze and mud with radiolarians	OMDR	7
1972	Elt/54	8	-56.8750	81.1860	piston core	4273.00	5.9000	Diatom ooze with radialarians and small amounts of sand	ODRS	6
1972	Elt/54	9	-57.7380	80.2750	piston core	1679.00	5.3400	Foraminifera ooze with diatoms	OFD	6
1972	Elt/54	10	-57.7560	80.6620	piston core	1753.00	5.2200	Foraminifera ooze with diatoms and radiolarians	OFDR	6
1972	Elt/54	11	-57.7810	81.0150	piston core	1850.00	3.8200	Foraminifera ooze, nannofossils and sand	OFNS	6
1972	Elt/54	12	-57.4880	82.3600	piston core	3496.00	0.0000	Mud	M	6
1971	Elt/47	1A	-51.5800	78.9680	trigger core	3626.00	0.5400	Diatom ooze and mud with radiolarians	OMDR	6
1971	Elt/47	3B	-62.3850	80.7880	trigger core	2812.00	0.1300	Foraminifera ooze	OF	6
1971	Elt/47	4A	-64.1180	80.3980	trigger core	3638.00	0.6200	Foraminifera mud and ooze with radiolarians	MOFR	6
1971	Elt/47	5A	-65.5430	80.4250	trigger core	2960.00	0.7600	Mud and sand	MS	6
1971	Elt/47	6A	-66.1110	78.4350	trigger core	2969.00	0.2400	Mud and sand with radiolarians	MSR	6
1971	Elt/47	7A	-66.6550	77.9000	trigger core	1443.00	0.5800	Mud and sand with radiolarians	MSR	6
1971	Elt/47	8A	-66.8260	77.8750	trigger core	296.00	0.1700	Sand and mud	SM	6
1971	Elt/47	9A	-66.3800	78.0200	trigger core	2460.00	0.2300	Mud and sand with diatoms and radiolarians	MSDR	6
1971	Elt/47	12A	-61.9450	84.0410	trigger core	2797.00	0.4800	Diatom ooze with radialarians and small amounts of sand	ODRS	6
1971	Elt/47	14A	-61.1180	71.2730	trigger core	4218.00	0.4000	Mud, ooze and sand with diatoms	MOSD	6
1971	Elt/47	16A	-54.8500	82.8410	trigger core	4541.00	0.4900	Ooze with radiolarians and diatoms	ORD	6
1971	Elt/47	20A	-49.1910	72.1450	trigger core	928.00	0.1000	Volcanic ash and mud with Diatoms and foraminifera	AMDF	6

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1971	Elt/47	22A	-47.4800	73.9260	trigger core	2701.00	0.3800	Mud with foraminifera and some sand with radiolarians	MFSR	6
1971	Elt/47	3A	-49.6910	70.8700	Phleger core	462.00	0.2800	Foraminifera ooze with diatoms	OFD	6
1971	Elt/47	4D	-49.7950	71.4000	Phleger core	618.00	0.0900	Mud with diatoms and foraminifera	MDF	6
1971	Elt/47	5A	-49.9830	73.6680	Phleger core	943.50	0.1900	Mostly sand with some foraminifera ooze and ash	SOAF	6
1971	Elt/47	32A	-58.7830	84.2460	Phleger core	2353.00	0.1200	Foraminifera ooze, mud and sand	OMFS	6
1971	Elt/47	39A	-53.9850	70.7500	Phleger core	3681.00	0.3000	Ooze and mud with diatoms and foraminifera	OMDF	6
1971	Elt/47	41A	-53.3500	70.9300	Phleger core	3126.00	0.1800	Ooze and mud with diatoms and foraminifera	OMDF	6
1971	Elt/47	56A	-51.3800	73.1500	Phleger core	281.00	0.2100	Volcanic ash with diatoms and foraminifera	ADF	6
1972	Elt/54	1	-48.1180	86.1910	trigger core	3907.00	0.6000	mud with diatoms and radiolarians	MDR	6
1972	Elt/54	2	-52.0830	84.5460	trigger core	4280.00	0.2700	Diatom ozze with radiolarians and some sand	ODRS	6
1972	Elt/54	6	-55.4680	76.0160	trigger core	2179.00	0.1000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1972	Elt/54	7	-55.8800	81.1180	trigger core	4132.00	0.0000	Mud with diatoms, foraminifera and some sand	MDFS	6
1972	Elt/54	8	-56.8750	81.1860	trigger core	4273.00	0.4900	Diatom ooze with radialarians and small amounts of sand	ODSR	6
1972	Elt/54	9	-57.7380	80.2750	trigger core	1670.00	0.6000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1972	Elt/54	10	-57.7560	80.6610	trigger core	1753.00	0.2000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1972	Elt/54	11	-57.7810	81.0150	trigger core	1850.00	0.0000	Nannofossil ooze with foraminifera	ONF	6
1972	Elt/54	12	-57.4880	82.3600	trigger core	3496.00	0.2800	Diatom ooze with radiolarians	ODR	6
1972	Elt/54	1	-53.7480	83.8300	Phleger core	4671.00	0.4400	Diatom ooze and mud with radiolarians	OMDR	6
1972	Elt/54	2	-56.2000	82.6280	Phleger core	4643.00	0.5900	Diatom ooze and mud with radiolarians	OMDR	6
1972	Elt/54	3	-57.4830	82.4180	Phleger core	3996.00	0.5300	Diatom ooze and mud with foraminifera	OMDF	6
1971	Elt/47	1	-49.7830	71.3230	bottom dredge	619.00	0.0000	Diatom ooze with radiolarians and foraminifera	ODRF	6
1971	Elt/47	1	-49.5950	70.3710	Campbell grab	111.00	0.0000	Sand with spicules	SSp	6
1971	Elt/47	2	-51.1580	75.7750	bottom dredge	1581.00	0.0000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1971	Elt/47	2	-49.7250	71.0360	Campbell grab	462.00	0.0000	Ooze and sand with foraminifera and diatoms	OSFD	6
1971	Elt/47	3	-51.2330	76.7480	bottom dredge	3302.00	0.0000	Diatom ooze with ash and sand	ODAS	6
1971	Elt/47	3	-49.7830	71.3160	Campbell grab	619.00	0.0000	Diatom ooze with radiolarians	ODR	6
1971	Elt/47	4	-49.9810	73.6660	Campbell grab	952.00	0.0000	Ooze and sand with diatoms and radiolarians	OSDR	6
1971	Elt/47	5	-51.0910	76.5880	Campbell grab	1424.00	0.0000	Foraminifera ooze with spicules	OFSp	6
1971	Elt/47	6	-51.1580	75.7750	Campbell grab	1776.00	0.0000	Diatom ooze with foraminifera and sand	ODFS	6
1971	Elt/47	7	-51.1480	76.0630	Campbell grab	2345.00	0.0000	Foraminifera ooze with diatoms and radiolarians	OFDR	6
1971	Elt/47	8	-51.5560	78.9360	Campbell grab	3626.00	0.0000	Mud and sand with diatoms and radiolarians	MSDR	6
1971	Elt/47	9	-66.4830	78.2000	Campbell grab	1100.00	0.0000	Mud and sand	MS	6
1971	Elt/47	10	-66.6360	78.1120	Campbell grab	1609.00	0.0000	Mud and sand with radiolarians and spicules	MSRSp	6
1971	Elt/47	11	-66.8010	77.9610	Campbell grab	333.00	0.0000	Sand and mud	SM	6
1971	Elt/47	12	-53.9850	70.7500	Campbell grab	3607.00	0.0000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1971	Elt/47	13	-53.3500	70.9300	Campbell grab	3108.00	0.0000	Diatom ooze with foraminifera and radiolarians	ODFR	6
1971	Elt/47	14	-53.3550	70.9750	Campbell grab	2738.00	0.0000	Diatom ooze with foraminifera	ODF	6
1971	Elt/47	15	-53.3530	71.1000	Campbell grab	2312.00	0.0000	Diatom ooze	OD	6
1971	Elt/47	16	-53.3510	71.3030	Campbell grab	1942.00	0.0000	Diatom ooze with foraminifera	ODF	6

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1971	Elt/47	17	-53.3400	71.6560	Campbell grab	1711.00	0.0000	Diatom ooze with foraminifera	ODF	6
1971	Elt/47	18	-53.2980	71.7180	Campbell grab	1489.00	0.0000	Diatom ooze with foraminifera	ODF	6
1971	Elt/47	19	-53.2960	71.8010	Campbell grab	1328.00	0.0000	Diatom ooze with foraminifera	ODF	6
1971	Elt/47	20	-53.2930	71.9160	Campbell grab	1137.00	0.0000	Diatom ooze with foraminifera and sand	ODFS	6
1971	Elt/47	21	-53.3330	72.2400	Campbell grab	943.00	0.0000	Foraminifera ooze with diatoms and some sand	OFDS	6
1971	Elt/47	22	-53.3300	72.9430	Campbell grab	769.00	0.0000	Foraminifera ooze and sand	OFS	6
1971	Elt/47	23	-52.9480	72.9150	Campbell grab	218.00	0.0000	Mud with diatoms, volcanic ash and sand	MDAS	6
1971	Elt/47	24	-52.9330	72.9160	Campbell grab	222.00	0.0000	Volcanic ash and nannofossil ooze	AON	6
1971	Elt/47	25	-52.7860	72.4030	Campbell grab	447.00	0.0000	sand with diatom ooze, some foraminifera present	SODF	6
1971	Elt/47	26	-52.7760	72.7760	Campbell grab	555.00	0.0000	Sand with diatom ooze and volcanic ash	SODA	6
1971	Elt/47	27	-47.3360	73.8430	Campbell grab	3239.00	0.0000	Diatom ooze with foraminifera and some sand	ODFS	6
1971	Elt/47	28	-47.4680	73.9280	Campbell grab	2732.00	0.0000	Foraminifera ooze with diatoms and some sand	OFDS	6
1971	Elt/47	29	-47.5180	73.9280	Campbell grab	2368.00	0.0000	Foraminifera ooze with radiolarians and diatoms	OFRD	6
1971	Elt/47	30	-48.2460	73.0480	Campbell grab	1961.00	0.0000	Diatom ooze	OD	6
1971	Elt/47	31	-47.9410	73.4100	Campbell grab	1572.00	0.0000	Diatom ooze with radiolarians and some sand	ODRS	6
1986	MD48	Dr1	-51.9667	77.7667	Dredge	2300	0.0000	Basalt	B	7
1986	MD48	Dr2	-57.3000	77.6000	Dredge	2400	0.0000	Basalt	B	7
1986	MD48	Dr3	-57.3000	77.5833	Dredge	2000	0.0000	chert	Ch	7
1986	MD48	Dr4	-57.2833	77.6167	Dredge	2600	0.0000	chert	Ch	7
1986	MD48	Dr5	-58.1000	76.9167	Dredge	2200	0.0000	Basalt	B	7
1986	MD48	Dr 6	-58.2833	76.9167	Dredge	1550	0.0000	Basalt	B	7
1986	MD48	Dr7	-55.3000	77.4667	Dredge	2265	0.0000	Conglomerate	Cg	7
1986	MD48	Dr 8	-50.3167	74.8167	Dredge	2175	0.0000	Basalt	B	7
1986	MD48	G	-58.3167	77.0167	Free-fall grab	1750	0.0000	Basalt	B	7
1986	MD48	697	-57.3833	79.6500	piston core	1680	0.7350	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	698	-57.2500	80.1667	piston core	1980	0.6270	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	699	-57.1333	80.9500	piston core	2625	0.3750	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	700	-57.1000	81.1833	piston core	3130	0.1340	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	701	-57.0667	81.3833	piston core	3850	0.7880	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	702	-57.1000	81.2167	piston core	3115	0.6050	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	703	-57.0667	81.4000	piston core	3800	1.2030	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	704	-57.2833	77.8000	piston core	1890	0.2450	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1986	MD48	705	-57.2833	77.5167	piston core	2272	0.7900	Ooze with foraminifera, radiolaria and diatoms	OFRD	7
1991	MD67	Dr	-55.3000	83.0000	Dredge	3000	0.0000	metamorphic and granitic rocks	Gran	8
1998	MD109	Dr1	-50.3167	63.7983	Dredge		0.0000	ice-rafted debris	Deb	9
1998	MD109	Dr4	-51.5200	71.1467	Dredge		0.0000	pillow basalts	B	9
1998	MD109	Dr5	-51.5183	71.1433	Dredge		0.0000	pillow basalts	B	9
1998	MD109	Dr6	-51.0217	71.0650	Dredge		0.0000	pillow basalts	B	9
1983	MD35	83479	-40.5640	65.5710	piston core	4253.00	7.3000	Nannofissil ooze with diatoms	OND	10

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1983	MD35	83480	-45.2460	66.3010	piston core	37.18	2.9000	Nannofossil ooze with foraminifera and diatoms	ONFD	10
1983	MD35	83481	-45.4870	66.3420	piston core	2390.00	4.2000	Nannofossil ooze with foraminifera and diatoms	ONFD	10
1983	MD35	83482	-45.4100	66.3710	piston core	2750.00	8.0000	Nannofossil ooze with foraminifera and diatoms	ONFD	10
1983	MD35	83483	-49.1100	72.1030	piston core	1294.00	4.5000	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83484	-49.1070	72.0960	piston core	1154.00	8.2000	Diatom ooze with basalt fragments	ODB	10
1983	MD35	83485	-49.1730	72.5710	piston core	2368.00	8.5000	Diatom ooze and mud with some sand	ODMS	10
1983	MD35	83486	-49.5770	73.3680	piston core	778.00	0.5000	Basalt blocks	B	10
1983	MD35	83487	-49.5770	73.3640	piston core	709.00	0.4000	Shells and shell debris	Sh	10
1983	MD35	83488	-49.5760	73.3670	piston core	809.00	0.2000	Basalt blocks and shells	BSh	10
1983	MD35	83489	-49.5750	73.3630	piston core	793.00	5.1500	Shells and shell debris	Sh	10
1983	MD35	83490	-49.5840	73.3920	piston core	881.00	0.6500	Diatom ooze with ice-rafted debris and some sand	ODDebS	10
1983	MD35	83491	-49.5790	73.3880	piston core	953.00	0.4000	Diatom ooze with ice-rafted debris and some sand	ODDebS	10
1983	MD35	83001	-49.5870	73.4200	Dredge	990.00	8.0000	Chalk and ice-rafted block of basalt	ChDeb	10
1983	MD35	83492	-50.0180	73.4130	piston core	873.00	0.2000	Shale with zeolites	Sha	10
1983	MD35	83493	-50.0380	73.4320	piston core	734.00	6.8000	Diatom ooze with some shells, debris and sand	ODSh	10
1983	MD35	83494	-50.0280	73.4290	piston core	765.00	0.5500	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83495	-49.5540	73.3670	piston core	1095.00	0.5000	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83496	-49.5580	73.3640	piston core	1020.00	5.0000	Diatom ooze with shells and ice-rafted debris	ODSh	10
1983	MD35	83497	-49.5790	73.3920	piston core	942.00	0.6000	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83498	-49.4190	73.5870	piston core	2440.00	7.4500	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83499	-49.4080	74.0120	piston core	2592.00	6.0000	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83500	-49.3440	73.4890	piston core	2485.00	7.0000	Foraminifera ooze and mud with ice-rafted debris	OFMDeb	10
1983	MD35	83501	-49.3560	73.5040	piston core	2438.00	1.6100	Diatom ooze and mud with fragments of basalt	ODMB	10
1983	MD35	83502	-50.1070	74.2510	piston core	985.00	7.8000	Diatom ooze with shells and ice-rafted debris	ODSh	10
1983	MD35	83503	-50.3191	74.7473	piston core	1300	4.0000	Shells and cherts	ShCh	7
1983	MD35	83504	-50.1930	74.4740	piston core	1635.00	0.2000	Foraminifera ooze and mud	OFM	10
1983	MD35	83505	-50.1880	74.7476	piston core	1820	0.7800	Nannofossil chalk	Ch	7
1983	MD35	83506	-50.1980	74.4720	piston core	1300	0.8000	Nannofossil chalk with basalt fragments	ChB	7
1983	MD35	83507	-50.2190	74.5680	piston core	1766.00	3.1000	Diatom and foraminifera ooze with ice-rafted debris	ODFDeb	10
1983	MD35	83508	-50.2210	74.5660	piston core	1505.00	1.1100	Blocks of basalt in diatom ooze	ODB	10
1983	MD35	83509	-50.1580	74.2880	piston core	925.00	5.6000	Diatom ooze and mud with radiolarians and forams	ODRF	10
1983	MD35	83510	-50.1920	74.4720	piston core	1517	0.2150	calcareous and siliceous ooze	OFD	7
1983	MD35	83002	-50.1890	74.4640	Dredge	0.00	0.0000	Cherts and limestone	Ch	10
1983	MD35	83511	-49.5880	74.3660	piston core	2500.00	7.5000	Diatom ooze and mud	ODM	10
1983	MD35	83512	-49.5710	74.2200	piston core	1609.00	7.3000	Diatom ooze with radiolarians and forams, mud with shells	ODRF	10
1983	MD35	83513	-49.5790	73.3630	piston core	780.00	0.7500	Limestone	Lime	10
1983	MD35	83003	-49.5790	73.3750	Dredge	883.00	0.0000	Chalk	Ch	10
1983	MD35	83514	-49.5790	73.3920	piston core	985.00	7.8000	Diatom ooze with ice-rafted debris	ODDeb	10
1983	MD35	83515	-50.2350	63.5640	piston core	3300.00	6.4000	Foraminifera and diatom ooze and mud	OMFD	10
1983	MD35	83516	-50.0650	63.5460	piston core	1485.00	3.2000	Foraminifera and diatom ooze and mud	OMFD	10

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1983	MD35	83517	-50.1860	63.5490	piston core	1891.00	3.5700	Foraminifera ooze	OF	10
1983	MD35	83518	-50.2070	63.5360	piston core	2260.00	4.1000	Foraminifera and diatom ooze and mud	OMFD	10
1983	MD35	83519	-50.0110	63.5660	piston core	1350.00	6.7000	Foraminifera and diatom ooze and mud	OMFD	10
1983	MD35	83520	-49.5040	65.4270	piston core	770.00	0.1000	Basalt	B	10
1984	MD38	84527	-43.4880	51.3180	piston core	3262.00	14.9000	Diatom and calcareous ooze	ODF	11
1984	MD38	84528	-46.1750	53.0600	piston core	3408.00	16.3200	Diatom ozoe with some calcareous component	ODF	11
1984	MD38	84529	-48.9050	61.9960	piston core	2600.00	14.5000	Diatom ozoe with some calcareous component	ODF	11
1984	MD38	84530	-66.1100	73.9850	piston core	2412.00	10.0000	Mud with some sand	MS	11
1984	MD38	84531	-66.9620	75.4100	piston core	365.00	0.2100	sand and pebbles	SP	11
1984	MD38	84532	-66.1150	76.7600	piston core	2700.00	10.8500	Mud and diatom ooze	MOD	11
1984	MD38	84533	-65.1520	78.3530	piston core	3363.00	6.7000	Mud with some diatom ooze	MOD	11
1984	MD38	84534	-64.1100	79.9660	piston core	3623.00	4.7000	Mud mostly of calcareous composition	M	11
1984	MD38	84535	-63.8000	83.9680	piston core	3654.00	0.0100	Mud with gravel	MG	11
1984	MD38	84536	-63.4030	84.0000	piston core	3012.00	5.3000	Foraminifera ooze, debris of calcareous composition	OFDeb	11
1984	MD38	84537	-62.3250	85.5000	piston core	3555.00	14.8000	Mud, foraminifera and diatom ooze	MOFD	11
1984	MD38	84538	-61.3250	85.2020	piston core	2608.00	12.0500	Foraminifera and nannoplankton ooze with some debris	OFNDeb	11
1984	MD38	84539	-61.0000	85.9510	piston core	4150.00	15.5500	Diatom ooze and mud	ODM	11
1984	MD38	84540	-60.7420	86.3880	piston core	3964.00	16.6000	Diatom ooze and mud	ODM	11
1984	MD38	84541	-59.9300	84.5780	piston core	1854.00	4.1500	Foraminifera and diatom ooze with debris and some sand	OFDDebS	11
1984	MD38	84542	-60.0750	83.3050	piston core	1332.00	5.7000	Diatom ooze with foraminifera and radiolarians, fragments of gneiss	ODFR	11
1984	MD38	84543	-60.5600	79.3250	piston core	2518.00	7.6500	Diatom and foraminifera ooze and mud with some debris	ODFDeb	11
1984	MD38	84544	-60.6833	78.2667	piston core	3107	14.8500	Calcareous ooze with some siliceous component	OFD	11
1984	MD38	84545	-60.9980	75.3250	piston core	3357.00	15.4000	Diatom and nannoplancton ooze with a lot of cacarous debris	DebODN	11
1984	MD38	84546	-61.5210	75.0730	piston core	3988.00	10.9000	Mud, diatom ooze and some volcanoclastic material	MODV	11
1984	MD38	84547	-59.4500	76.4080	piston core	1163.00	7.9500	Diatom and nannoplancton ooze with some debris	ODNDeb	11
1984	MD38	84548	-57.7880	74.7080	piston core	2390.00	6.8000	Diatom ooze with some foraminifera	ODF	11
1984	MD38	84549	-56.8760	73.3420	piston core	2650.00	7.4000	Foraminifera and nannoplancton ooze with debris	OFNDeb	11
1984	MD38	84550	-56.7670	71.3850	piston core	4080.00	6.7000	Diatom ooze	OD	11
1984	MD38	84551	-55.0000	73.2810	piston core	2230.00	7.6800	Diatom ooze	OD	11
1984	MD38	84552	-54.9230	73.8380	piston core	1780.00	7.5000	Diatom ooze	OD	11
1984	MD38	84553	-54.6850	76.5570	piston core	1504.00	6.3800	Diatom ooze with foraminifera and debris	ODFDeb	11
1984	MD38	84554	-54.9500	77.1000	piston core	2357	5.3000	Gravel and pebbles of different rocks	GP	11
1984	MD38	84555	-53.5667	79.3833	piston core	4235	7.8000	Foraminifera ooze and mud with some volcanic ash	OMFV	11
1984	MD38	84556	-52.5450	79.6330	piston core	3987.00	6.0200	Diatom ooze and mud with volcanic component	ODMV	11
1984	MD38	84557	-53.3270	75.8030	piston core	1084.00	6.5200	Diatom ooze	OD	11
1984	MD38	84558	-53.1670	74.1260	piston core	270.00	0.1500	Volcanic sand	SV	11
1984	MD38	84559	-53.1870	73.7660	piston core	120.00	2.1000	Volcanic sand	SV	11
1984	MD38	84560	-53.1180	72.1680	piston core	950.00	6.6500	Diatom ooze with foraminifera, shells, sand and volcanic ash	ODFSV	11
1984	MD38	84561	-53.0880	71.6070	piston core	1764.00	7.2500	Diatom and nannoplancton ooze	ODN	11

Year	Survey	Core_id	Latitude	Longitude	Sample_type	Water_dep	Penetration (m)	Surface_sediments	SS_code	Source
1984	MD38	84562	-51.9180	68.2270	piston core	3553.00	9.6400	Diatom and nannoplancton ooze	ODN	11
1984	MD38	84563	-50.7120	68.1520	piston core	1720.00	10.9500	Diatom ooze with some nannoplancton	ODN	11
1984	MD38	84564	-50.8700	68.7850	piston core	2140.00	6.9000	Diatom ooze with some nannoplancton	ODN	11
1984	MD38	84565	-50.5300	70.7530	piston core	614.00	7.3000	Diatom ooze with some nannoplancton	ODN	11
1984	MD38	84566	-49.8560	70.6650	piston core	195.00	3.2000	Sand and debris of calcareous organisms	SSh	11
1984	MD38	84567	-48.9250	71.1150	piston core	810.00	7.7000	Diatom ooze with some nannofossils and volcanic material	ODNV	11
1984	MD38	84568	-48.5980	72.6650	piston core	2241.00	16.2500	Diatom ooze	OD	11
1984	MD38	84569	-47.6430	73.3850	piston core	2385.00	11.4500	Diatom ooze with nannofossils and some mud	ODNM	11
1980	MD20	80310	-45.9330	66.5660	piston core	2310.00		Diatom-rich nanno-ooze	ODN	12
1981	MD26	81320	-49.9670	73.9500	piston core	799.00		Chalk and argilite pebbles	ChP	12
1999	TH98	D1901	-59.7720	85.1670	Dredge	3193.00	0.0000	Aplite, basalt, granite, diorite and gneiss	Gran	13
1999	TH98	GC1901	-61.4930	90.0550	piston core	4062.00	3.7600	Siliceous clay intercalated with silty clay layers	ODM	13
1999	TH98	GC1902	-62.4760	94.9480	piston core	3661.00	3.7700	Siliceous clay with scattered granules	ODGr	13
1999	TH98	GC1903	-60.8740	95.0820	piston core	4281.00	2.8500	Siliceous clay to siliceous ooze with silt and fine sand	ODMS	13
1999	TH98	GC1904	-64.1610	80.6380	piston core	3638.00	1.8900	Clay intercalated silty clay layers to siliceous silty clay	OMD	13
1999	TH98	GC1905	-64.1700	85.3060	piston core	3655.00	3.8200	Clay intercalated with fine sandy silt and siliceous silty clay	MS	13
1999	TH98	GC1906	-65.1980	85.9990	piston core	2981.00	5.0400	Clay with diatoms and radiolarians	ODR	13
1999	TH98	GC1907	-62.0320	97.4870	piston core	4105.00	4.4900	Siliceous ooze	OD	13

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Appendix 6: Geoscience Australia (AGSO) Surveys 179/180 (Kerguelen) sonobuoy details.

Sono ID	Seismic Line	Latitude	Longitude	Start SP	End SP	SP origin	*Sono depth*	Offset range (km)	adav (m/s)	Scaled SP interval (m)
179_5	179/05	58 27 22.52S	65 00 40.41E	2170	2744	2170	122	0.0 – 28.7	1500	50.0
179_7a	179/07	58 02 59.18S	71 48 24.66E	2105	2687	2100	122	0.25 – 29.35	1570	47.8
179_7b	179/07	56 43 13.57S	76 17 14.04E	8484	9083	8480	122	0.2 – 30.65	1830	41.0
179_7c	179/07	54 57 24.32S	80 23 35.57E	16240	16749	16240	122	0.0 – 25.55	1500	50.0
179_7d	179/07	54 31 23.86S	80 59 24.60E	17470	17963	17470	122	0.0 – 24.65	1500	50.0
179_7e	179/07	54 11 19.36S	81 26 46.15E	18423	18949	18420	122	0.15 – 26.55	1570	47.8
180_1b	180/01	55 49 45.72S	84 46 21.10E	1633	2100	1630	305	0.15 – 23.5	1480	50.7
180_1c	180/01	56 30 36.37S	83 37 26.10E	3715	4210	3710	305	0.25 – 25.0	1600	46.9
180_1d	180/01	56 40 22.76S	82 06 15.64E	5740	6162	5740	18 [E]	0.0 – 21.1	1340	56.0
180_2a	180/02	59 29 47.80S	84 01 33.11E	1052	1560	1050	18*	0.1 – 25.5	1450	51.7
180_2b	180/02	59 44 58.97S	84 19 58.94E	1714	2180	1710	18	0.2 – 23.5	1735	43.2
180_3	180/03	61 36 11.67S	87 02 52.29E	2929	3201	2920	18*	0.45 – 14.05	1500	50.0
180_4	180/04	61 54 47.92S	88 45 22.84E	1514	1925	1510	18	0.2 – 20.75	1580	47.5
180_5a	180/05	61 12 58.10S	89 04 40.61E	1349	1781	1340	18*	0.45 – 22.05	1290	58.1

180_5b	180/05	61 06 28.03S	87 50 16.18E	2706	3156	2700	18[*]	0.3 – 22.8	1310	57.3
180_5c	180/05	61 11 25.26S	85 53 00.60E	4821	5280	4820	18	0.05 – 23.0	1460	51.4
180_6a	180/06	58 13 33.57S	88 48 45.57E	1666	2210	1660	122[E]	0.3 – 27.5	1660	45.2
180_6b	180/06	58 24 12.38S	87 13 32.99E	3566	4140	3560	122[E]	0.3 – 29.0	1540	48.7
180_6c	180/06	58 33 27.63S	85 06 02.88E	6070	6538	6070	18	0.0 – 23.4	1450	51.7
180_7a	180/07	57 44 35.13S	83 43 12.09E	2590	3040	2590	18[*]	0.0 – 22.5	1450	51.7
180_7b	180/07	57 01 11.13S	85 10 34.70E	4970	5470	4970	305	0.0 – 25.0	1570	47.8
180_8	180/08	55 47 34.38S	83 37 55.92E	1404	1866	1400	305[*]	0.2 – 23.3	1400	53.6

Notes: Nominal SP (shotpoint) interval for both surveys was 50m. Scaled SP interval is determined by the formula: (1500/adav) * (nom SP interval).
The latitude/longitude pair is the position of the midpoint between source and near-trace for the start shotpoint.
The sonobuoy depth is in metres: [*]Depth not logged but most likely guess; [E]Empirically determined.
Shading represents sonobuoys that could not be successfully modelled.
Abbr: **sono** = sonobuoy; **adav** = apparent direct arrival velocity.

Appendix 7: Procedure for modelling sonobuoy records, Geoscience Australia (AGSO) Surveys 179 and 180

Sonobuoy data

The AGSO Survey 179 and 180 sonobuoy records normally have a maximum offset of between 20 and 30 km. The nominal shotpoint (SP) interval for the surveys was 50 metres. The records were initially interpreted with all significant events being marked and individually digitised. The events chosen include direct arrival, the pre-critical water bottom reflection, other reflections, all first-break refraction energy and other deeper events. The data were then exported into an ASCII file, reformatted, and finally input into MacRay[1].

In most instances, the records were artificially stretched or compressed to some degree as a result of sonobuoy drift. This was readily noticeable when modelling the direct arrival, which in the normal case is expected to have a velocity equal to the speed of sound in water (~1500 m/s). However, after fitting a straight line of best fit to the direct arrival events, the apparent direct arrival velocity (*adav*) was found to vary between 1290 and 1830 m/s over the survey. Where *adav* differed from 1500 m/s, the shotpoint interval was adjusted according to the formula:

Scaled SP interval = 1500/adav * nominal SP interval

The above relationship assumes a constant speed of drift in the direction of shooting of the seismic survey. In our procedure, irregular and lateral drift cannot be corrected nor detected respectively. However there was little evidence of irregular drift speed in this study while the effect of lateral drift is generally comparatively small.

The data were then formatted a second time using the scaled SP interval rather than the nominal SP interval to determine along-line distance (Appendix 6). This data file was then re-imported into MacRay and was ready for final modelling.

Model data

Reflection seismic data for the relevant portion of the seismic line were initially interpreted and digitised on-screen. Each layer was initially given an approximate interval velocity, which was determined by averaging the interval velocities of the layer from stacking velocities. Using the Petroseis[2] package, the horizons were then depth-converted using the preliminary interval velocities. The depths to each horizon were imported into MacRay for modelling and used as the starting point for further modelling.

[1] USGS 2D raypath modelling software package (for Macintosh operating system)
[2] Petroseis software, Petrosys Pty Ltd.

Modelling techniques

In order to verify the data, the direct arrival was modelled and pre-critical reflection raypaths off the water bottom were matched with the hyperbolic first breaks. For some sonobuoys, the sonobuoy depth was not logged and on these occasions, the depth was determined by directly matching the water bottom. Generally, shallow horizons posed little problem in providing a good match with the observed events on the sonobuoy records.

The modelling procedure involved modifying and fine-tuning each interface starting from the top downward. When testing refraction events, the first-break refraction arrival was first interpreted as a number of discrete straight-line segments with different slopes. Each refractor interface in turn had the velocity altered in order to best match the slope of the segment. Then the interface was moved up or down to provide the optimum match with the observed event. When a best fit was made to the first segment, the next deeper horizon was modified for velocity and depth to match the next segment and so on, until all segments were modelled by refracting horizons.

The model layers were generally given a velocity range of 100 or 200 m/s (increasing with depth), as this would be expected to approximately represent the physical nature of a given thick rock layer which becomes more compacted with depth. It was decided that a similar velocity range be chosen for all layers during modelling of Kerguelen sonobuoy data.

The deeper horizons, in particular, give rise to events on the records that cannot be modelled with the refraction technique, as valid raypaths cannot be returned within the maximum offset.

As a general rule, the original input model was modified as little as possible while providing the best fit. This ensured minimum departure from the original depth-converted model. These modifications included flattening out horizons in order to create physically possible raypaths; the creation of refracting layers where necessary; and changes to the velocities of refractors in order to fit the gradient of the first-break refraction events.

Discussion of errors

The final velocity and depth model is subject to some errors. They are difficult to quantify and are briefly outlined below:

- As mentioned above, sonobuoy drift will contribute an error into calculations.
- The assumption is made in the depth conversion that (i) there are no lateral velocity variations in the layers and (ii) the true interval velocity is an averaged value determined from the stacking velocities of reflection seismic. This is obviously not the physical reality within the earth, but for a regional assessment such as this, is considered to be a reasonable

approximation. It is difficult to quantify the error in depth and velocity, as a different velocity field will influence the raypath geometry.

- The modelling is not as constrained as it could be because the refraction records are acquired in one direction only. The main advantage of reciprocal shooting is that, as well as providing double the amount of data to be matched, the technique allows distinguishing the cause of changes of refraction slope between dip effects and the velocities. In our case however, provided that the depth conversion is reasonably accurate, the starting model should reflect the true dip. It is difficult to say just how much error is involved. What can be said with certainty is that the depth conversion technique will be improved in future by using modern software, which is attuned to the problem of true depth conversion.
- In conjunction with the point above, there will be some thickness/velocity “invariance”. Individual layer thicknesses and velocities within a multi-layered system can be modified in combination to give similar modelled results. The error in layer velocity is difficult to quantify, but it is estimated to be in the order of $1\sigma \approx \pm 100$ m/s.

Appendix 8: Derived layer thicknesses and velocities from sonobuoy data of Geoscience Australia (AGSO) Surveys 179 & 180.

Sonobuoy no	Geographical location	Layer name or no	Depth top	twt top	Input velocity top of layer	Output velocity top of layer	Thickness	Input velocity Bottom of layer	Output velocity Bottom of layer	Depth base	twt base	Model layer based on
17907a	Enderby Basin	water	0	0	1.49	1.50	4.46	1.51	1.52	4.46	5.91	Reflection seismic data
17907a	Enderby Basin	Near mid-olig	4.46	5.91	1.59	1.59	0.2	1.61	1.61	4.66	6.16	Reflection seismic data
17907a	Enderby Basin	Intra-basement	4.66	6.16	2.39	2.39	0.55	2.41	2.41	5.21	8.8	Reflection seismic data
17907a	Enderby Basin	Intra-basement	5.21	8.8	4.59	4.59	1.09	4.61	4.61	6.3	9.27	Refraction first breaks
17907a	Enderby Basin	Intra-basement	6.3	9.27	5.19	5.4	1.17	5.21	5.5	7.47	9.7	Refraction first breaks
17907a	Enderby Basin	Intra-basement	7.47	9.7	5.69	6.25	N/a	5.71	6.35	N/a	N/a	Refraction first breaks
17907b	Sth Kerguelen Plateau	Water	0	0	1.49	1.49	2.33	1.51	1.51	2.33	3.11	Reflection seismic data
17907b	Sth Kerguelen Plateau	Tertiary	2.33	3.11	1.59	1.59	0.2	1.61	1.61	2.53	3.36	Reflection seismic data
17907b	Sth Kerguelen Plateau	Basement	2.53	3.36	1.99	1.69	0.22	2.01	1.79	2.75	3.62	Reflection seismic data
17907b	Sth Kerguelen Plateau	Intra-basement	2.75	3.62	3.99	3.94	0.38	4.01	3.96	3.13	3.81	Refraction first breaks
17907b	Sth Kerguelen Plateau	Intra-basement	3.13	3.81	4.39	4.89	1.42	4.41	4.91	4.55	4.39	Refraction first breaks
17907b	Sth Kerguelen Plateau	Intra-basement	4.55	4.39	5.39	5.39	2.29	5.41	5.41	6.84	5.24	Refraction first breaks
17907b	Sth Kerguelen Plateau	Intra-basement	6.84	5.24	6.49	6.4	N/a	6.51	6.6	N/a	N/a	Refraction first breaks
17907c	North Labuan Basin	water	0	0	1.49	1.49	3.66	1.51	1.51	3.66	4.88	Reflection seismic data
17907c	North Labuan Basin	Pre-lower Miocene	3.66	4.88	1.94	1.75	1.18	1.96	1.85	4.84	6.2	Reflection seismic data
17907c	North Labuan Basin	Pre-basement	4.84	6.2	3.29	3.05	1.48	3.31	3.15	6.32	7.15	Reflection seismic data
17907c	North Labuan Basin	Intra-basement	6.32	7.15	4.44	3.45	1.13	4.46	3.55	7.45	7.8	Reflection seismic data
17907c	North Labuan Basin	Intra-basement	7.45	7.8	n/a	5.0	1.44	n/a	5.1	8.89	8.35	Refraction first breaks
17907c	North Labuan Basin	Intra-basement	8.89	8.35	n/a	6.5	2.36	n/a	6.6	11.25	9.07	Refraction first breaks
17907c	North Labuan Basin	Intra-basement	11.25	9.07	n/a	8.1	N/a	n/a	8.2	N/a	N/a	Refraction first breaks
17907d	North Labuan Basin	water	0	0	1.49	1.49	3.67	1.51	1.51	3.67	4.89	Reflection seismic data
17907d	North Labuan Basin	mid-Oligocene	3.67	4.89	1.99	1.85	1.26	2.01	1.9	4.93	6.23	Reflection seismic data
17907d	North Labuan Basin	Campanian	4.93	6.23	3.14	3.25	1.28	3.16	3.35	6.21	7.01	Refraction first breaks
17907d	North Labuan Basin	Campanian	6.21	7.01	3.49	3.7	0.28	3.51	3.8	6.49	7.16	Refraction first breaks
17907d	North Labuan Basin	Intra-basement	6.49	7.16	4.74	4.2	1.5	4.76	4.3	7.99	7.87	Refraction first breaks
17907d	North Labuan Basin	Intra-basement	7.99	7.87	n/a	5.85	2.63	n/a	5.95	10.62	8.76	Refraction first breaks
17907d	North Labuan Basin	Intra-basement	10.62	8.76	n/a	7.7	N/a	n/a	7.8	N/a	N/a	Refraction first breaks
17907e	North Labuan Basin	water	0	0	1.49	1.49	3.77	1.51	1.51	3.77	5.03	Reflection seismic data
17907e	North Labuan Basin	Lower Miocene	3.77	5.03	1.84	1.7	0.72	1.86	1.72	4.49	5.87	Reflection seismic data

Sonobuoy no	Geographical location	Layer name or no	Depth top	twt top	Input velocity top of layer	Output velocity top of layer	Thickness	Input velocity Bottom of layer	Output velocity Bottom of layer	Depth base	twt base	Model layer based on
17907e	North Labuan Basin	Campanian	4.49	5.87	3.09	3.09	0.34	3.11	3.11	4.83	6.09	Reflection seismic data
17907e	North Labuan Basin	Pre-basement	4.83	6.09	3.49	3.49	0.24	3.51	3.51	5.07	6.23	Reflection seismic data
17907e	North Labuan Basin	Intra-basement	5.07	6.23	4.19	4.1	1.35	4.21	4.2	6.42	6.88	Refraction first breaks
17907e	North Labuan Basin	Intra-basement	6.42	6.88	n/a	5.3	0.95	n/a	5.4	7.37	7.23	Refraction first breaks
17907e	North Labuan Basin	Intra-basement	7.37	7.23	n/a	6.4	N/a	n/a	6.5	N/a	N/a	Refraction first breaks
18001b	Central Labuan Basin	Water	0	0	1.49	1.49	4.8	1.51	1.51	4.8	6.39	Reflection seismic data
18001b	Central Labuan Basin	Upper Miocene	4.8	6.39	1.59	1.79	0.29	1.61	1.81	5.09	6.72	Reflection seismic data
18001b	Central Labuan Basin	Near Eocene	5.09	6.72	1.74	2.19	0.48	1.76	2.21	5.57	7.16	Reflection seismic data
18001b	Central Labuan Basin	Near Campanian	5.57	7.16	2.09	2.59	0.48	2.11	2.61	6.05	7.52	Reflection seismic data
18001b	Central Labuan Basin	Campanian	6.05	7.52	3.99	3.29	N/a	4.01	3.31	N/a	N/a	Refraction first breaks
18001d	Central Labuan Basin	Water	0	0	1.49	1.49	4.52	1.51	1.51	4.52	6.02	Reflection seismic data
18001d	Central Labuan Basin	Oligocene	4.52	6.02	1.54	1.74	0.35	1.56	1.76	4.87	6.42	Reflection seismic data
18001d	Central Labuan Basin	Tertiary	4.87	6.42	1.99	2.19	0.44	2.01	2.21	5.31	6.83	Reflection seismic data
18001d	Central Labuan Basin	SKVP basement	5.31	6.83	2.59	2.59	0.3	2.61	2.61	5.61	7.05	Reflection seismic data
18001d	Central Labuan Basin	Intra-basement	5.61	7.05	4.29	3.99	0.4	4.31	4.01	7.01	7.76	Refraction first breaks
18001d	Central Labuan Basin	Intra-basement	7.01	7.76	N/a	N/a	N/a	5.89	5.91	N/a	N/a	Refraction first breaks
18002a	Sth Kerguelen Plateau	Water	0	0	1.49	1.49	1.64	1.51	1.51	1.64	2.19	Reflection seismic data
18002a	Sth Kerguelen Plateau	Tertiary	1.64	2.19	1.59	1.59	0.08	1.61	1.61	1.72	2.28	Reflection seismic data
18002a	Sth Kerguelen Plateau	Tertiary	1.72	2.28	1.69	1.69	.11	1.71	1.71	1.83	2.41	Reflection seismic data
18002a	Sth Kerguelen Plateau	SKVP Basement	1.83	2.41	1.99	1.99	.21	2.01	2.01	2.04	2.62	Reflection seismic data
18002a	Sth Kerguelen Plateau	Intra-basement	2.04	2.62	3.99	3.99	.9	4.01	4.01	2.94	3.07	Refraction first breaks
18002a	Sth Kerguelen Plateau	Intra-basement	2.94	3.07	4.99	4.99	1.49	5.01	5.01	4.43	3.67	Refraction first breaks
18002a	Sth Kerguelen Plateau	Intra-basement	4.43	3.67	5.79	5.79	N/a	5.81	5.81	N/a	N/a	Refraction first breaks
18002b	Sth Kerguelen Plateau	Water	0	0	1.49	1.49	1.77	1.51	1.51	1.77	2.36	Reflection seismic data
18002b	Sth Kerguelen Plateau	Tertiary	1.77	2.36	1.64	1.64	0.3	1.66	1.66	2.07	2.73	Reflection seismic data
18002b	Sth Kerguelen Plateau	SKVP basement	2.07	2.73	2.19	2.19	0.47	2.21	2.21	2.54	3.15	Reflection seismic data
18002b	Sth Kerguelen Plateau	Intra-basement	2.54	3.15	3.79	3.79	0.7	3.81	3.81	3.24	3.52	Refraction first breaks
18002b	Sth Kerguelen Plateau	Intra-basement	3.24	3.52	4.69	4.99	1.03	4.71	5.01	4.27	3.93	Refraction first breaks
18002b	Sth Kerguelen Plateau	Intra-basement	4.27	3.93	5.59	5.39	2.55	5.61	5.41	6.82	4.88	Refraction first breaks
18002b	Sth Kerguelen Plateau	Intra-basement	6.82	4.88	5.99	7.9	N/a	6.01	8.0	N/a	N/a	Refraction first breaks
18003	South Labuan Basin	Water	0	0	1.49	1.49	3.88	1.51	1.51	3.88	5.17	Reflection seismic data
18003	South Labuan Basin	Near Eocene	3.88	5.17	1.59	1.79	0.47	1.61	1.81	4.35	5.69	Reflection seismic data
18003	South Labuan Basin	Near basement	4.35	5.69	1.69	2.29	0.32	1.71	2.31	4.67	5.98	Reflection seismic data

Sonobuoy no	Geographical location	Layer name or no	Depth top	twt top	Input velocity top of layer	Output velocity top of layer	Thickness	Input velocity Bottom of layer	Output velocity Bottom of layer	Depth base	twt base	Model layer based on
18003	South Labuan Basin	Intra-basement	4.67	5.98	2.39	2.79	0.55	2.41	2.81	5.22	6.37	Reflection seismic data
18003	South Labuan Basin	Intra-basement	5.22	6.37	3.32	3.72	0.38	3.34	3.84	5.6	6.57	Reflection seismic data
18003	South Labuan Basin	Intra-basement	5.6	6.57	4.99	4.99	3.71	5.01	5.01	N/a	N/a	Refraction first breaks
18004	South Labuan Basin	water	0	0	1.49	1.49	3.93	1.51	1.51	3.93	5.24	Reflection seismic data
18004	South Labuan Basin	lower Miocene	3.93	5.24	1.54	1.64	0.2	1.56	1.66	4.13	5.49	Reflection seismic data
18004	South Labuan Basin	mid-Eocene	4.13	5.49	1.62	1.82	0.72	1.64	1.84	4.85	6.27	Reflection seismic data
18004	South Labuan Basin	volcanic	4.85	6.27	2.09	2.09	0.28	2.11	2.11	5.13	6.54	Reflection seismic data
18004	South Labuan Basin	basement	5.13	6.54	2.79	3.4	0.37	2.81	3.5	5.5	6.75	Reflection seismic data
18004	South Labuan Basin	Intra-basement	5.5	6.75	4.89	4.8	0.66	4.91	4.9	6.16	7.03	Refraction first breaks
18004	South Labuan Basin	Intra-basement	6.16	7.03	5.79	5.2	1.53	5.81	5.3	7.69	7.61	Refraction first breaks
18004	South Labuan Basin	Intra-basement	7.69	7.61	6.39	5.7	N/a	6.41	5.8	N/a	N/a	Refraction/reflection
18005a	South Labuan Basin	water	0	0	1.49	1.49	4.3	1.51	1.51	4.3	5.73	Reflection seismic data
18005a	South Labuan Basin	mid-Oligocene	4.3	5.73	1.64	1.64	.48	1.66	1.66	4.77	6.31	Reflection seismic data
18005a	South Labuan Basin	mid-Eocene	4.77	6.31	1.69	1.69	.58	1.71	1.71	5.36	7	Reflection seismic data
18005a	South Labuan Basin	Pre-basement	5.36	7	1.84	1.84	.75	1.86	1.86	6.11	7.81	Reflection seismic data
18005a	South Labuan Basin	Intra-basement	6.11	7.81	5.69	6.1	1.16	5.71	6.2	7.22	8.17	Refraction first breaks
18005a	South Labuan Basin	Intra-basement	7.22	8.17	5.89	6.5	3.57	5.91	6.6	7.91	8.38	Refraction first breaks
18005a	South Labuan Basin	Intra-basement	n/a	n/a	6.19	n/a	n/a	6.21	n/a	n/a	n/a	n/a
18005b	South Labuan Basin	Water	0	0	1.49	1.49	4.14	1.51	1.51	4.14	5.52	Reflection seismic data
18005b	South Labuan Basin	Near Oligocene	4.14	5.52	1.59	1.59	0.42	1.61	1.61	4.56	6.04	Reflection seismic data
18005b	South Labuan Basin	Eocene	4.56	6.04	1.79	1.89	0.55	1.81	1.91	5.11	6.62	Reflection seismic data
18005b	South Labuan Basin	Basement	5.11	6.62	2.59	2.69	0.44	2.61	2.71	5.55	6.95	Reflection seismic data
18005b	South Labuan Basin	Intra-basement	5.55	6.95	4.99	4.9	0.68	5.01	5.0	6.23	7.22	Refraction first breaks
18005b	South Labuan Basin	Intra-basement	6.23	7.22	4.69	5.9	1.07	5.71	6.0	7.3	7.58	Refraction first breaks
18005b	South Labuan Basin	Intra-basement	7.3	7.58	none	6.5	N/a	none	6.6	N/a	N/a	Refraction first breaks
18005c	Sth Kerguelen Plateau	Water	0	0	1.49	1.49	2.81	1.51	1.51	2.81	3.74	Reflection seismic data
18005c	Sth Kerguelen Plateau	Pre-basement	2.81	3.74	2.09	2.09	0.22	2.11	2.11	3.03	3.96	Refraction first breaks
18005c	Sth Kerguelen Plateau	Intra-basement	3.03	3.96	3.99	3.8	0.64	4.01	3.9	3.67	4.29	Refraction first breaks
18005c	Sth Kerguelen Plateau	Intra-basement	3.67	4.29	4.49	5.1	0.8	4.51	5.2	4.47	4.6	Refraction first breaks
18005c	Sth Kerguelen Plateau	Intra-basement	4.47	4.6	5.09	5.9	3.0	5.11	6.0	7.47	5.61	Refraction first breaks
18005c	Sth Kerguelen Plateau	Intra-basement	n/a	n/a	5.59	n/a	n/a	5.61	n/a	n/a	n/a	n/a
18006c	Central Labuan Basin	water	0	0	1.49	1.49	4.09	1.51	1.51	4.09	5.45	Reflection seismic data
18006c	Central Labuan Basin	lower Miocene	4.09	5.45	1.54	1.8	0.31	1.56	2	4.4	5.77	Reflection seismic data

Sonobuoy no	Geographical location	Layer name or no	Depth top	twt top	Input velocity top of layer	Output velocity top of layer	Thickness	Input velocity Bottom of layer	Output velocity Bottom of layer	Depth base	twt base	Model layer based on
18006c	Central Labuan Basin	Pre-basement	4.4	5.77	1.59	2.2	0.23	1.61	2.4	4.63	5.98	Reflection seismic data
18006c	Central Labuan Basin	Intra-basement	4.63	5.98	3.29	3.5	0.59	3.31	3.6	5.22	6.31	Refraction first breaks
18006c	Central Labuan Basin	Intra-basement	5.22	6.31	3.69	4.4	0.46	3.71	4.5	5.68	6.52	Refraction first breaks
18006c	Central Labuan Basin	Intra-basement	5.68	6.52	4.69	5	1.83	4.71	5.1	7.51	7.24	Refraction first breaks
18006c	Central Labuan Basin	Intra-basement	7.51	7.24	4.99	6.9	N/a	5.01	7.0	N/a	N/a	Refraction first breaks
18008	Central Labuan Basin	water	0	0	1.49	1.49	4.79	1.51	1.51	4.79	6.39	Reflection seismic data
18008	Central Labuan Basin	Upper Miocene	4.79	6.39	1.59	1.59	0.21	1.61	1.61	5	6.65	Reflection seismic data
18008	Central Labuan Basin	Eocene	5	6.65	1.99	1.79	0.6	2.01	1.81	5.6	7.32	Reflection seismic data
18008	Central Labuan Basin	Campanian	5.6	7.32	2.29	2.09	0.34	2.31	2.11	5.94	7.64	Reflection seismic data
18008	Central Labuan Basin	basement	5.94	7.64	2.79	2.49	0.44	2.81	2.51	6.38	7.99	Reflection seismic data
18008	Central Labuan Basin	Intra-basement	6.38	7.99	3.99	4.29	1.14	4.01	4.31	7.52	8.52	Refraction first breaks
18008	Central Labuan Basin	Intra-basement	7.52	8.52	5.49	5.24	n/a	5.51	5.26	N/a	N/a	Refraction first breaks

Appendix 9: Summary of refraction-derived crustal thickness and velocity estimates.

Reference	Location/Basin/Sonobuoy No	Name layer	Layer thickness (km)	Velocity (km/s)	Geological interpretation/comments
Charvis & Operto (1999)	Enderby Basin & basement	Sediments	0.03-0.3	1.6	Pelagic sediments
Charvis & Operto (1999)	Enderby Basin & basement	Upper crust	1.5-3.7	5.0-6.5	Oceanic crust layer
Charvis & Operto (1999)	Enderby Basin & basement	Lower crust	8.3-11.5	6.7-7.3	Thickened oceanic crust
Charvis & Operto (1999)	Kerguelen-Heard Basin & basement	Sediments	1.2-2.3	3.8-4.9	Low density basaltic lavas intercalated with volcano-sedimentary material
Charvis & Operto (1999)	Kerguelen-Heard Basin & basement	Upper crust	2.3-3.3	4.7-6.7	Basaltic layer
Charvis & Operto (1999)	Kerguelen-Heard Basin & basement	Lower crust	17	6.6-7.4	Thickened oceanic crust
Gladczenko & Coffin (2001)	Elan Bank & basement RS179-701-SB1	H1	4.48	1.9	sediments
Gladczenko & Coffin (2001)	Elan Bank & basement RS179-701-SB1	H2	0.42	2.5	Sediments
Gladczenko & Coffin (2001)	Elan Bank & basement RS179-701-SB1	H3	0.35	2.8	Sediments
Gladczenko & Coffin (2001)	Elan Bank & basement RS179-701-SB1	H4	0.93	5.4	Upper crust extrusives
Gladczenko & Coffin (2001)	Elan Bank & basement RS180-801-SB2	H1	4.76	2.1	Sediments
Gladczenko & Coffin (2001)	Elan Bank & basement RS180-801-SB2	H2	1.3	3.4	Sediments
Gladczenko & Coffin (2001)	Elan Bank & basement RS180-801-SB2	H3	1.1	5.0	Upper crust extrusives
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-704-SB3	H1	3.56	1.6	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-704-SB3	H2	0.24	1.9	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-704-SB3	H3	0.43	2.4	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-704-SB3	H4	0.93	4.3	Upper crust extrusives
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-704-SB3	H5	1.98	5.6	Mid-crust intrusives
Gladczenko & Coffin	Labuan Basin & basement RS179-705-	H1	3.68	1.6	Sediments

(2001)	SB4				
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB4	H2	0.33	2.1	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB4	H3	0.74	2.7	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB4	H4	0.75	3.9	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB4	H5	1.33	5.4	Upper crust extrusives
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB5	H1	3.75	1.6	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB5	H2	0.2	2.4	Sediments
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB5	H3	1.38	4.7	Upper crust extrusives
Gladczenko & Coffin (2001)	Labuan Basin & basement RS179-705-SB5	H4	1.24	6.2	mid-crust intrusives
Konnecke et al. (1998)	Ragatt Basin & basement	P1	< 0.5	2.5-3.1	Sediments, Lower Tertiary
Konnecke et al. (1998)	Ragatt Basin & basement	K3	< 0.5	3.1-4.1	Sediments, Upper Cretaceous
Konnecke et al. (1998)	Ragatt Basin & basement	K2	< 1.5	2.2-2.9	Terrestrial & terrigenous sediment, Lower Cretaceous
Konnecke et al. (1998)	Ragatt Basin & basement	Basement crust 2	< 2.0	4.6-4.7	Thin basalt flows intercalated with sediment
Konnecke & Coffin (1998)	Ragatt Basin & basement	Basement crust 1	> 3.0	4.7-5.9	Thick basalt flows
Operto & Charvis (1996)	Ragatt Bsin & basement	Sediments	1.0-2.3	1.7-3.4	Sediments
Operto & Charvis (1996)	Ragatt Basin & basement	Upper crust	4.5-6.5	4.8-6.2	Upper crust, basalts
Operto & Charvis (1996)	Ragatt Basin & basement	Lower crust	14	6.6-7.3	Lower crust, thickened oceanic crust, Mg rich gabbros at base with intercalated ultramafics
Charvis *et al.* (1993)	Kerguelen-Heard Basin & basement	Sediments	2.2-2.9	1.7	Sediments
Charvis *et al.* (1993)	Kerguelen-Heard Basin & basement	Upper crust	3.0-3.8	4.3-5.5	Oceanic layer
Charvis *et al.* (1993)	Kerguelen-Heard Basin & basement	Lower crust	17.2-17.8	6.6-7.3	Thickened oceanic crust
Borissova *et al*. (this volume)	North Labuan Basin & basement	Sediments	< 2.6	< 3.8	Sediments, Campanian to recent
Borissova *et al*. (this volume)	North Labuan Basin & basement	Basement	< 5.0	3.4-6.6	Oceanic crust, basalts and low velocity intrusives

Borissova *et al*. (this volume)	North Labuan Basin & basement	Mantle	Not applicable	7.7-8.2	Mantle velocities
Borissova *et al*. (this volume)	Central Labuan Basin & basement	Sediments	< 1.5	1.8-3.3	Sediments, Campanian to recent
Borissova *et al*. (this volume)	Central Labuan Basin & basement	Basement	unknown	3.5-7.0	Oceanic crust, basalts, low velocity intrusives, gabbros
Borissova *et al*. (this volume)	Southern Kerguelen Plateau	Sediments	< 1.5	1.6-2.8	Sediments, Campanian to recent
Borissova *et al*. (this volume)	Southern Kerguelen Plateau	Basement	< 5.0	3.7-5.8	Oceanic crust, basalts and low velocity intrusives
Borissova *et al*. (this volume)	Southern Kerguelen Plateau	Mantle	Not applicable	7.9-8.0	Mantle velocities
Borissova *et al*. (this volume)	Southern Labuan Basin	Sediments	< 2.5	1.6-3.5	Sediments, Campanian to recent
Borissova *et al*. (this volume)	Southern Labuan Basin	Basement	unknown	3.8-6.6	Oceanic crust, basalts and low velocity intrusives

Appendix 10: Interpreted seismic sequences and correlation with previous work.

Sequence (this study)	**Boundary horizon**		**Age**	**Lithology from the ODP drillholes, seafloor cores and dredges**	**Correlations**			
	upper	lower			Colwell et al., 1988	Coffin et al., 1990		
Plio-Pleis	wb	miou	Pliocene-Pleistocene	Diatom ooze	A	NQ1		
Miol-miou	miou	miol	Lower Miocene–Upper Miocene	Diatom and nannofossil ooze				
Olig-miol	miol	olig	Oligocene – Lower Miocene	Calcareous ooze and some chert	B	PN1		
Eoc-olig	olig	eoc	Middle Eocene – Oligocene	Nannofossil ooze, chalk and chert	C	P2		
Pal-eoc	eoc	pal	Palaeocene – Middle Eocene	Nannofossil ooze and chalk	E	P1		
Maas-pal	pal	maas	Maastrichtian - Palaeocene	Nannofossil ooze, chalk, chert, conglomerate			K3	
Camp-maas	maas	camp	Campanian – Maastrichtian	Limestone, grainstone, chalk				K2
Alb-camp	camp	alb	Albian - Campanian	Limestone, chalk, sandstone, claystone				
Pre-alb - alb (?)	alb	pre-alb	Aptian – Albian(?)	Silty clay, coal, claystone	F	K1		
Bment-pre-alb (?)	pre-alb	Base ment	Valanginian – Aptian (?)	unknown				

Appendix 11: Seismic well ties for ODP wells Leg 119

Horizon	Age	ODP 736		ODP 737		ODP 738		ODP 744		ODP 746	
		Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)
miol	Lower Miocene			275	0.380	17	0.025				
olig	Oligocene			320	0.470	17	0.025				
eoc	Eocene			383	0.500						
other	mid/U Eocene unconf.			668	0.770						
maas	Maastrichtian					377	0.395				
camp	Campanian unconf.					437	0.442				
Basement	Barremian-Albian					496	0.474				
TD		371 Late E. Pliocene		715 Mid Eocene	0.805	534 Mid Eocene	0.494	176 Late Eocene		281 Late Miocene	

The principal source for the time and depth picks is the ODP Initial Report, volume 119 (Barron, Larson et al , 1989).
Seismic two-way times and depths are measured from sea floor.
Where the well terminated in basalts, and the basement lies below TD, its depth is (estimated) by using interval velocity of 4 km/sec in the basalt flows near and below TD.
Other (estimated) depths to horizons, eg at shallow levels, are those used in the ODP Initial Reports.

Appendix 12: Seismic well ties for ODP wells Leg 120

Horizon	Age	ODP 747		ODP 748		ODP 749		ODP 750		ODP 751	
		Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)
miol	Lower Miocene	125	0.150	69	0.09					(185)	0.240
olig	Oligocene .	151	0.190	124	0.160						
eoc	Middle Eocene.	173	0.210	243	0.290						
pal	Danian	182	0.220	408	0.450			317?	0.355		
maas	Maastrichtian	189	(0.230)	416	0.460			357	0.372		
camp	Campanian unconf.			685	0.630			526	0.560		
tdr	Top volcanics			899	0.830						
Basement	Barremian-Albian	297	0.350	1082	0.920	202	0.240	675	0.620		
TD		350.5	(0.376)	935	(0.938)	249.5	0.264	710	0.637	166	0.221

The principal source for the time and depth picks is the ODP Initial Report, volume 120 (Wise, Schlich et al., 1989).
Seismic two-way times and depths are measured from sea floor.
Where the well terminated in basalts, and the basement lies below TD, its depth is (estimated) by using interval velocity of 4 km/sec in the basalt flows near and below TD. Other (estimated) depths to horizons, eg at shallow levels, are those used in the ODP Initial Reports.

Appendix 13: Seismic well ties for ODP wells Leg 183

Horizon	Age	ODP 1135		ODP 1136		ODP 1137		ODP 1138		ODP 1139		ODP 1140	
		Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)	Depth (m)	TWT (s)
Miou	Upper Miocene							105	0.132	18	0.024		
Miol	Lower Miocene							266	0.327				
Olig	Oligocene					113	0.150			376	0.350		
Eoc	Eocene	131	0.165			198	0.228			461	0.401		
pal	Danian	247	0.298					489	0.547				
Maas	Maastrichtian	260	0.318					489	0.547				
Camp	Campanian unconf.	373	0.425			198	0.228	600	0.632				
NKP basement	Oligocene (32.8-34.3 Ma)											235	0.280
CKP and SKP basement	Barremian-Albian (117-102 Ma)			128	0.145			698	(0.701)				
EBB (top Volcnics)	Albian-Aptian. (108-110 Ma)					228	0.255						
TD		526	0.568	161	0.171	371	(0.320)	843	(0.788)	694	(0.535)	322	(0.328)

The principal source for the time and depth picks is the ODP Initial Report, volume 183 (Coffin, Frey, Wallace et al., 2000).
Seismic two-way times and depths are measured from sea floor.
Where the well terminated in basalts, and the basement lies below TD, its depth is (estimated) by using interval velocity of 4 km/sec in the basalt flows near and below TD.
Other (estimated) depths to horizons, eg at shallow levels, are those used in the ODP Initial Reports.

Appendix 14: Tectonic events in the Kerguelen Region

AGE	REGIONAL TECTONIC EVENTS AND CHANGES IN PALEOENVIRONMENT	KERGUELEN PLATEAU
Oxfordian – Valanginian (160 – 131 Ma)	Gondwana breakup - triple junction around India, Antarctica and Australia	Continental fragments may have existed prior to formation of the Kerguelen Large Igneous Province.
Hauterivian-Albian (131 - 97 Ma)	Bunbury Basalts in Western Australia (132-122 Ma). Rajmahal Flood Basalts (118-115 Ma) in eastern India. A rift jump in the Albian tranfers Elan Bank from Indian to Antartctic Plate. Development of the extensional rift system along the future locus of breakup between Australia and Antarctica.	Formation of the Kerguelen LIP with magmatic output culminating in the Albian. Eruptions close to or above the sea level. Subaerial lava flows on SKP and Elan Bank. Beginning of subsidence with deposition of shallow water sands and clays.
Cenomanian - Santonian (97 - 83 Ma)	Continuing extension between Australia and Antarctica. Start of fast movement of India to the north in the Santonian.	Extensional faulting and formation of peridotite intrusions in Diamantina Zone/Labuan Basin. Rapid deepening of the Labuan Basin. Gradual change from non-marine to marine conditions across most of the plateau by the Santonian.
Campanian - MiddleEocene (83 - 45 Ma)	Breakup along most of the Southern margin of Australia in the Campanian (80 Ma). Slow spreading at the SEIR followed by fast spreading from about 52 Ma. Formation of the Ninetyeast Ridge (82-38 Ma), possibly by the Kerguelen Plume Tail.	Extension and formation of a major rift systems on the KP (77^0 E and 59^0 S grabens and SKP rift) between 75 and 69 Ma. Uplift and normal faulting of the western part of the Raggatt Basin. Subsidence at a rate of about 20 m/m.y. Pelagic sedimentation prevails.
Middle Eocene - Oligocene (45 - 34 Ma)	SEIR intersects the Kerguelen Plume and the hotspot magmatism becomes confined to the Antarctic Plate. Labuan Basin separates from Diamantina Zone followed by separation of NKP and Broken Ridge (43.8 and 42.9 Ma). New current system starts to develop in the Southern Ocean.	Eastern part of the KP uplifted close to the sea level and eroded. Faults are reactivated on the plateau and in the Labuan Basin. Renewed volcanism on the NKP. Intensification of current activity, local erosion by bottom currents. East Kerguelen Sedimentary Ridge (EKSR) starts to form.
Oligocene - Miocene (34 -24 Ma)	Establishment of the ice sheet on the Antarctic continent between 35 and 36 Ma.	Oligocene sub-marine volcanism on the NKP. Large sedimentary deposits are constructed by bottom currents on the NKP (West Heard Mound, Kerguelen-Heard Basin). Vigorous current activity in the Labuan Basin. Formation of the EKSR continues.
Early Miocene – Recent (24 – 0 Ma)	Antarctica becomes fully glaciated during the Late Miocene. Establishment of the Antarctic Circumpolar Current.	Subsidence accompanied by deposition of pelagic ooze with clastic component derived from the Kerguelen Islands. Change in sedimentation from nannofossil ooze to diatom ooze. Intermittent erosion related to Antarctic Circumpolar Current.

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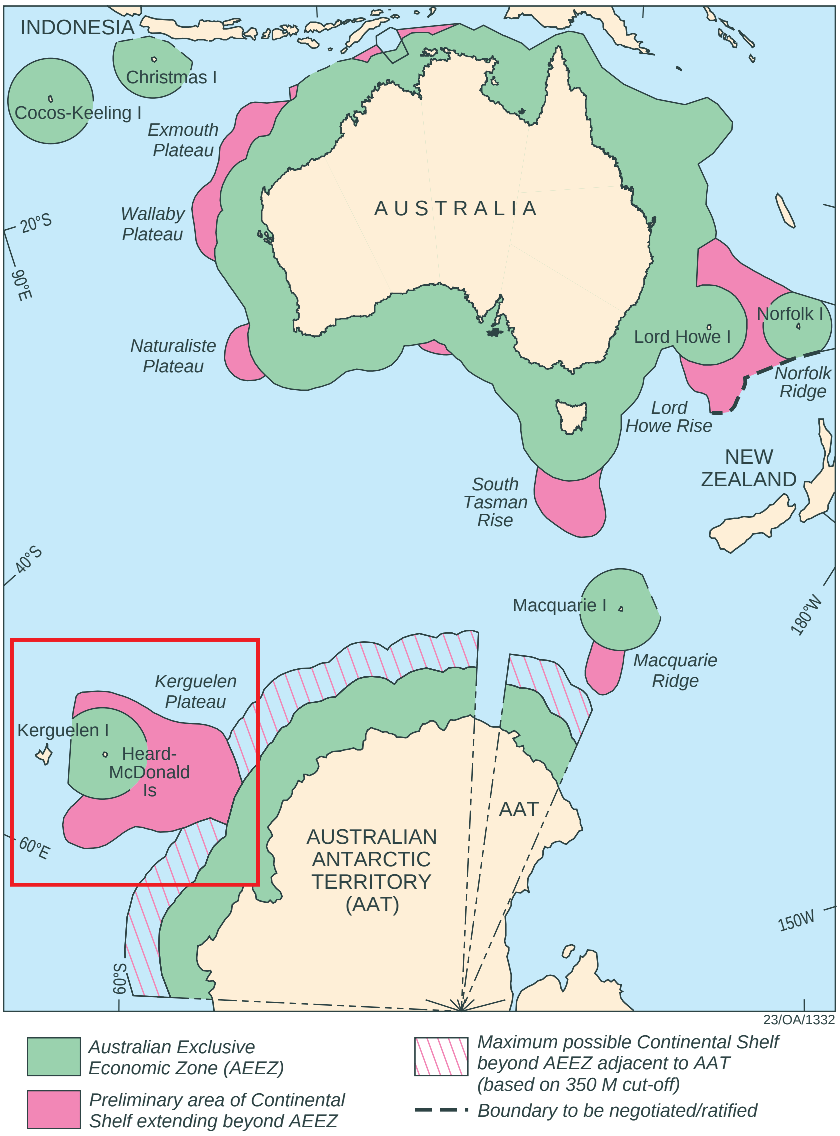

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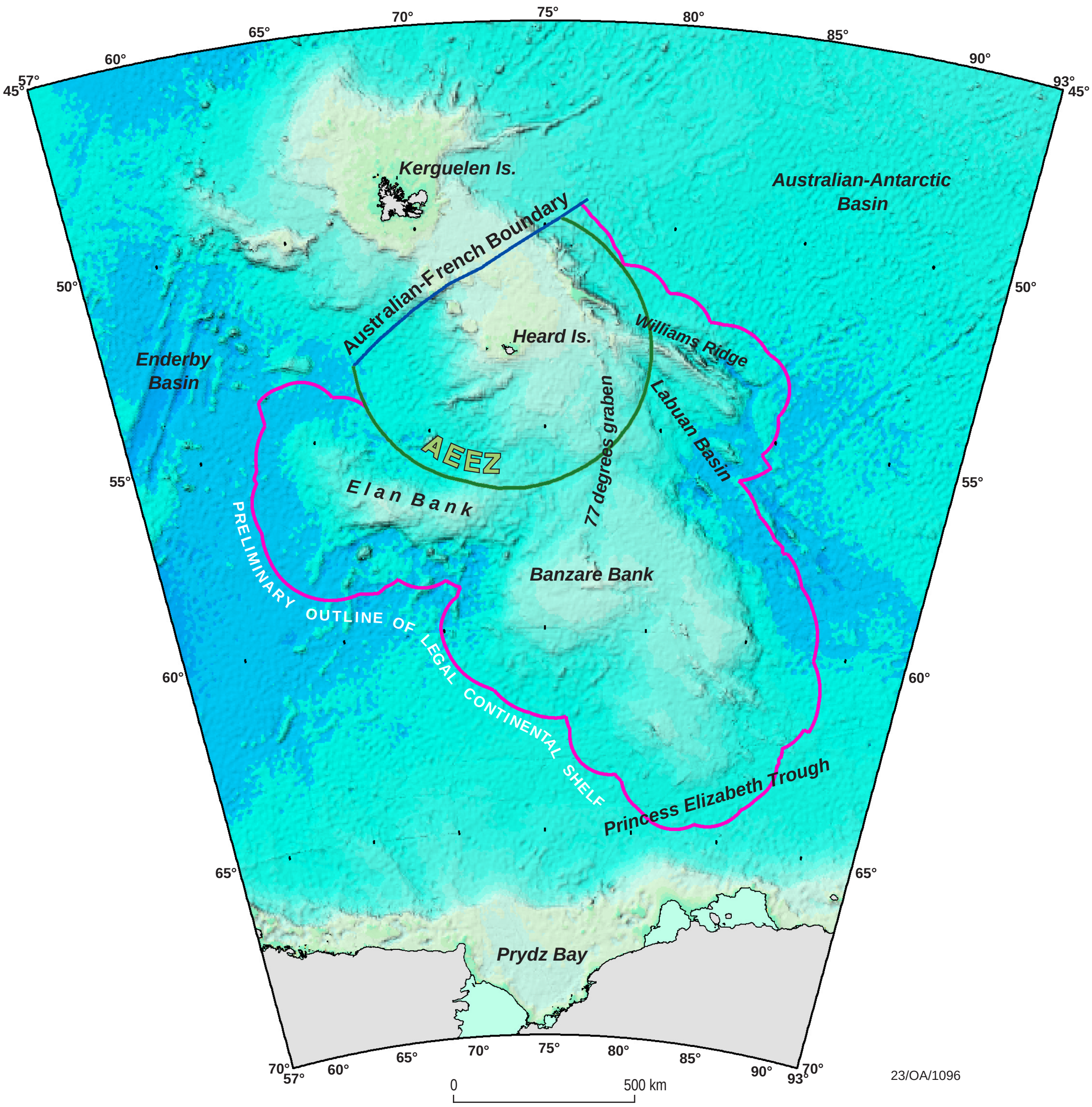

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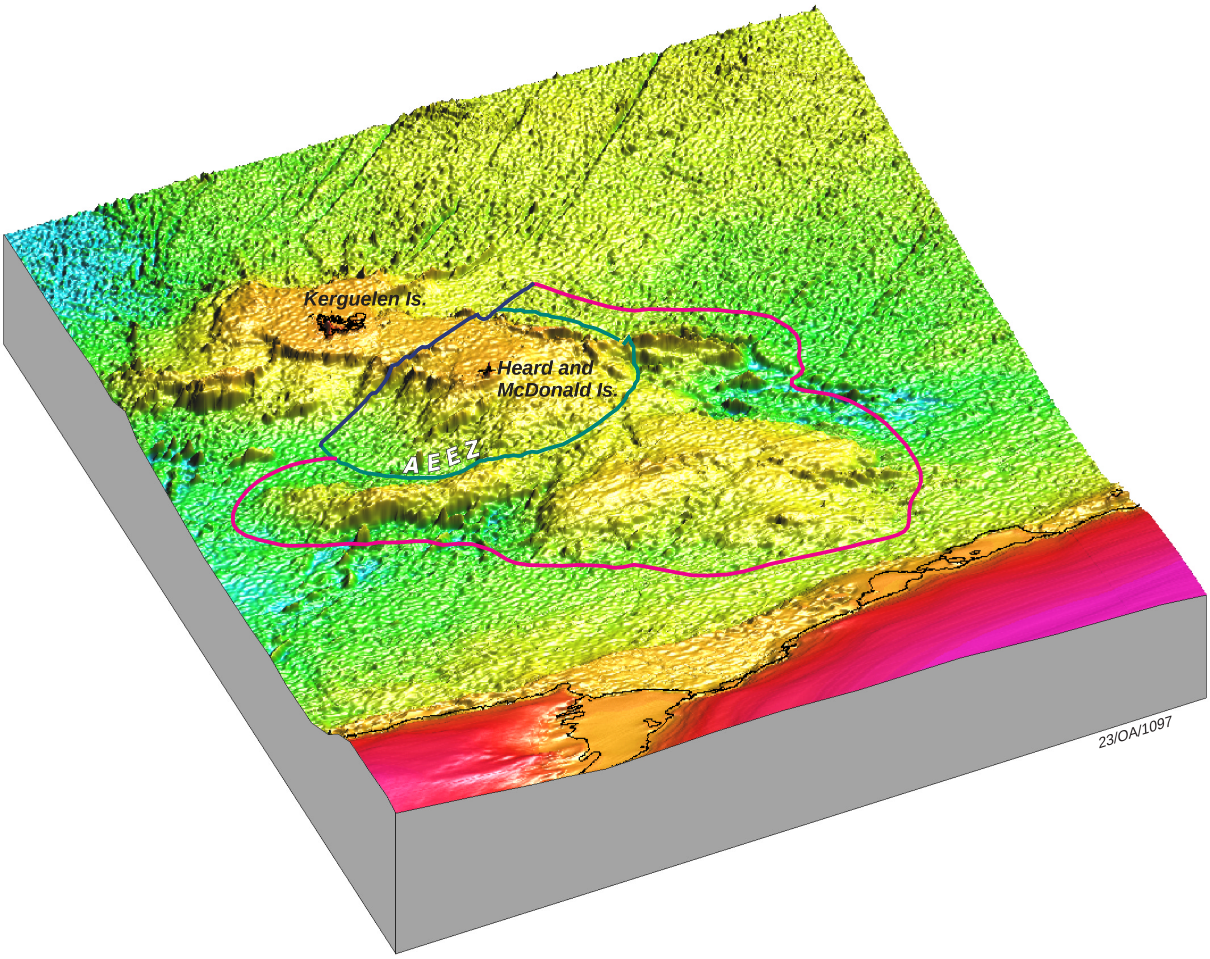

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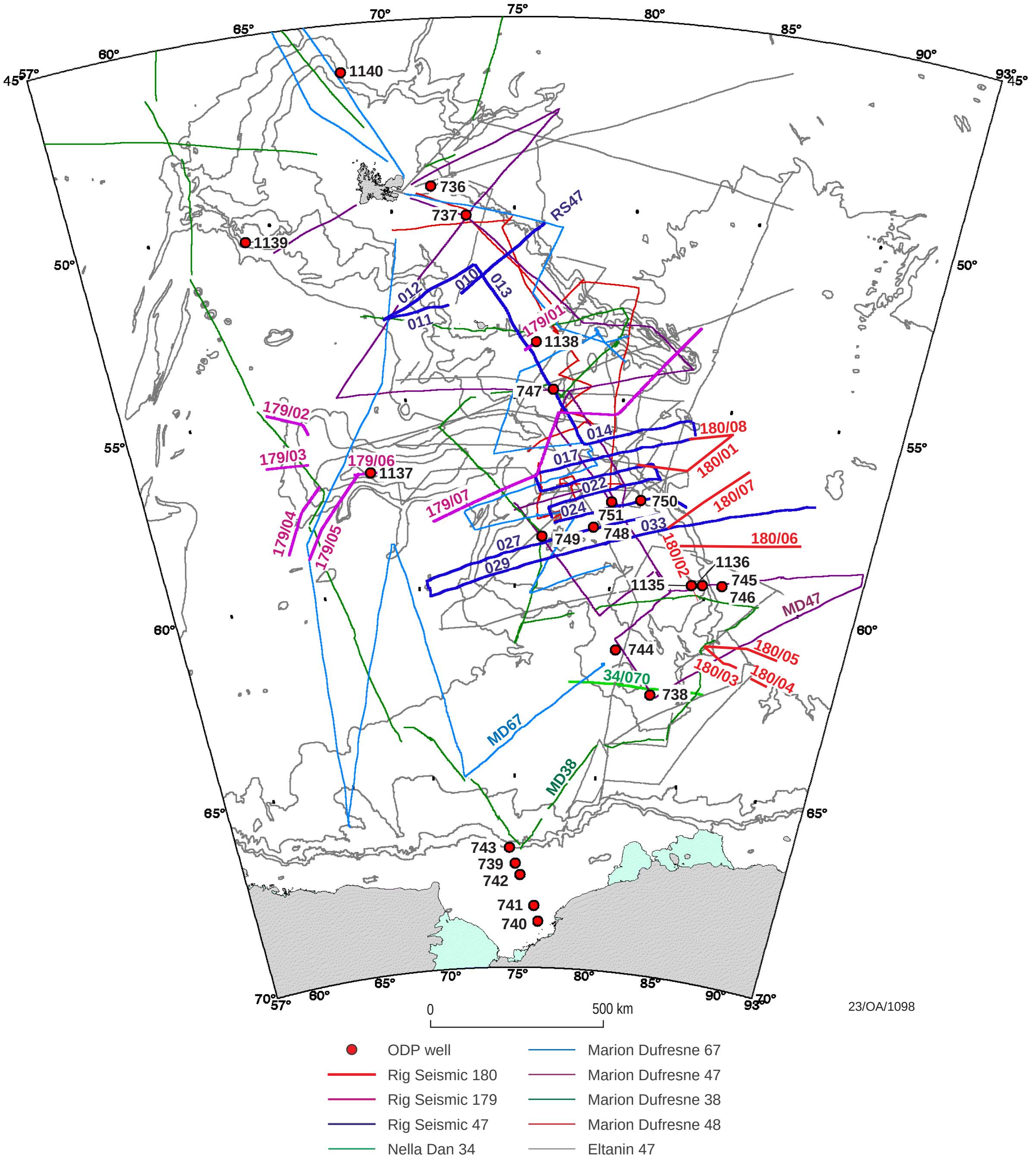

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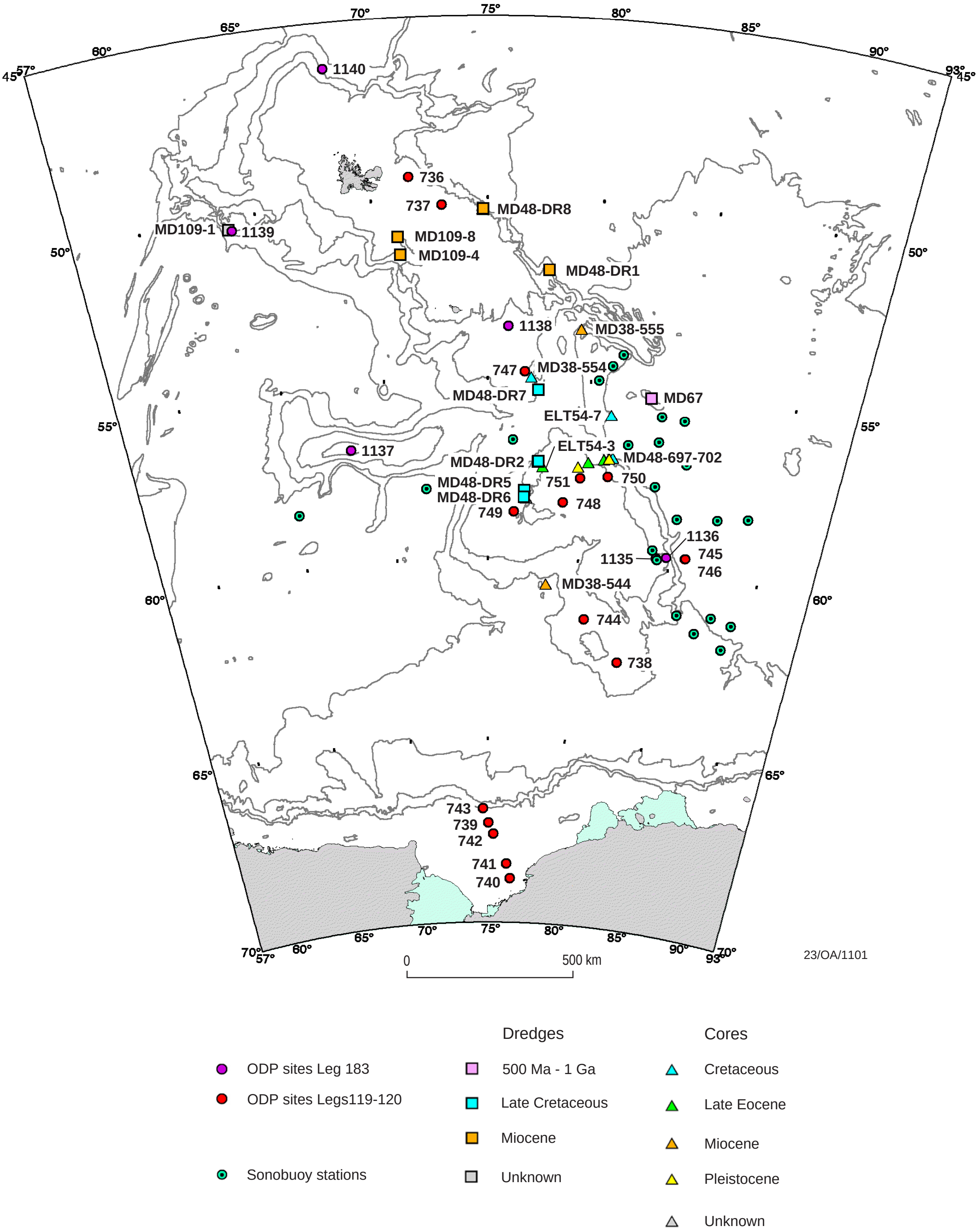

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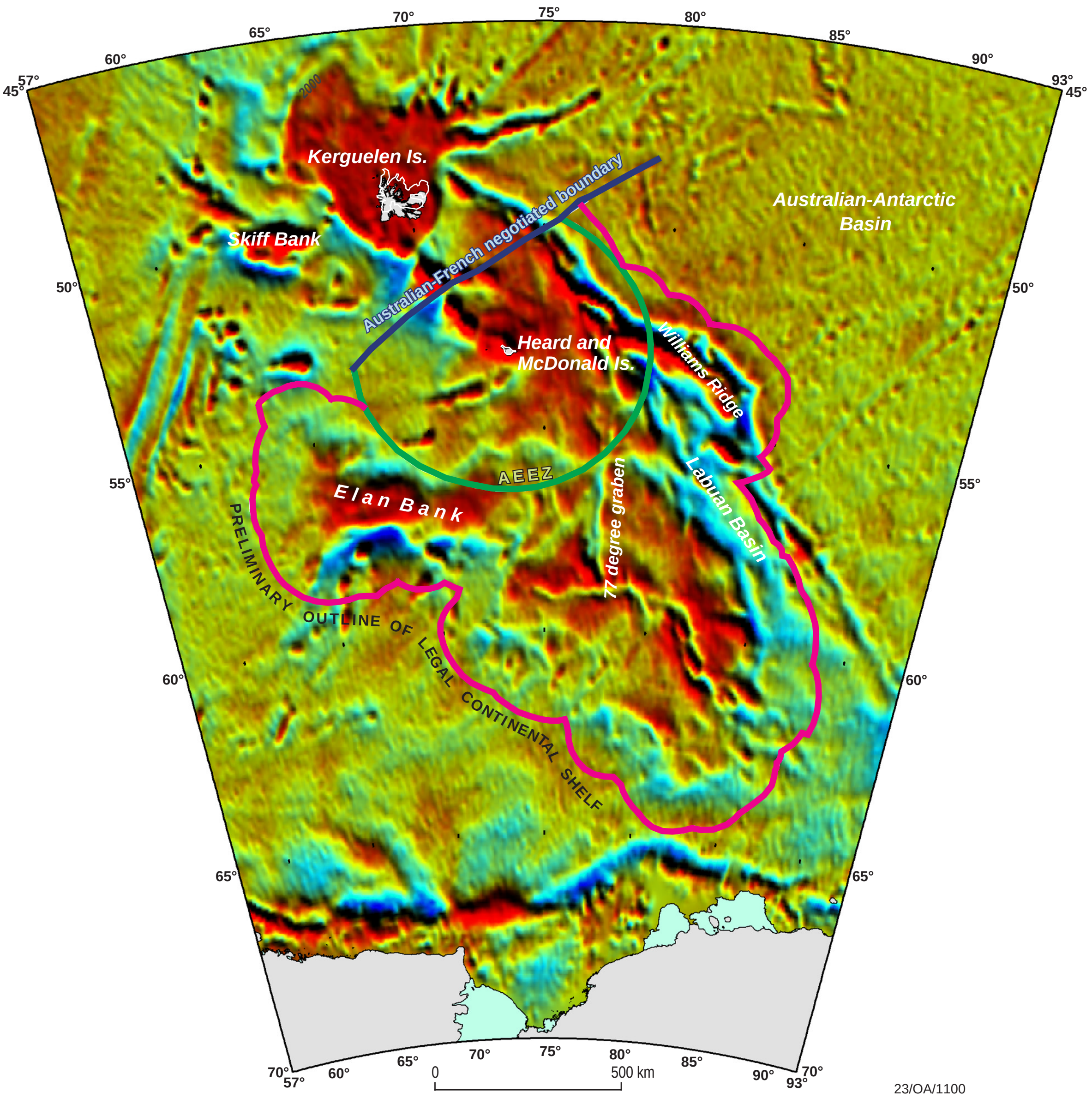

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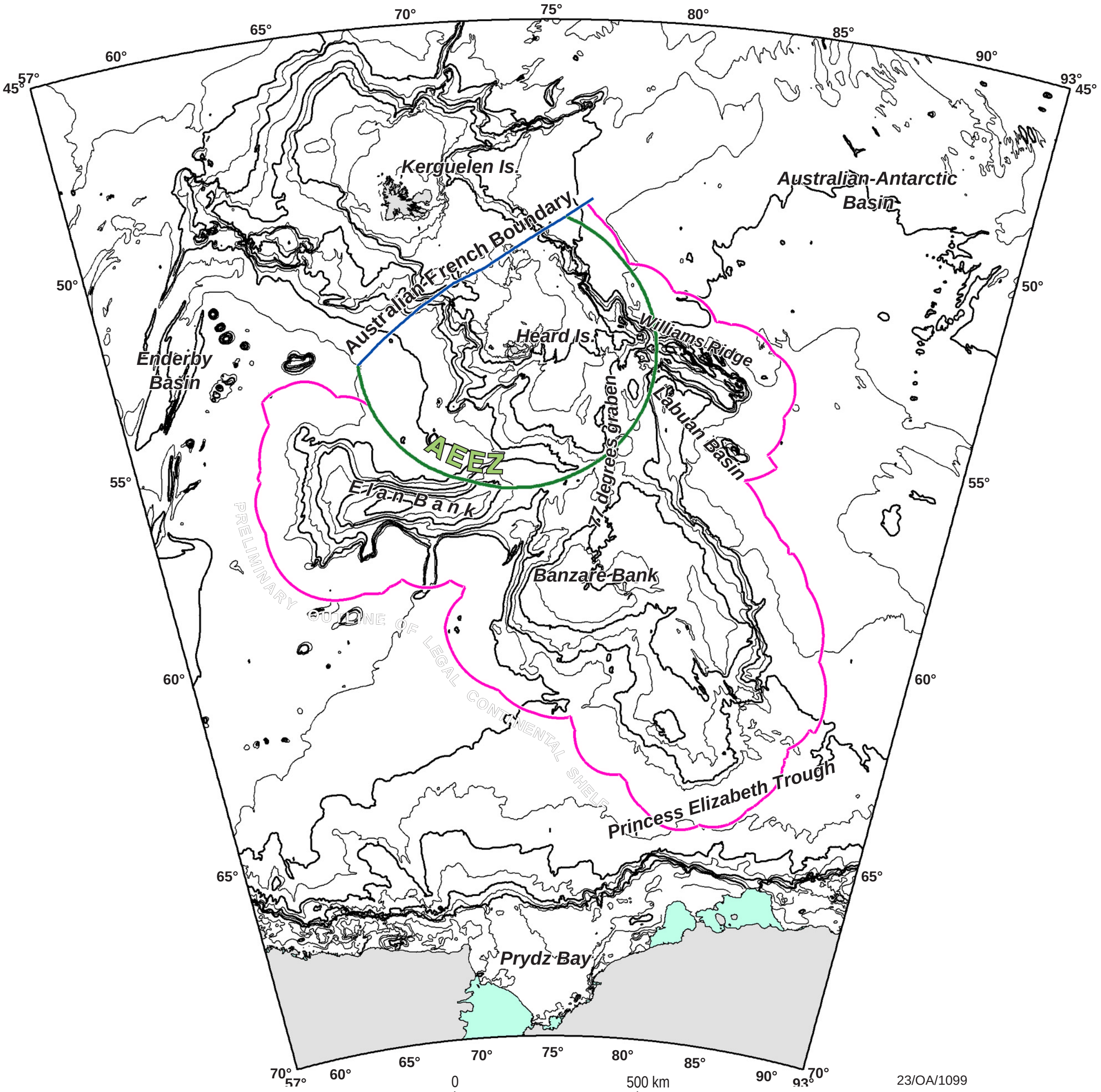

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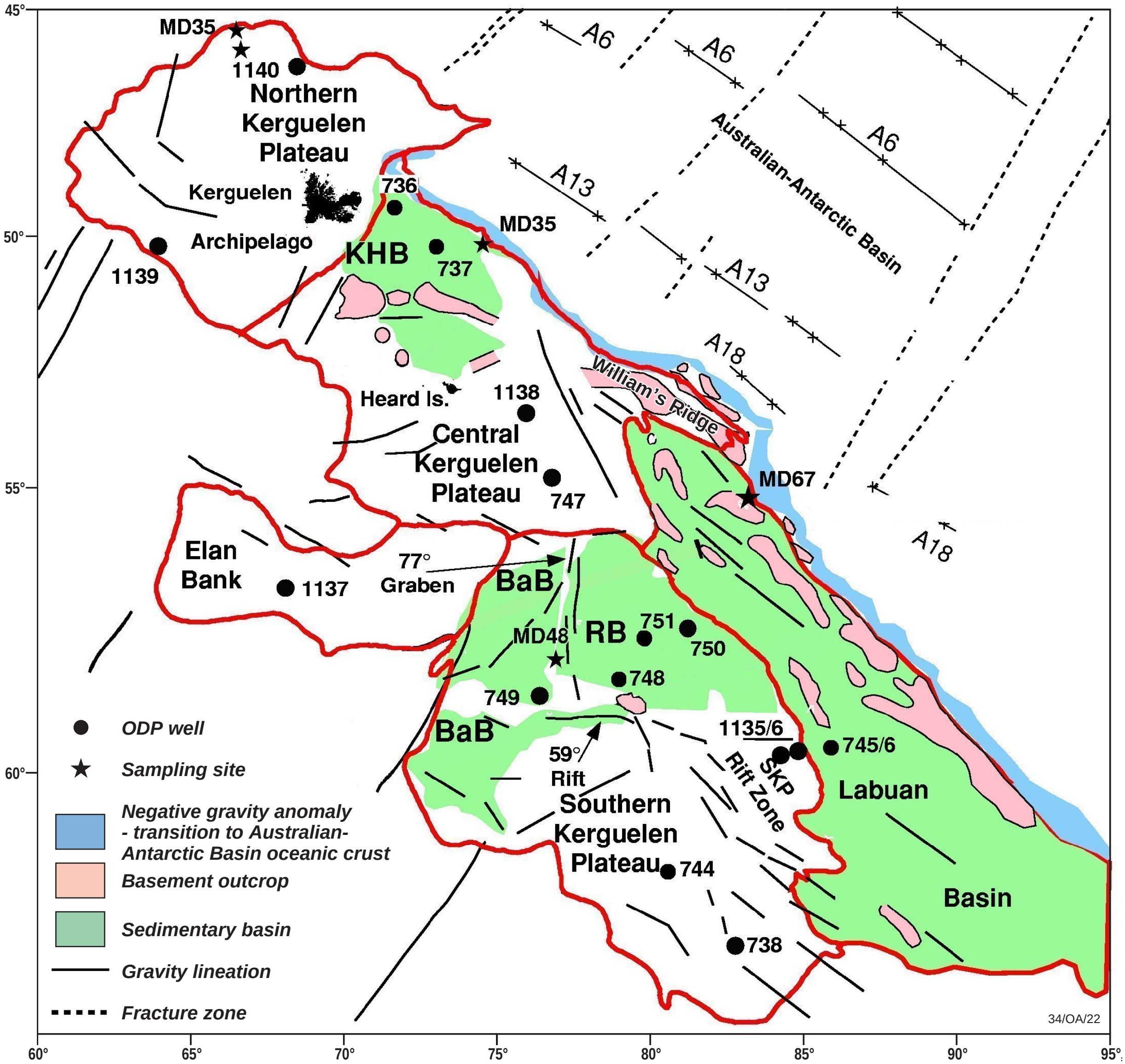

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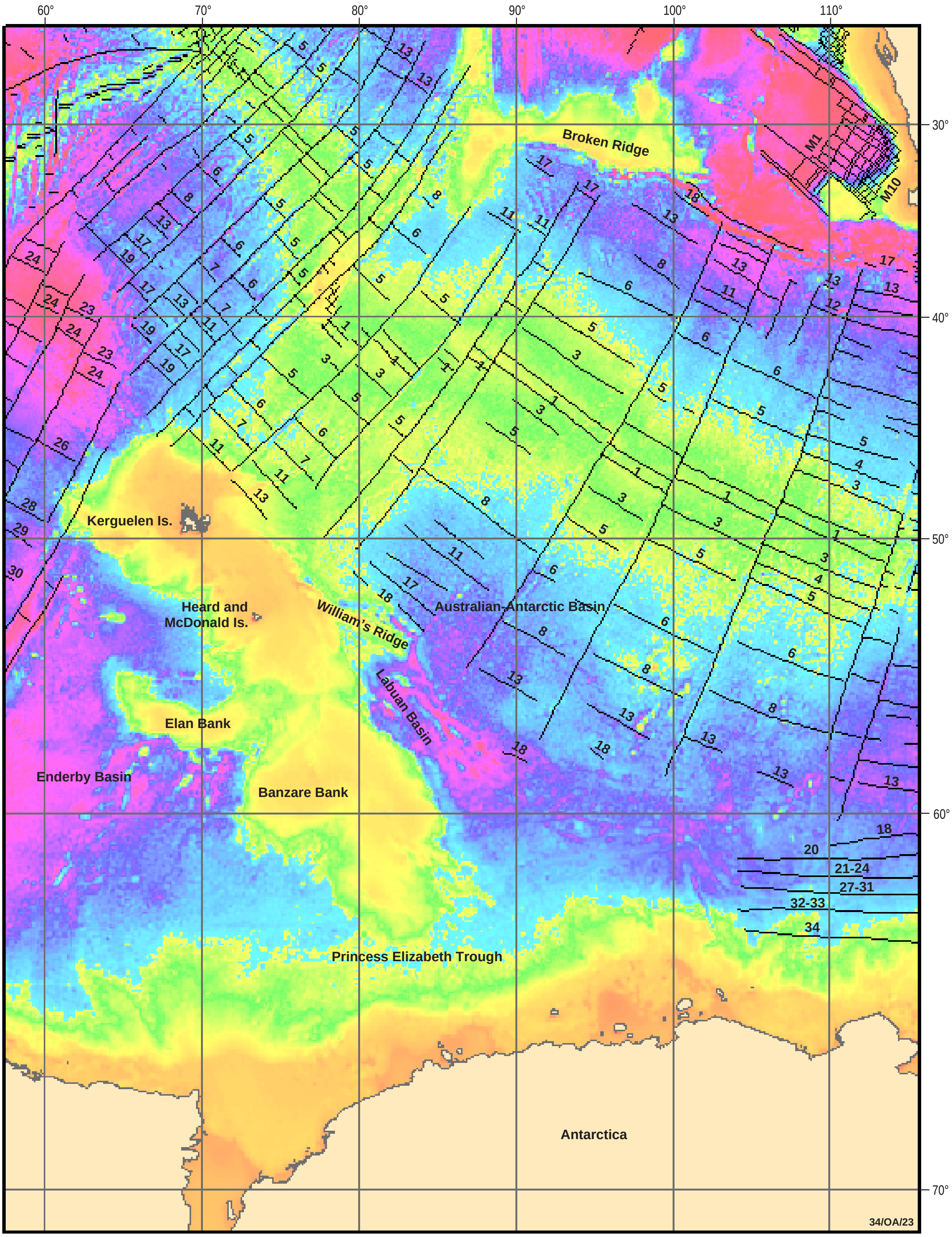

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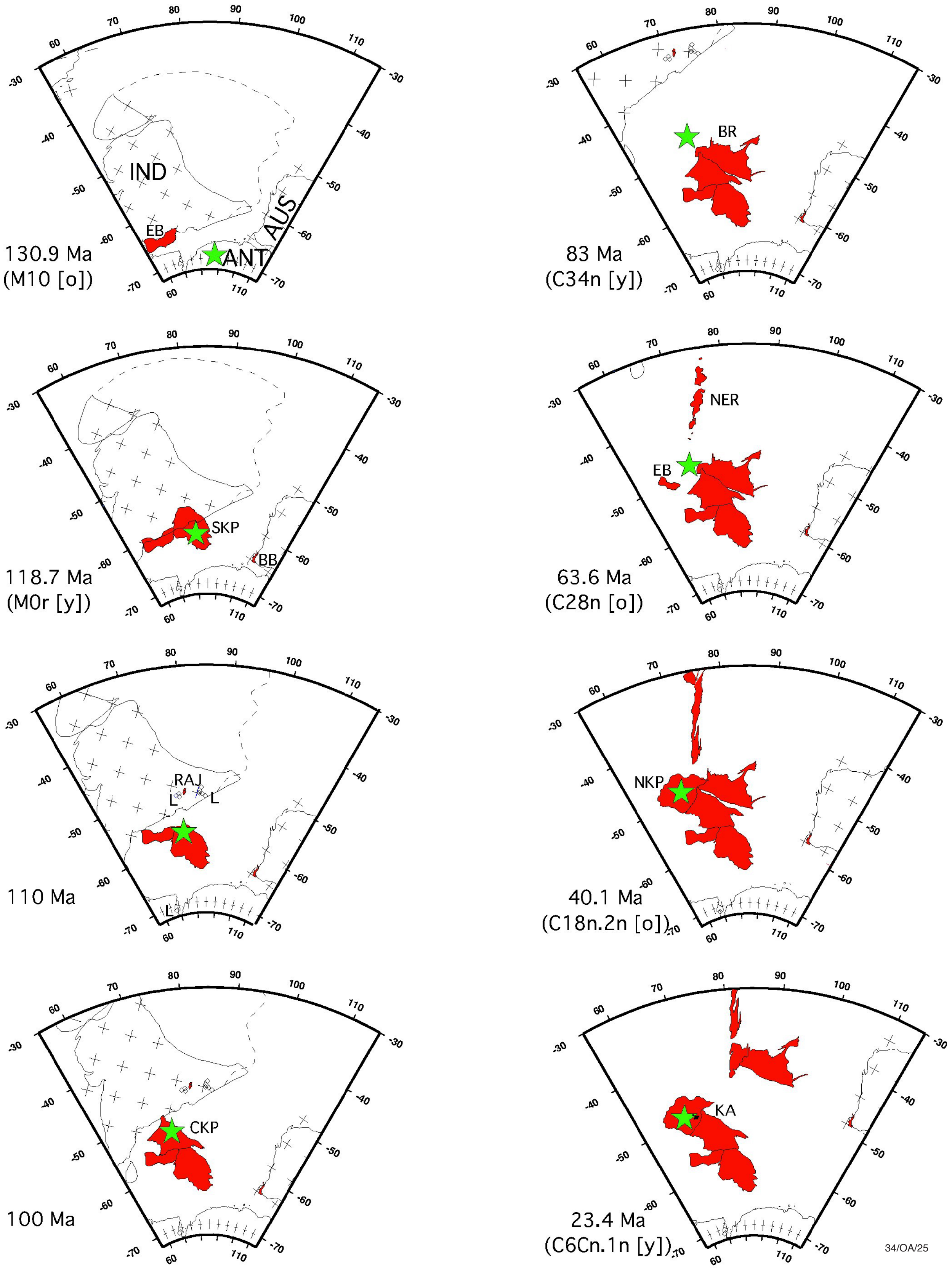

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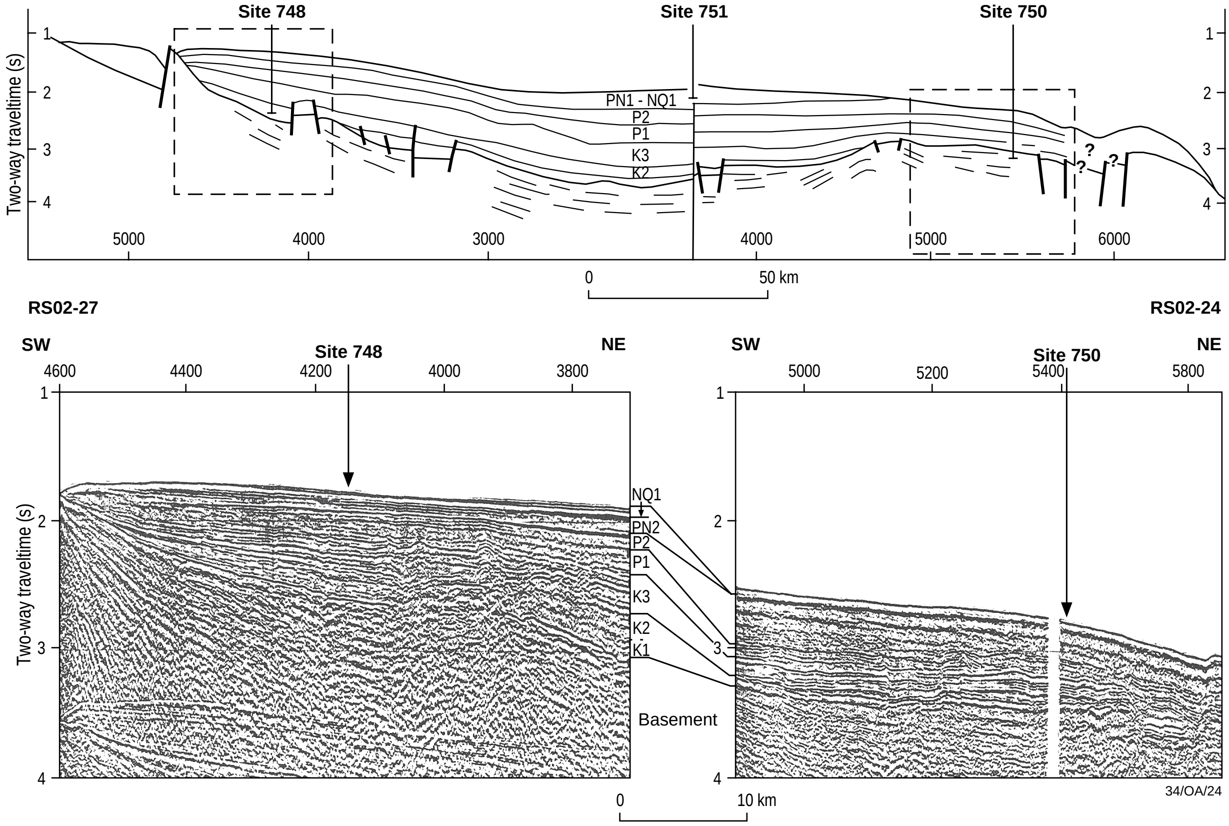

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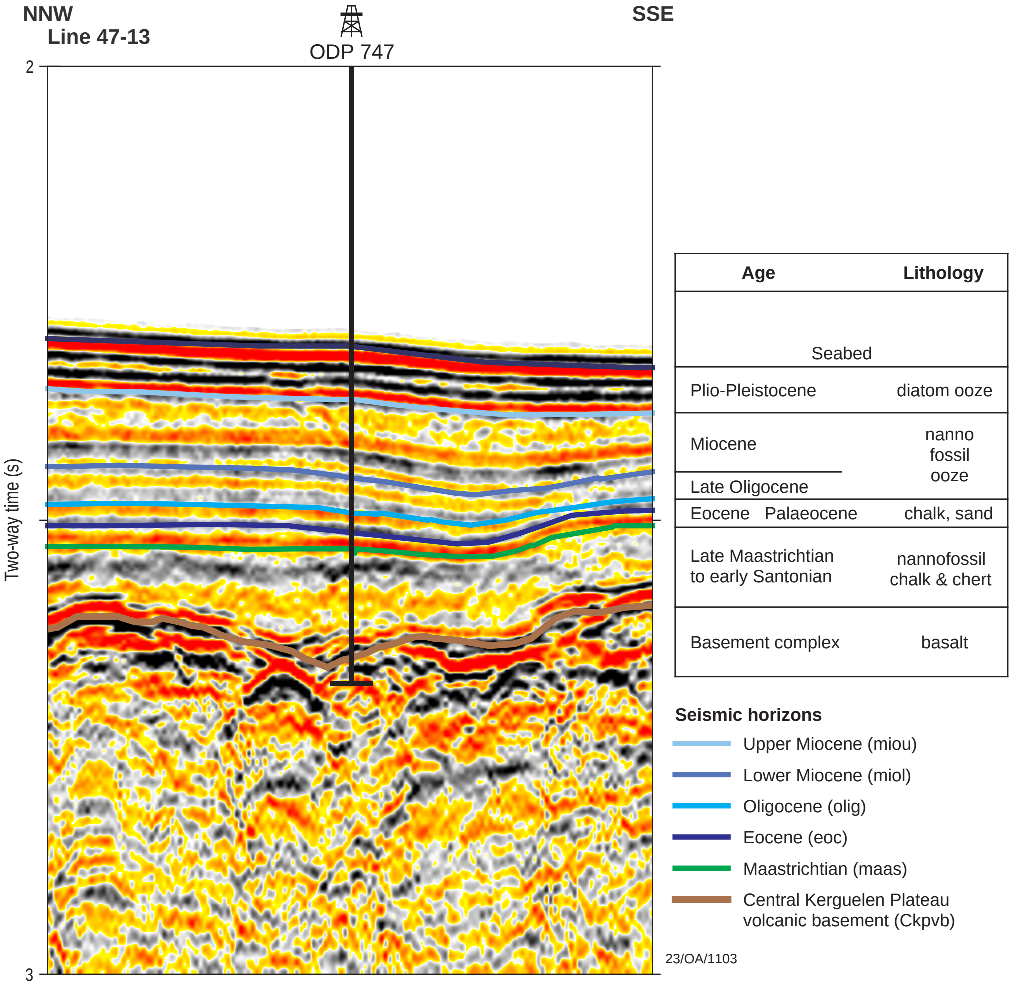

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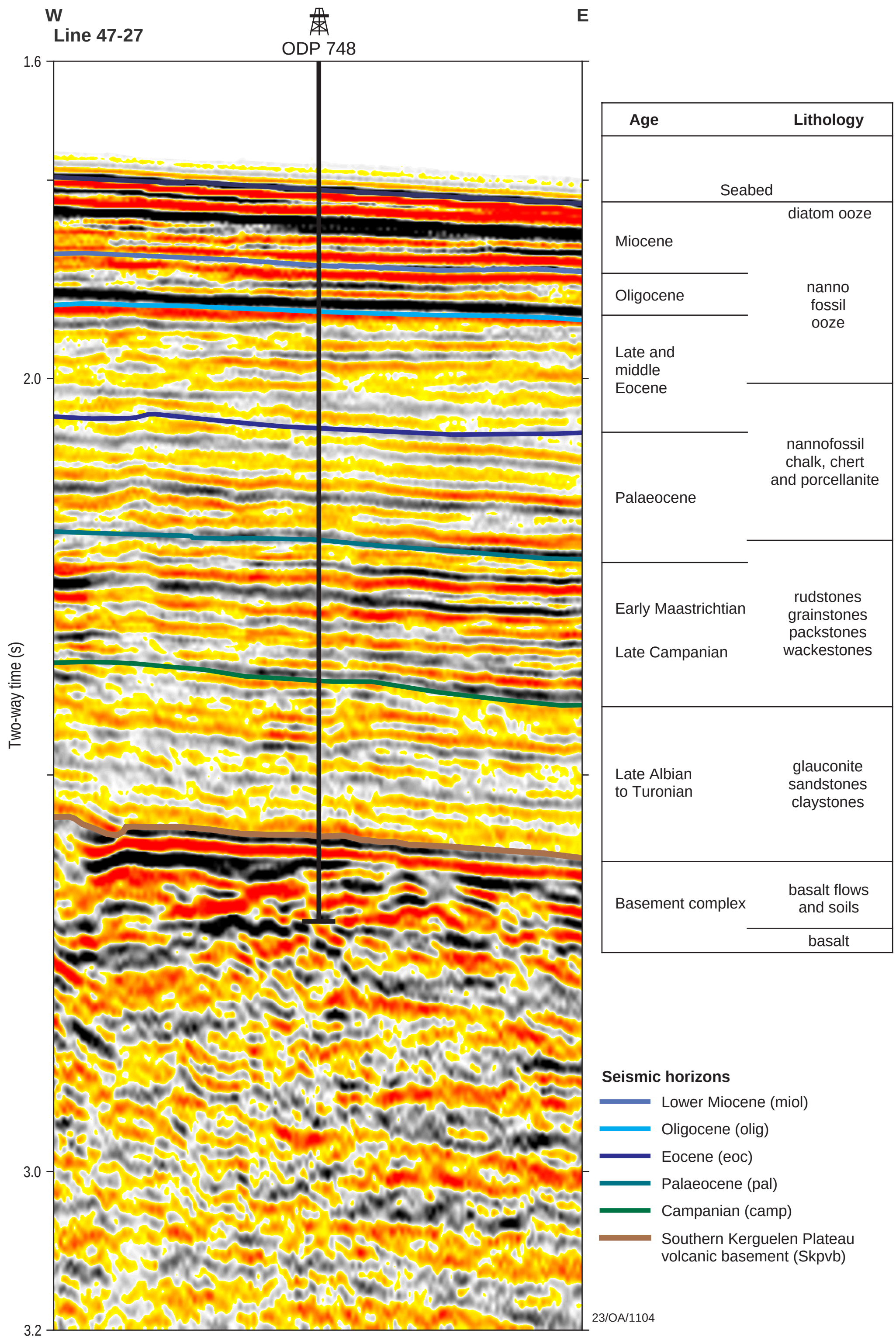

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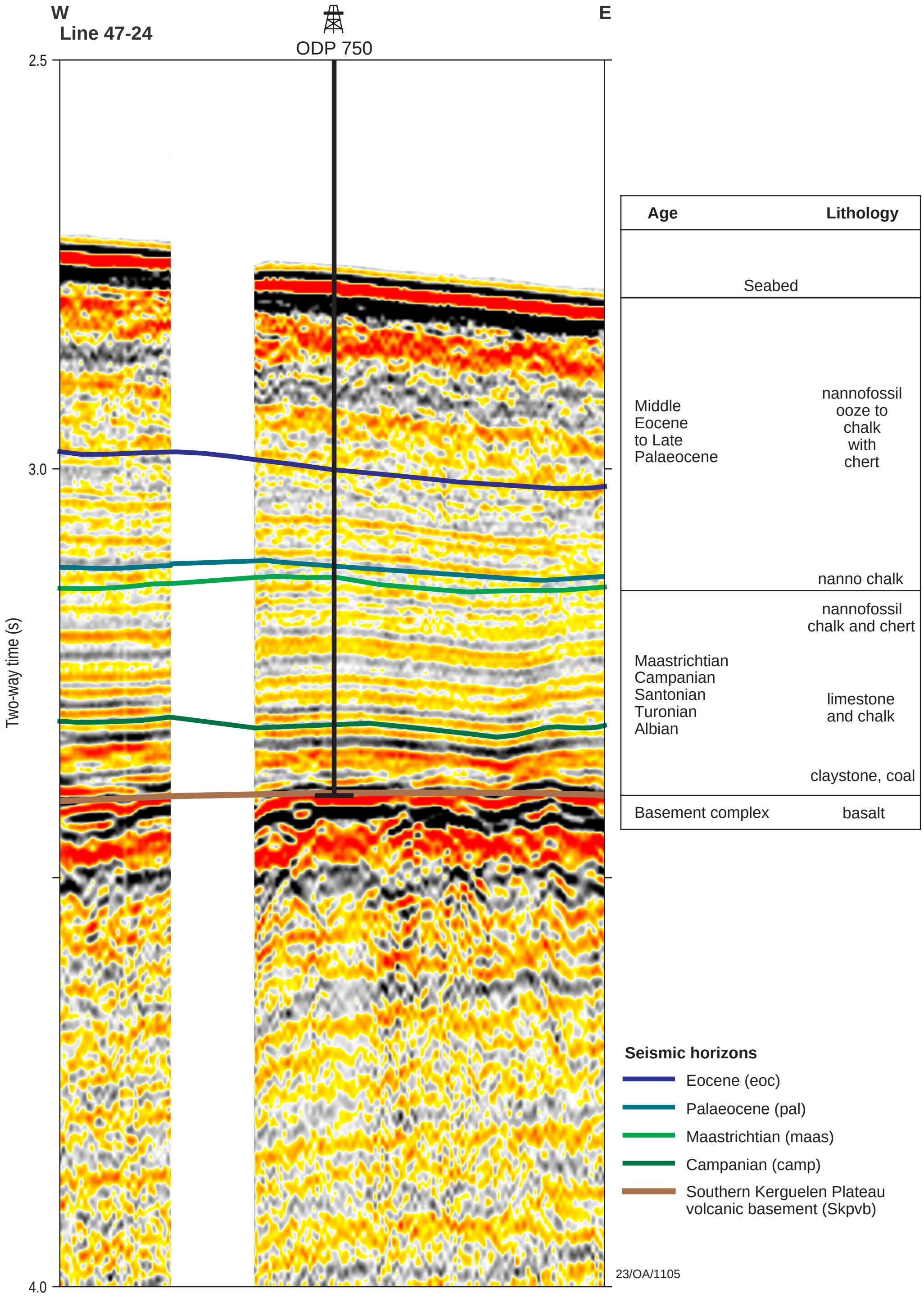

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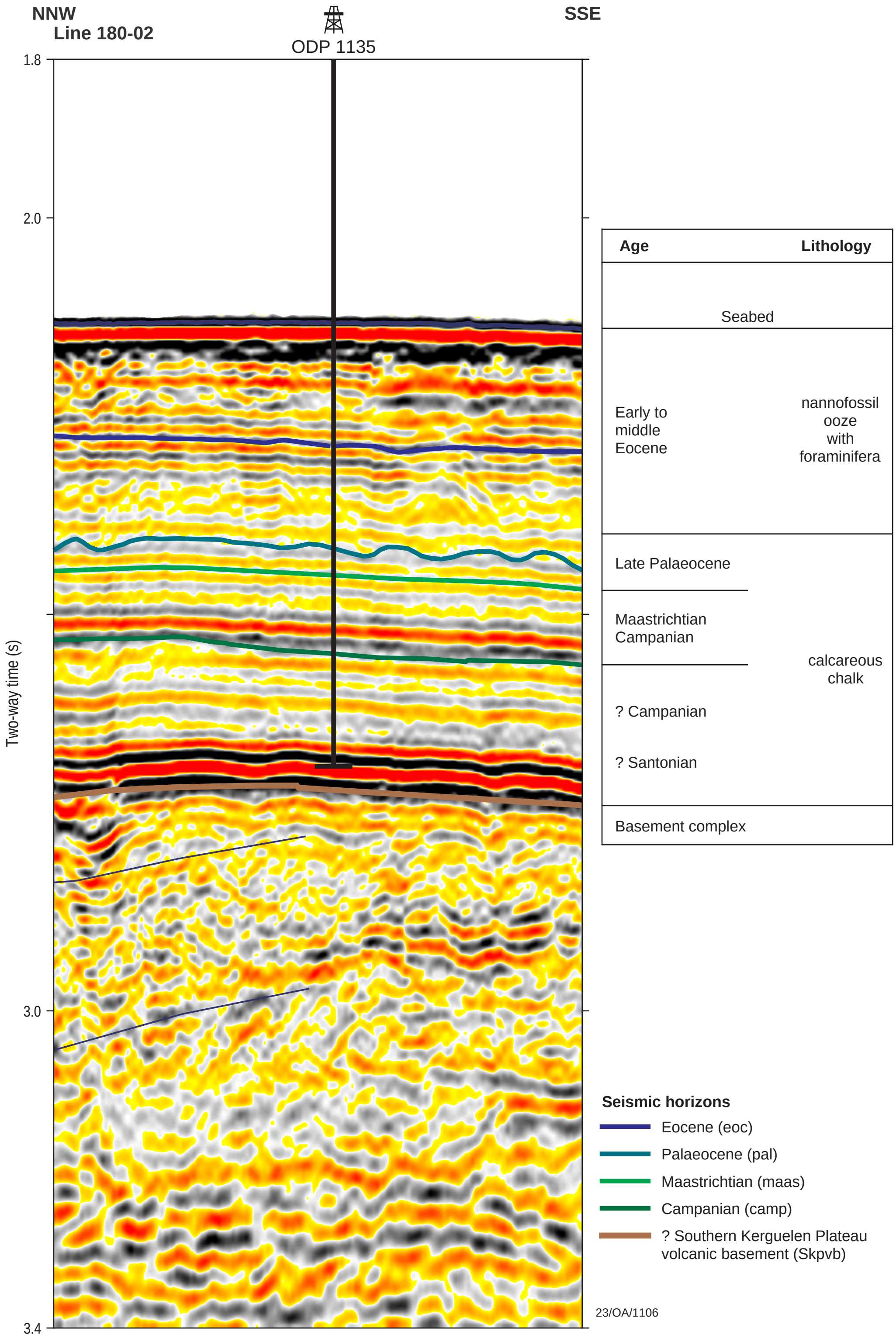

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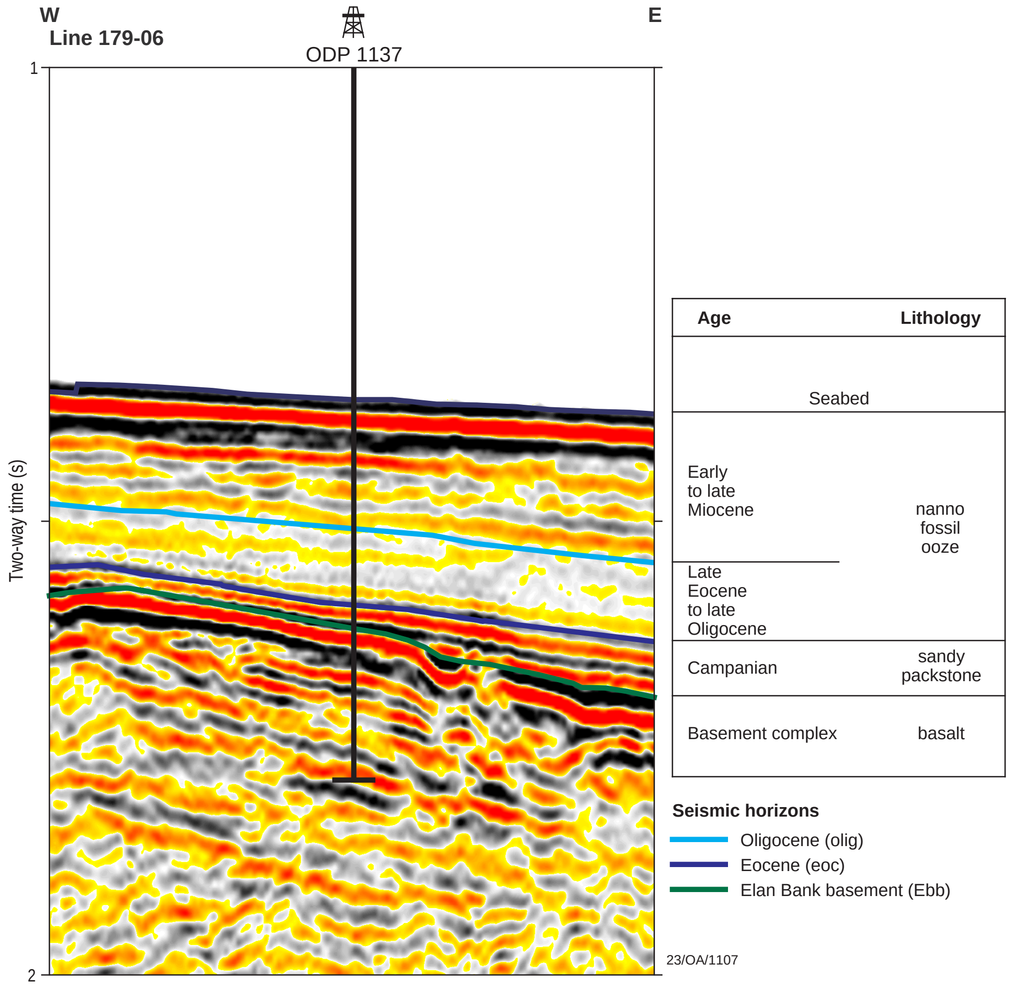

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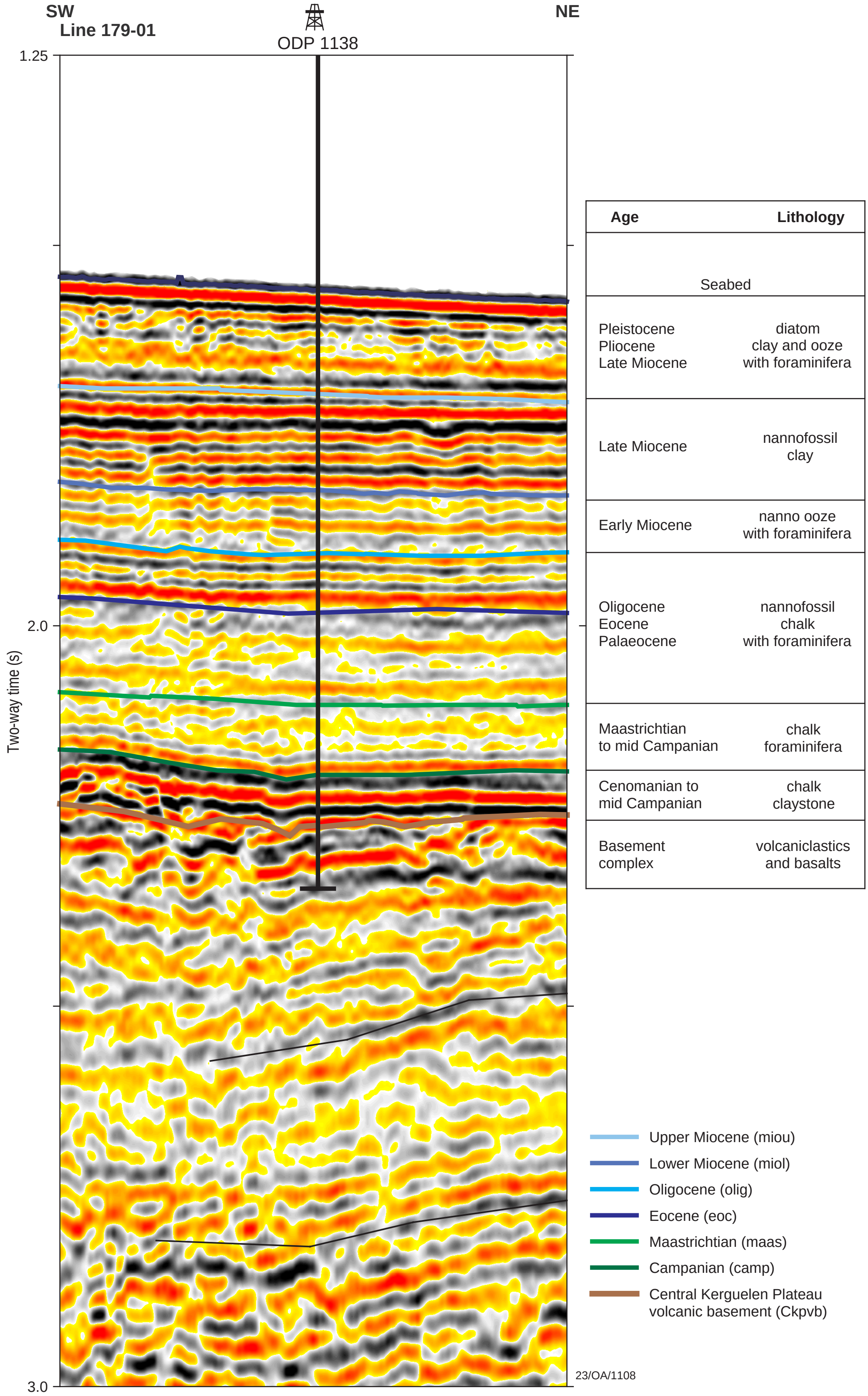


Fig. 17. Detail of seismic data at ODP Site 1138

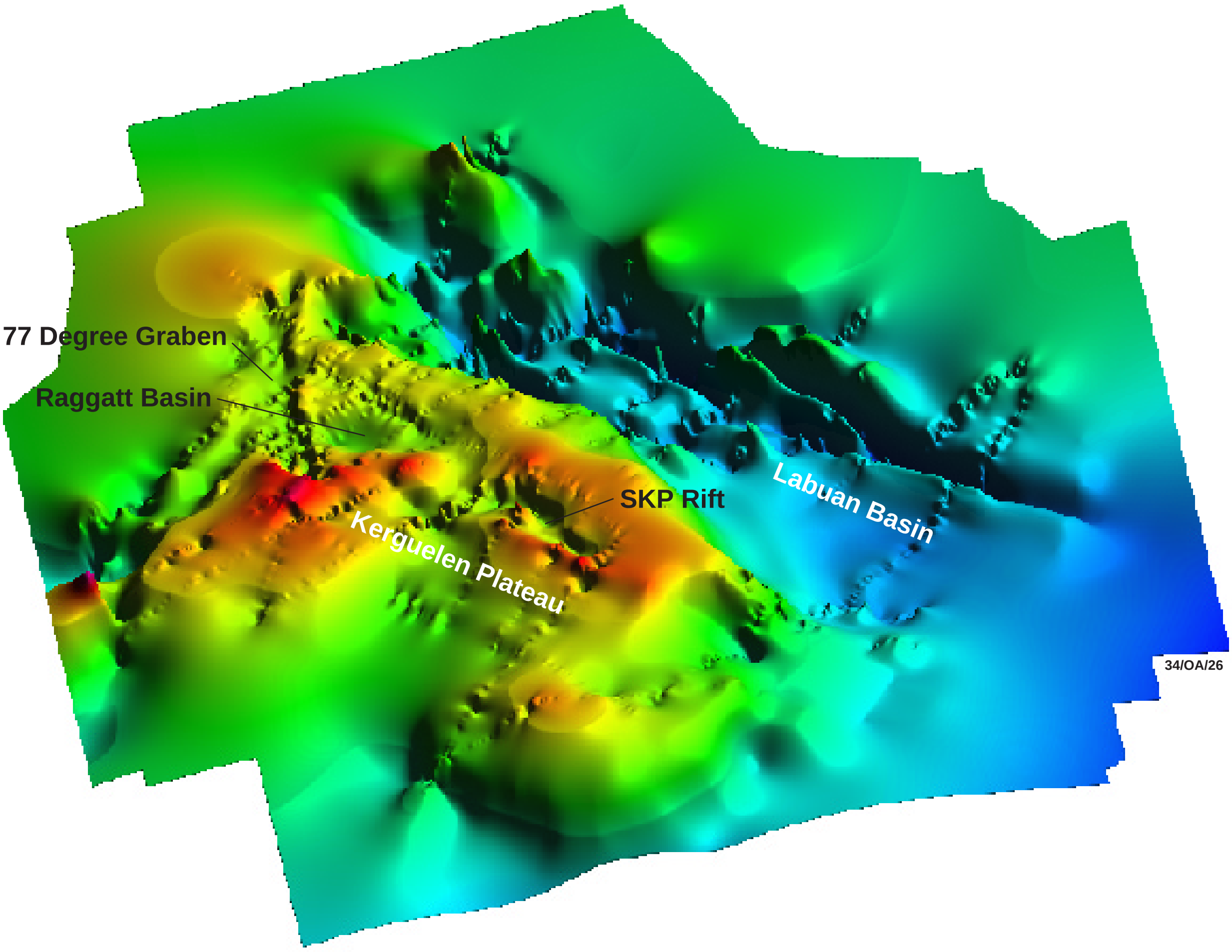


Fig. 18. Basement relief of the Southern Kerguelen Plateau and Labuan Basin based on interpreted seismic data from *Rig Seismic* surveys 47, 179, 180 and *Marion Dufresne* surveys 47 and 60. For location of survey lines see Fig. 4

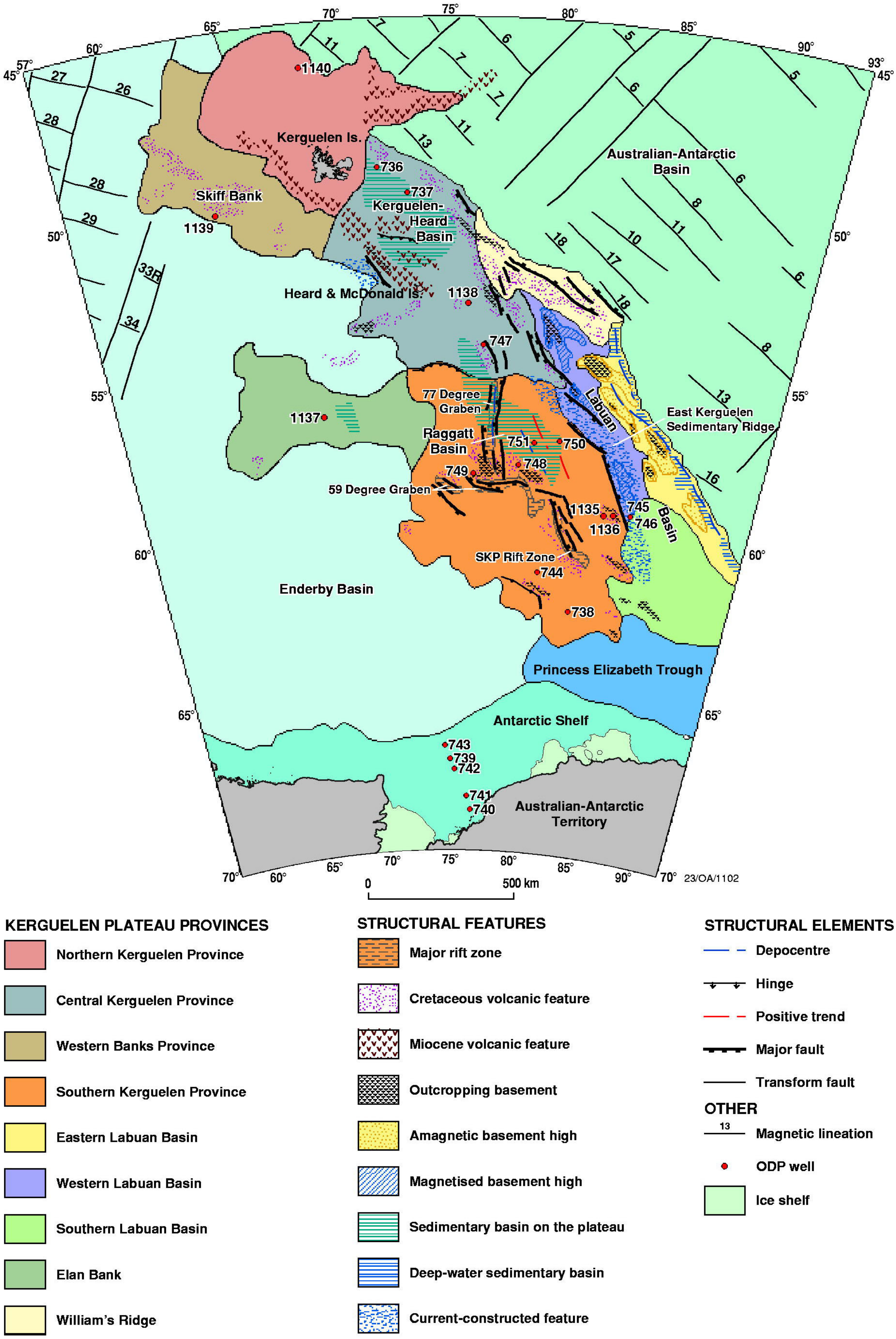


Fig. 19. Tectonic provinces of the Kerguelen Plateau and adjacent areas

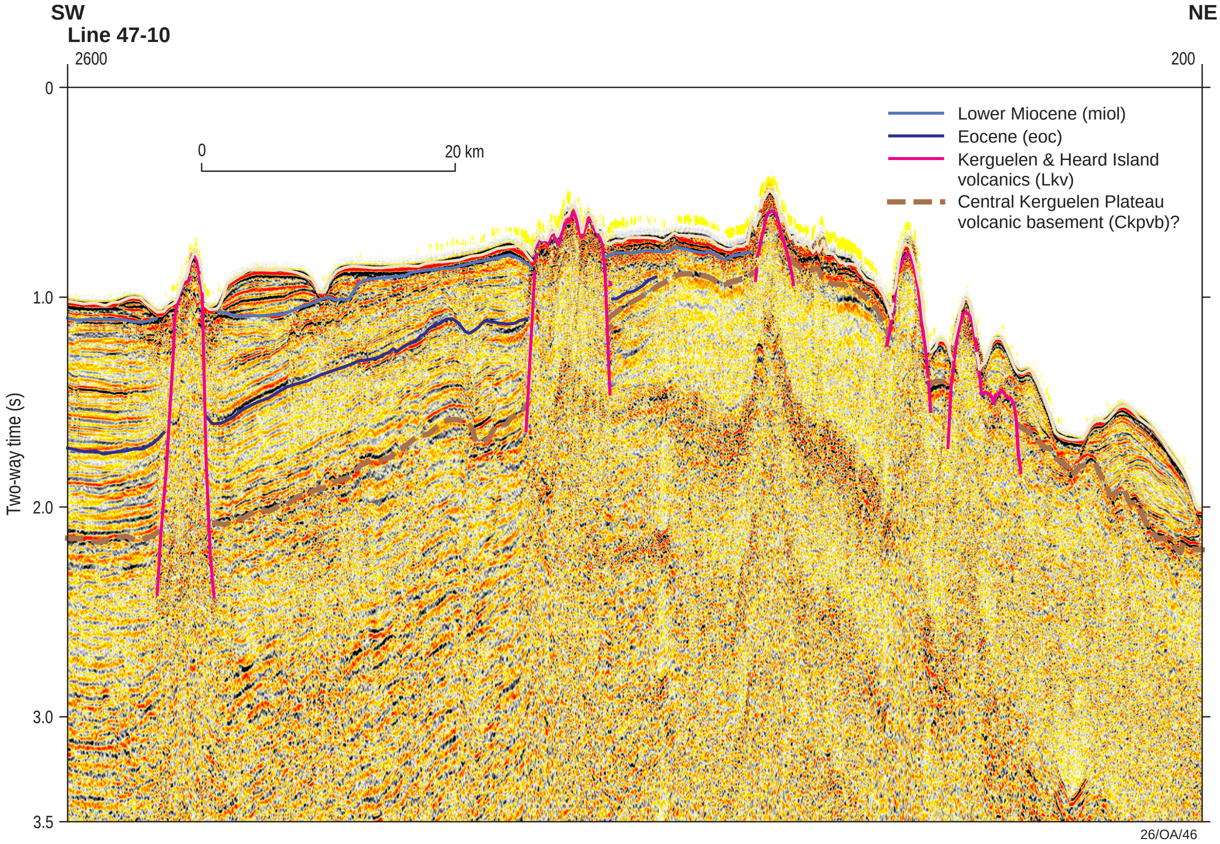


Fig. 20. Later Kerguelen volcanics (LKV) intruding Cretaceous basement ridge

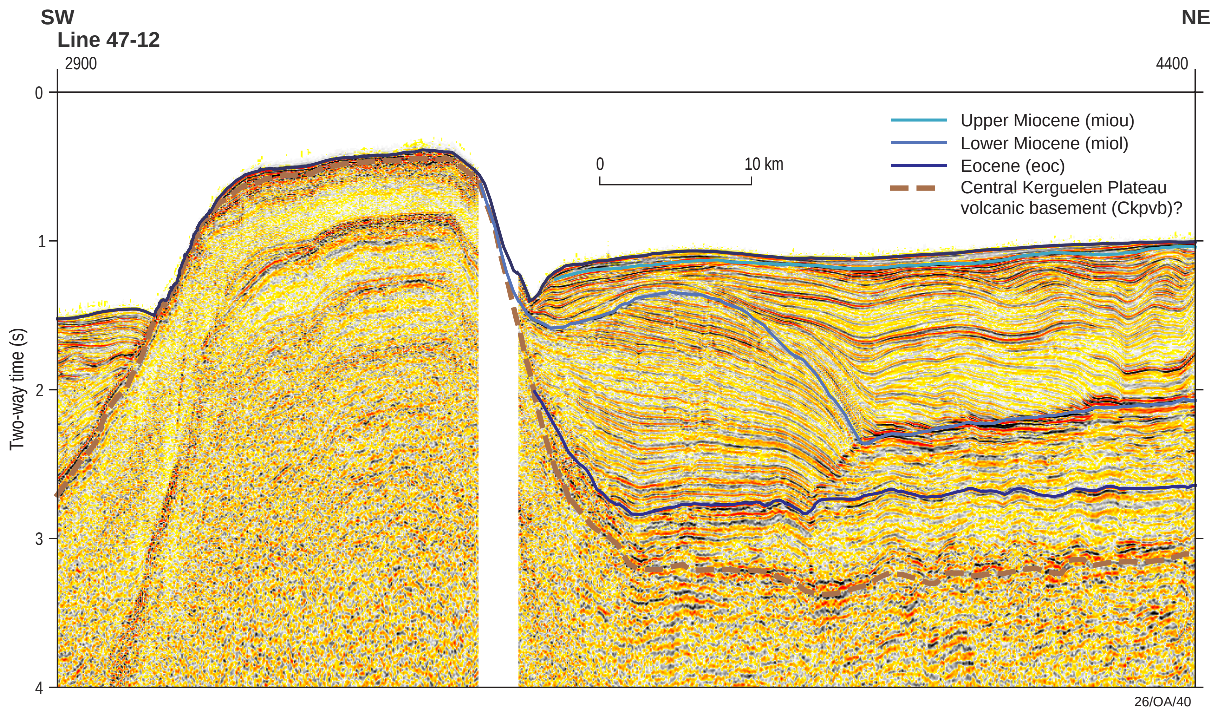


Fig. 21. Stratal geometries in the Kerguelen-Heard Basin

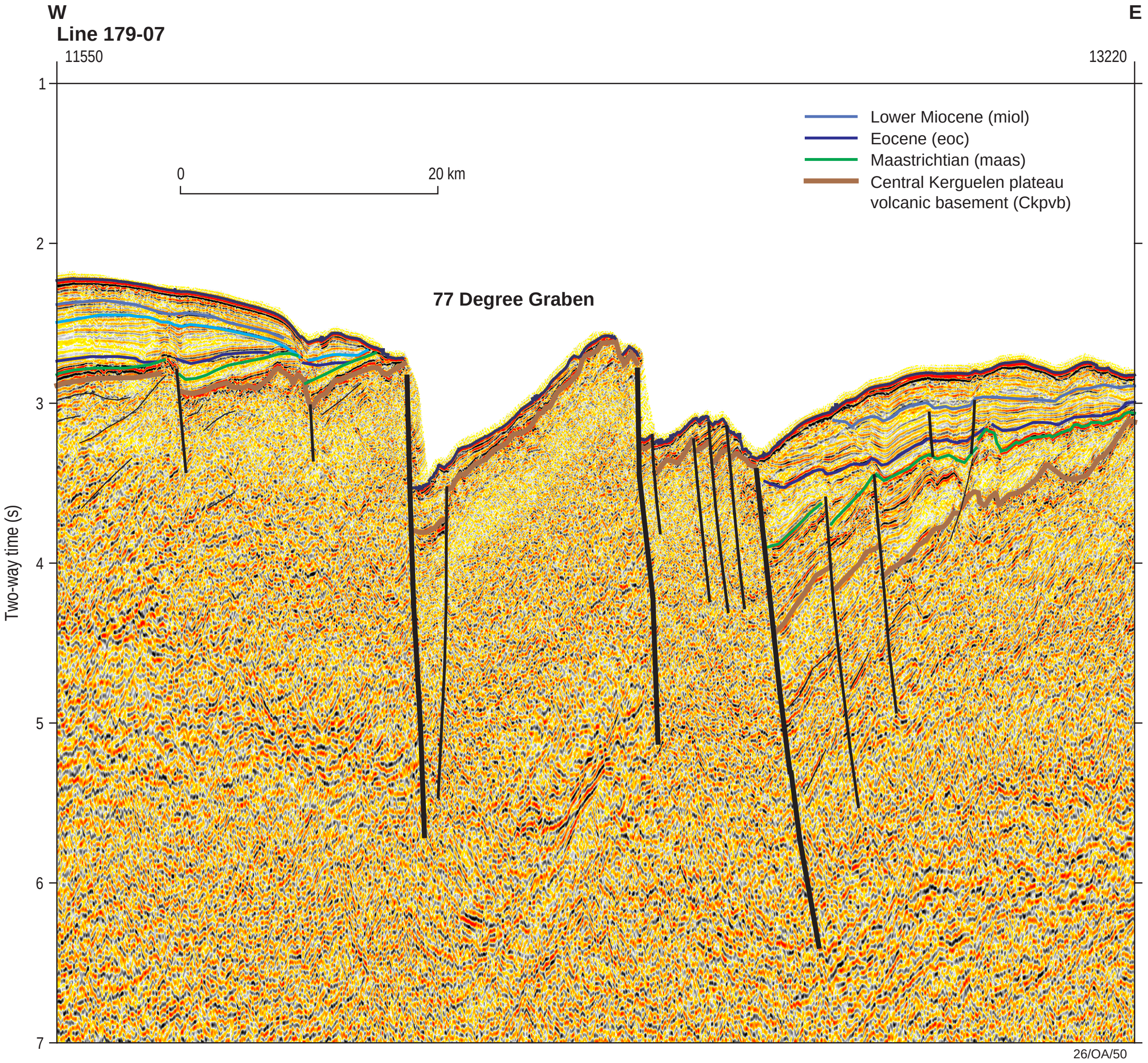


Fig. 22. Northern part of the 77 Degree Graben

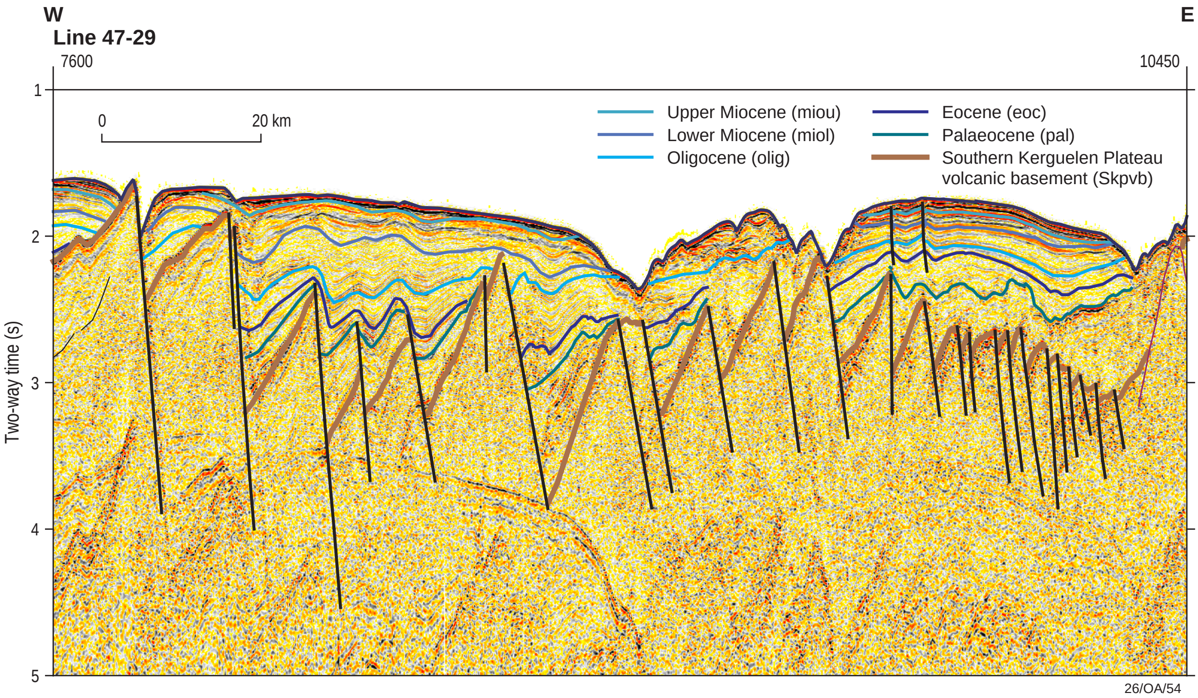


Fig. 23. Seismic line across the 59 Degree Graben

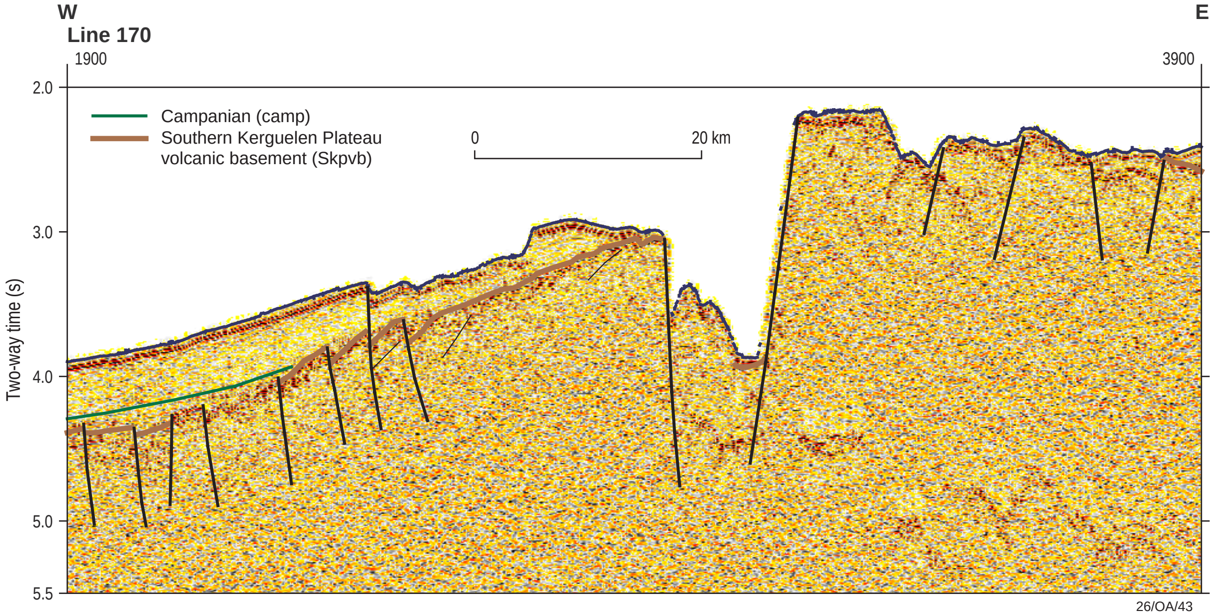


Fig. 24. Rift imaged by *Nella Dan* in the southernmost part of the Kerguelen Plateau

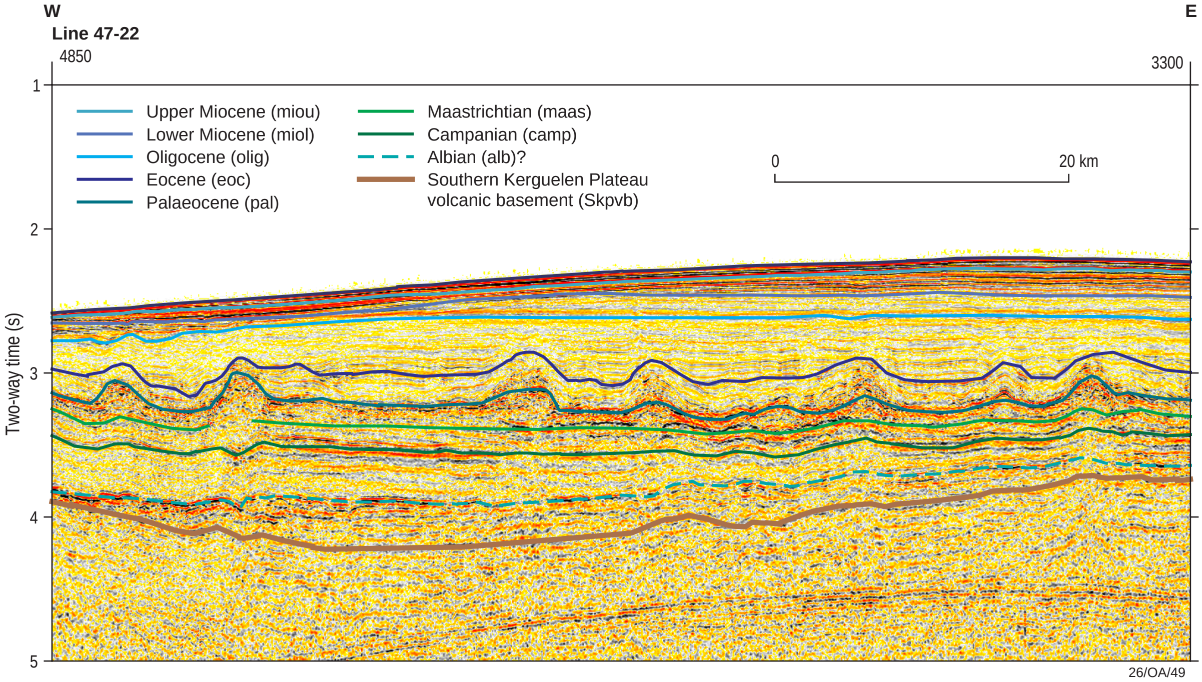


Fig. 25. Example of carbonate buildups in the Raggatt Basin

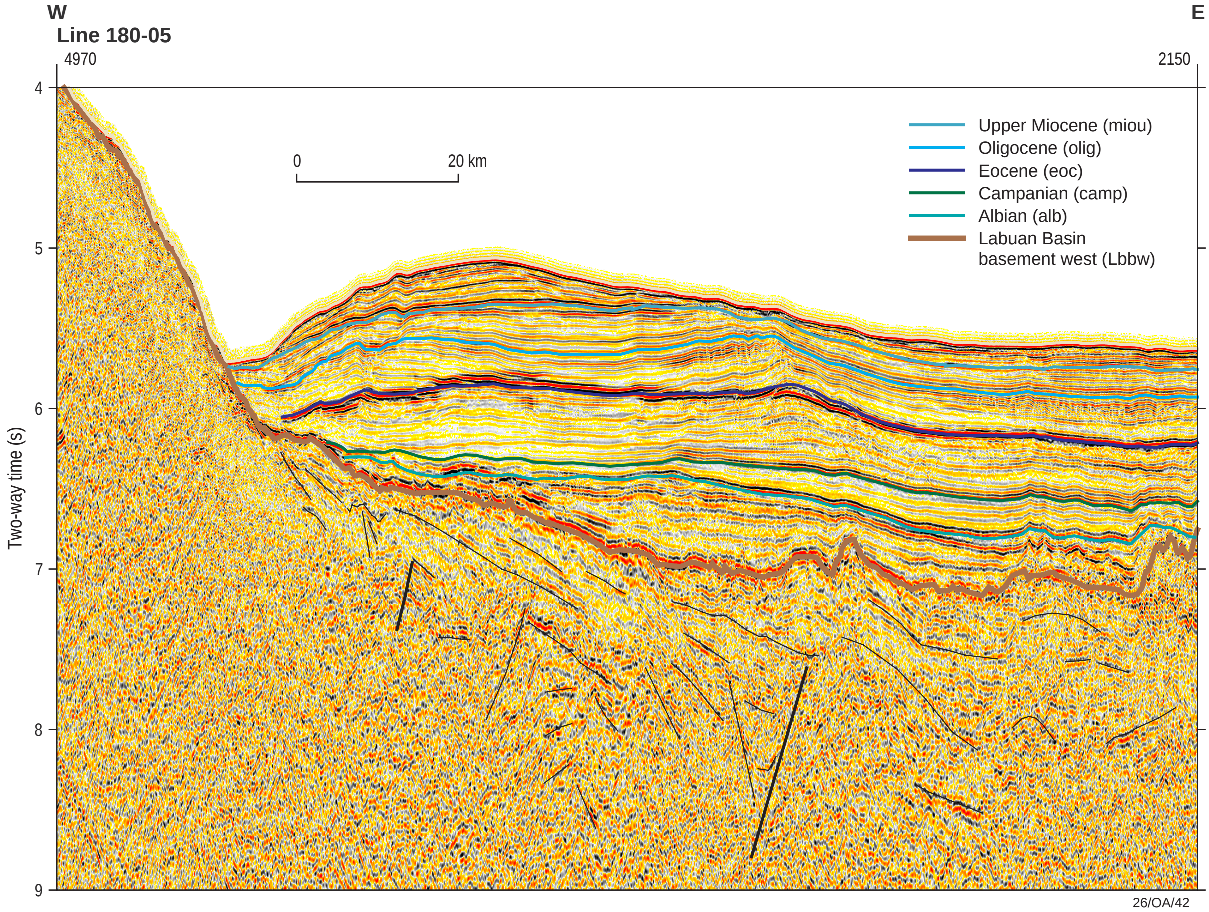


Fig. 26. East Kerguelen Sedimentary Ridge (EKSR)

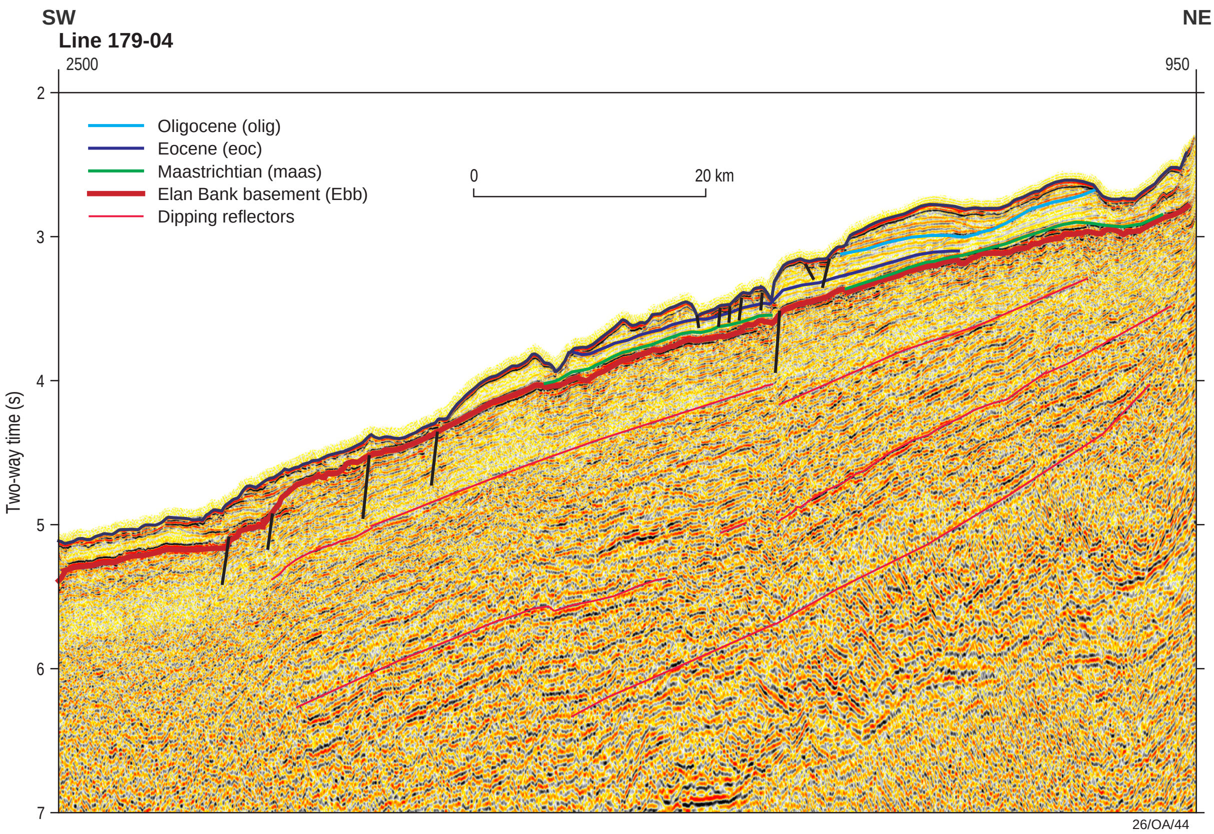


Fig. 27. Dipping reflectors in basement of Elan Bank

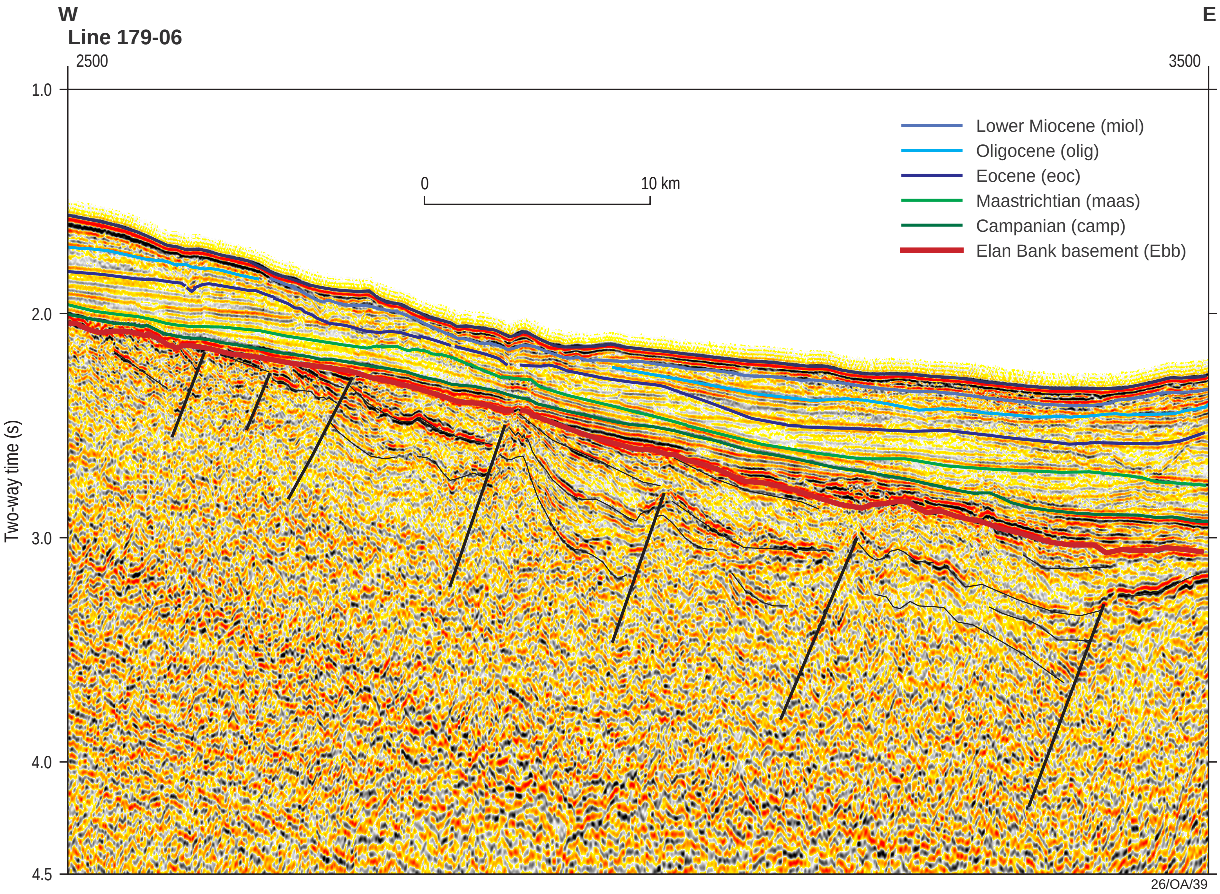


Fig. 28. Possible pre-Albian basin on Elan Bank

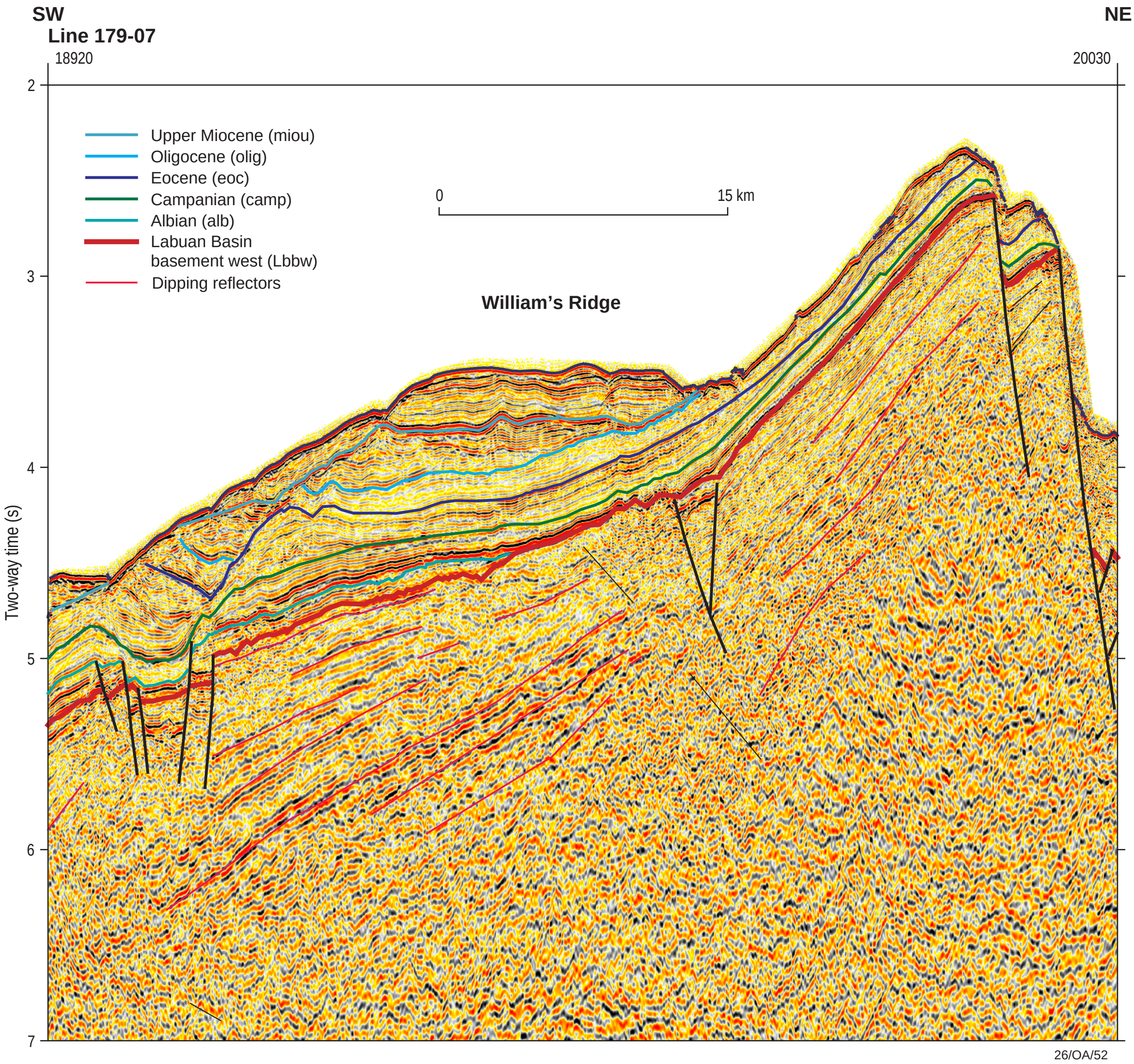


Fig. 29. Dipping reflectors on William's Ridge

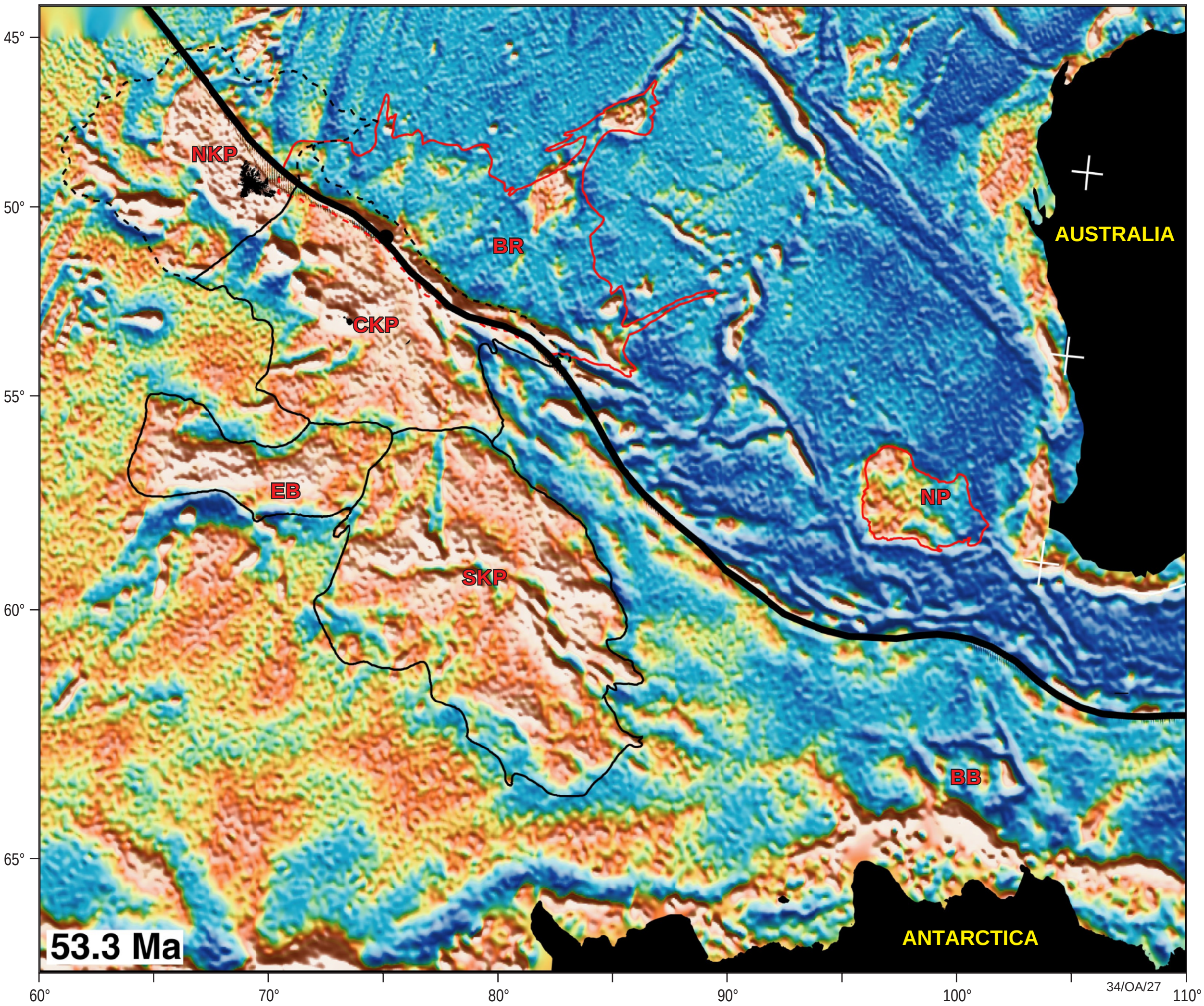


Fig. 30. Satellite gravity plate tectonic reconstruction of the Kerguelen Plateau and Broken Ridge for 53 Ma (after Gladczenko and Coffin, 2001). NP - Naturaliste Plateau; BB - Bruce Bank; EB - Elan Bank; BR - Broken Ridge; SKP - Southern Kerguelen Plateau; CKP - Central Kerguelen Plateau; NKP - Northern Kerguelen Plateau.

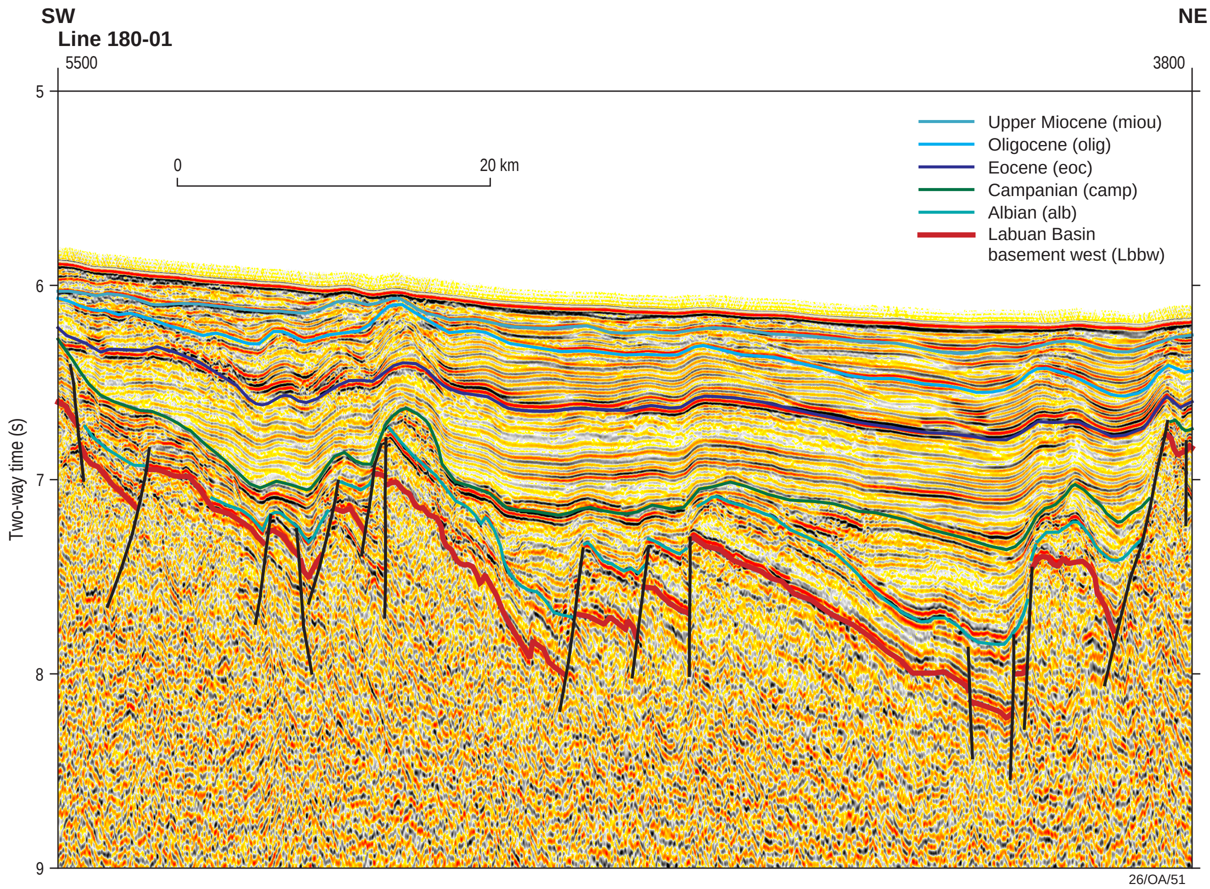


Fig. 31. Faulted basement of the western Labuan Basin

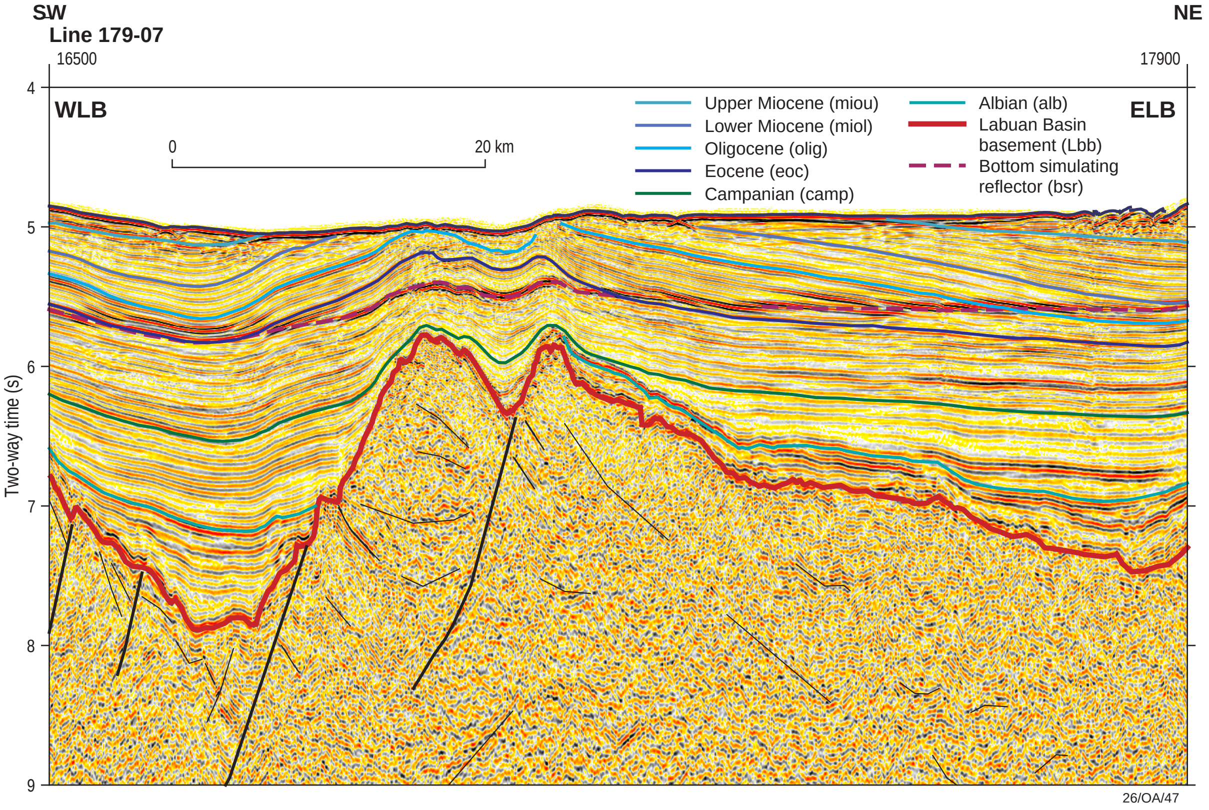


Fig. 32. Boundary zone between western (WLB) and eastern (ELB) provinces in the Labuan Basin

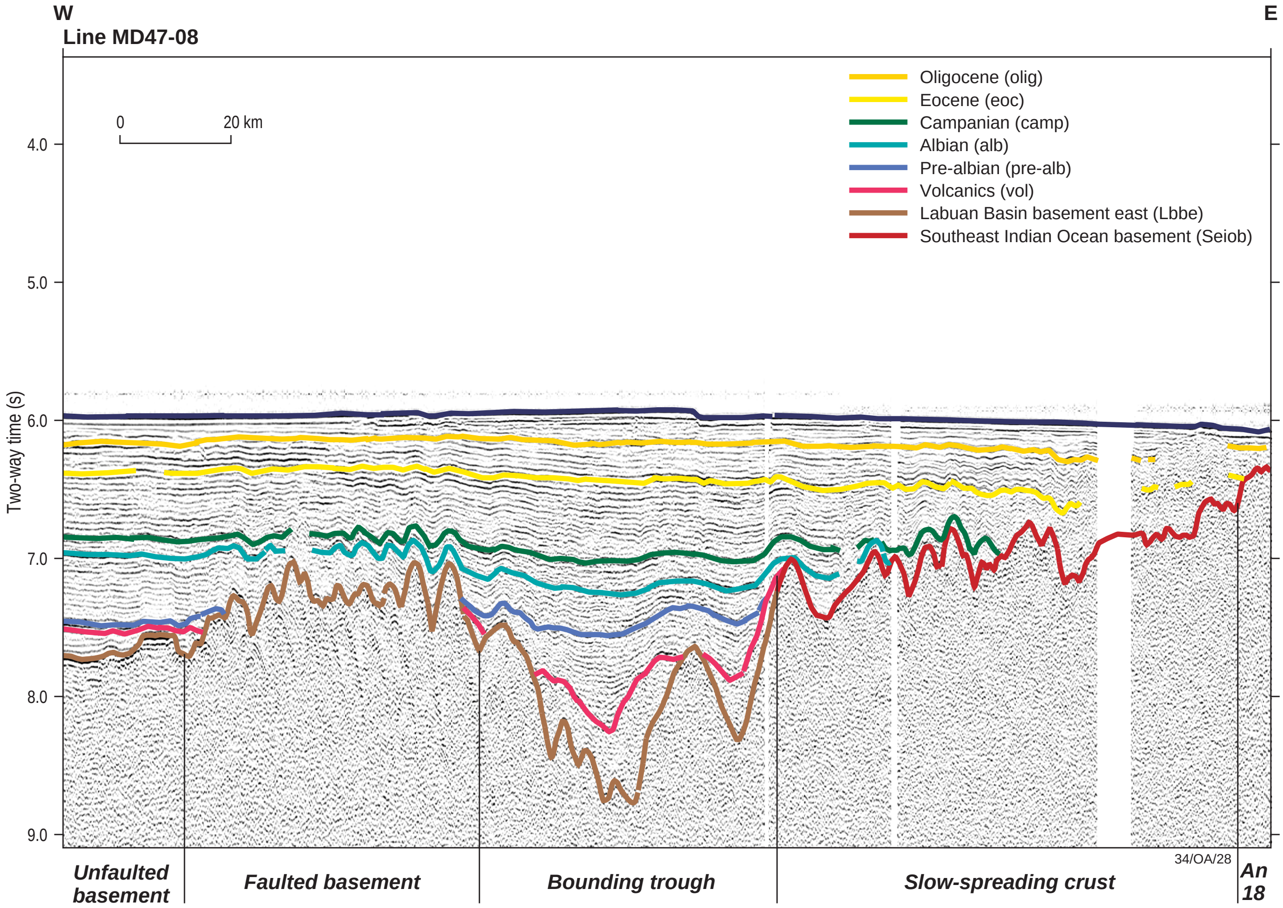


Fig. 33. Transition between Labuan Basin and Australian-Antarctic basin, Line MD47-08

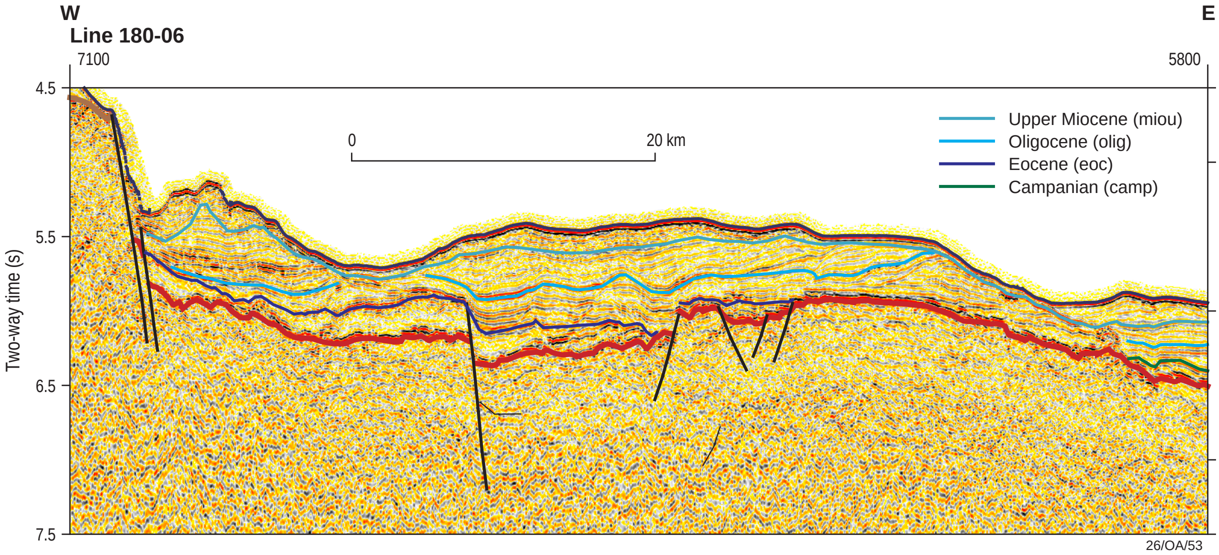


Fig. 34. Current-induced sedimentary structures in the western Labuan Basin

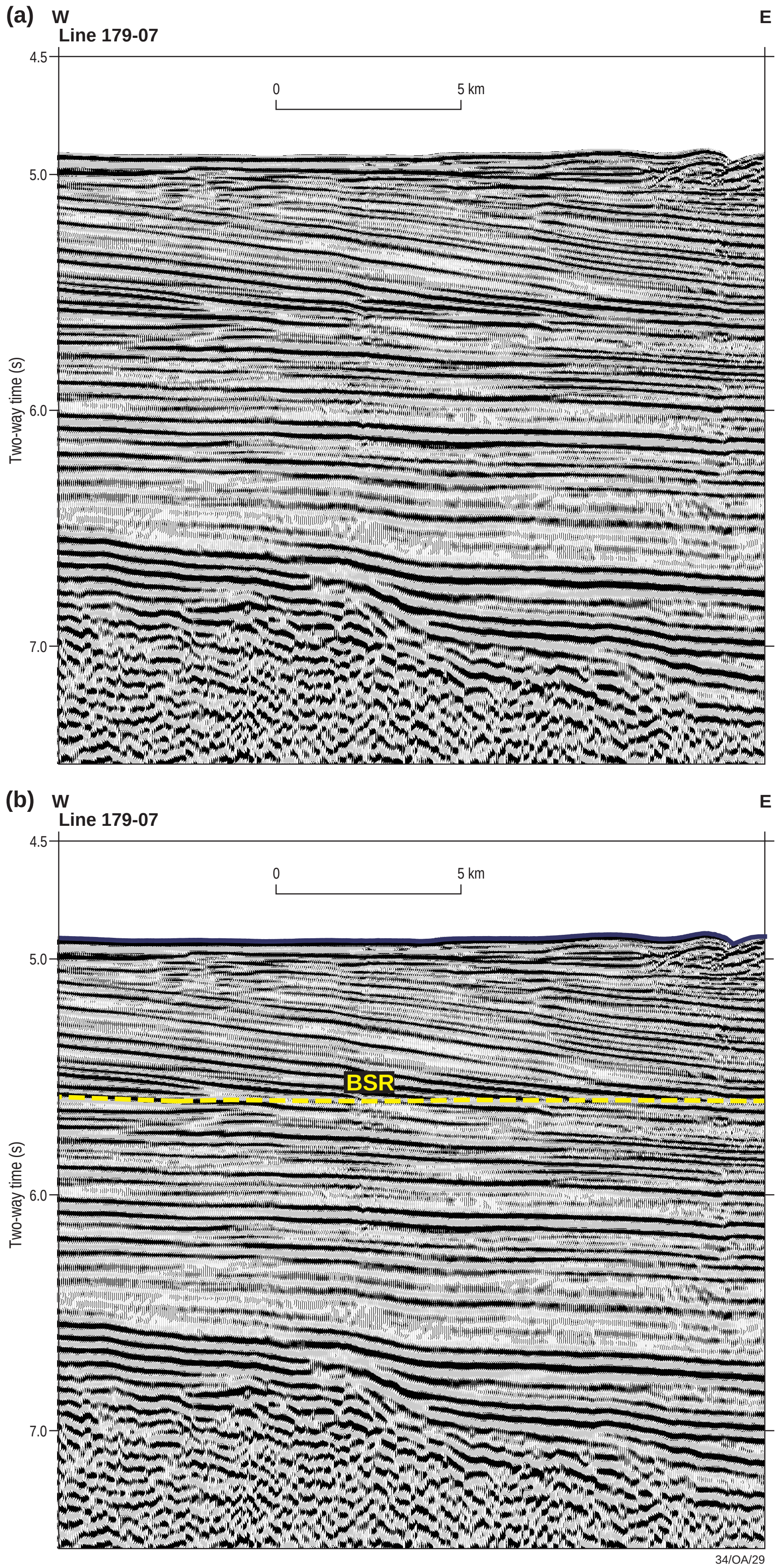


Fig. 35. **BSR in the northern Labuan Basin, Line 179-07: (a) without interpretation; (b) with interpreted BSR (yellow line)**

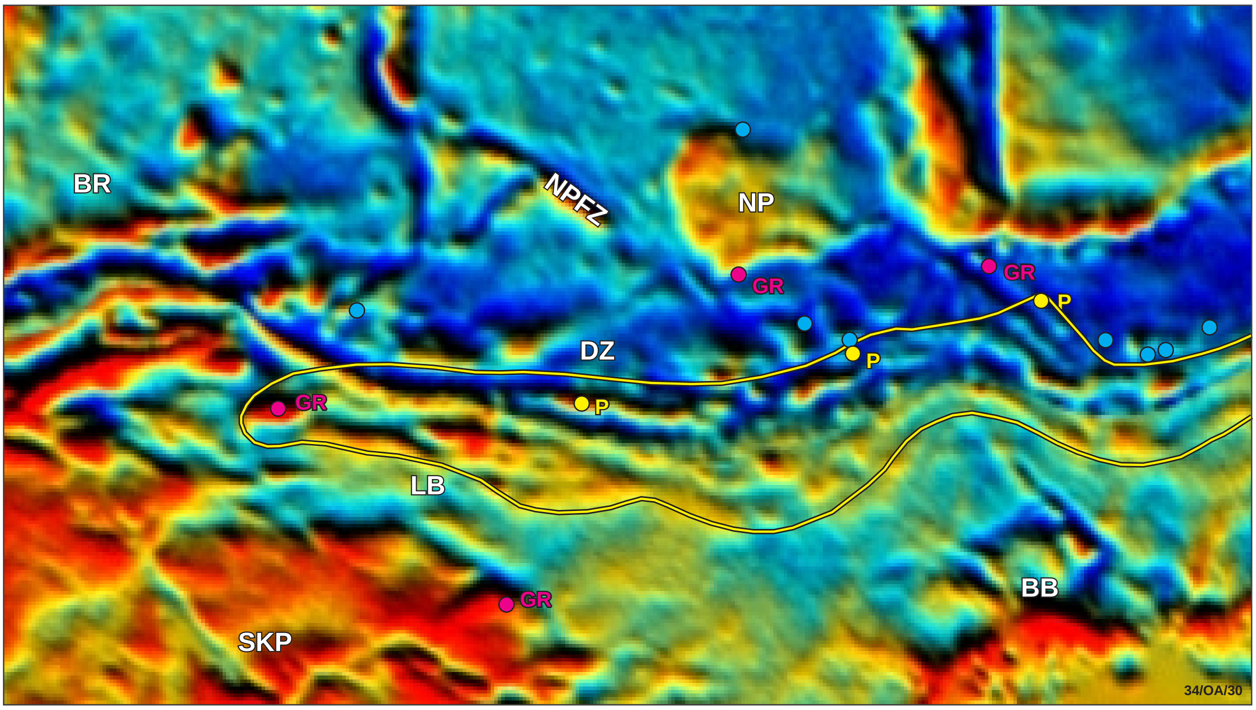


Fig 36. Satellite gravity pre-breakup reconstruction of Labuan Basin and Diamantina Zone with location of sampling sites. BR - Broken Ridge; NP - Naturaliste Plateau; NPFZ - Naturaliste Plateau Fracture Zone; LB - Labuan Basin; DZ - Diamantina Zone; BB - Bruce Bank; SKP - Southern Kerguelen Plateau. Pink circles (GR) - granitic and metamorphic rocks; yellow circles (P) - peridotites; blue circles - basalts. Yellow line outlines possible extent of the peridotite zone.

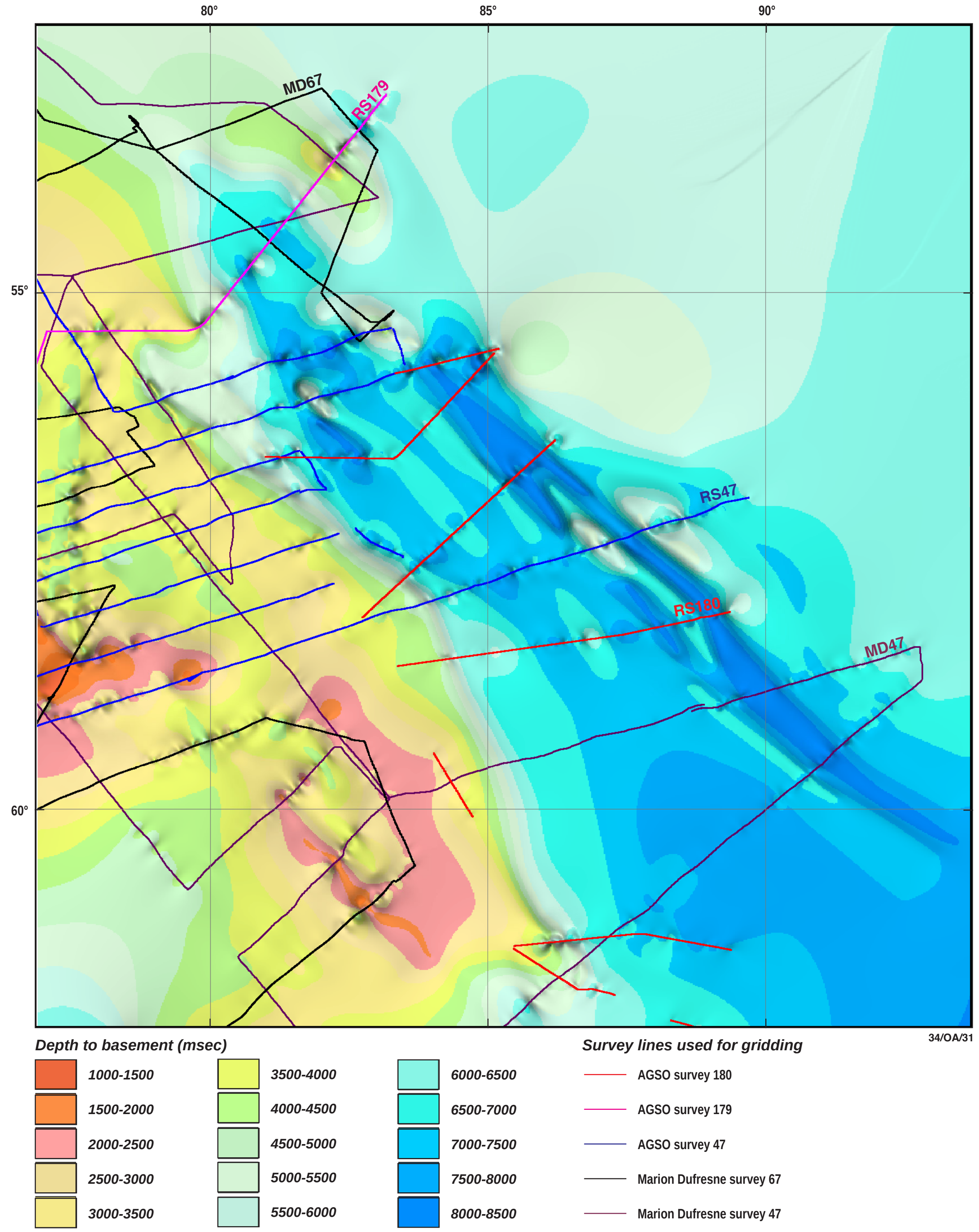
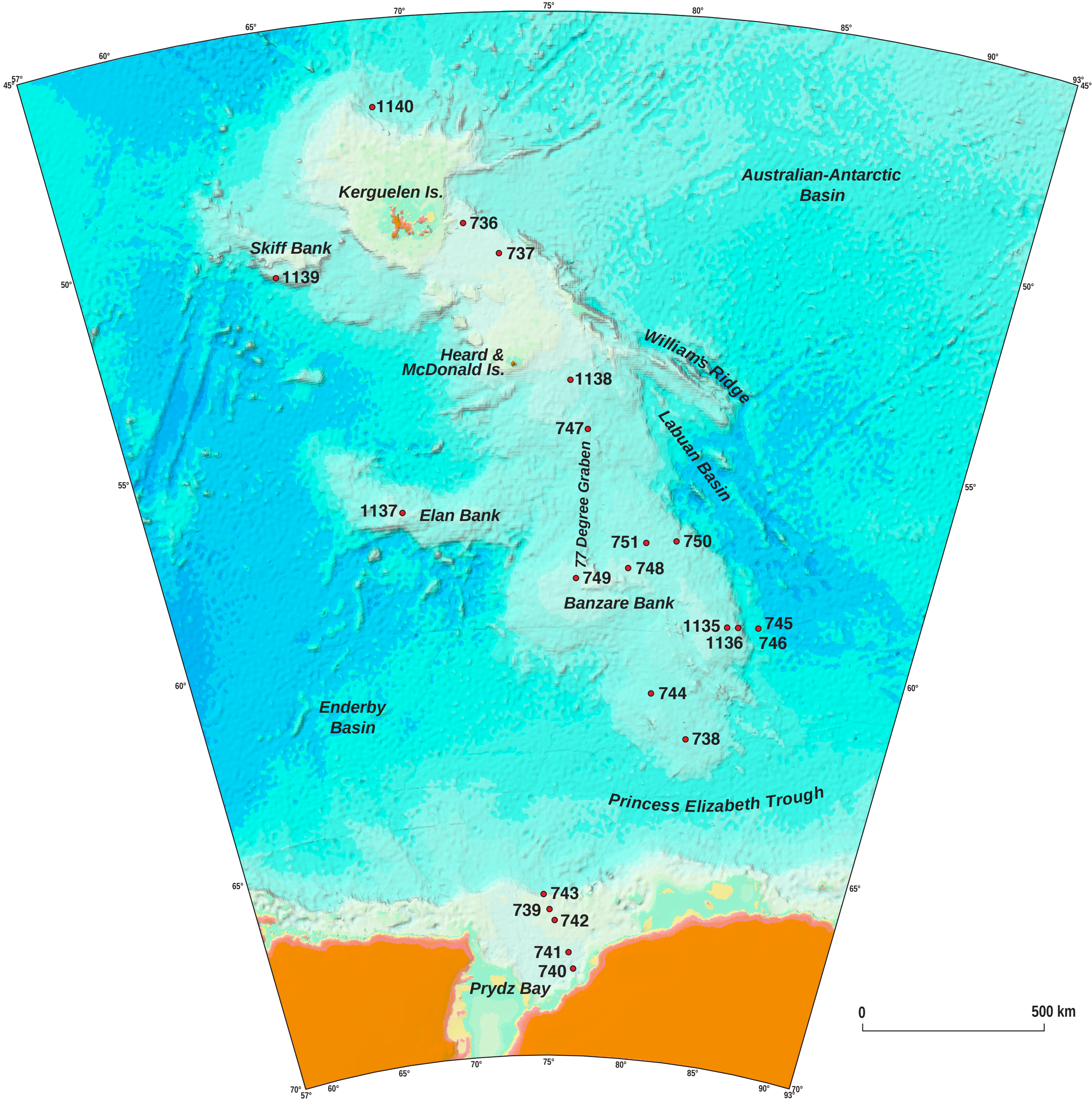


Fig. 37. Depth to basement in the Labuan Basin and adjacent parts of the Kerguelen Plateau. The image is based on interpretation of seismic lines shown here and controls provided by satellite gravity

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD



0 500 km

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Plate 1

Bathymetry and major physiographic features of the Kerguelen Plateau region

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1110

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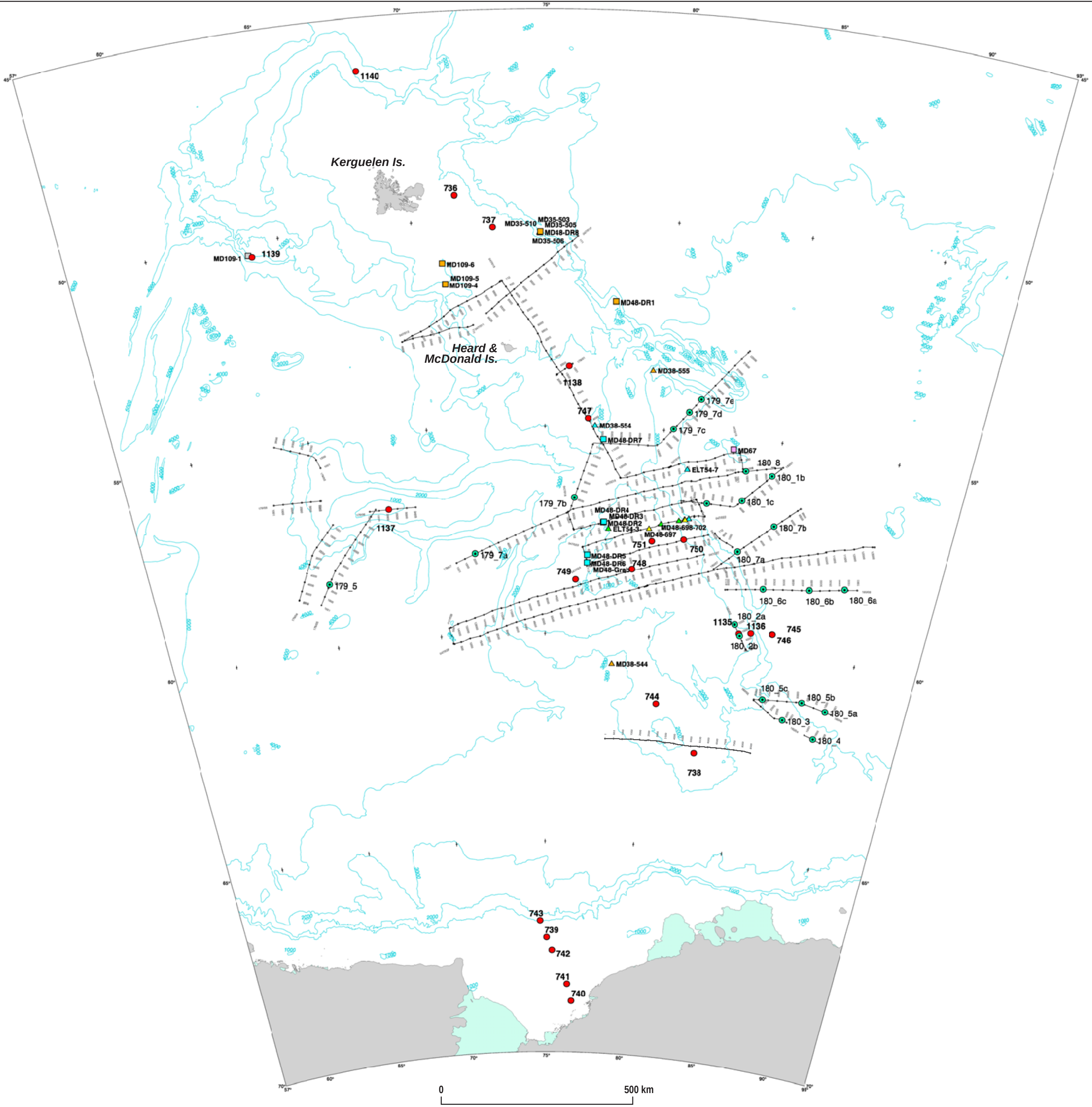

ODP sites

DREDGES

Oldest age of recovered material

- 500 Ma - 1 Ga
- Late Cretaceous
- Miocene
- Unknown

CORES

Oldest age of recovered material

- Cretaceous
- Late Eocene
- Miocene
- Pleistocene
- Unknown

Sonobuoy stations

Interpreted seismic lines with shotpoints

Geoscience Australia - Law of the Sea Project

Plate 2

Location of ODP wells, geological sampling sites, sonobuoy stations and seismic lines used in this study

GEOSCIENCE AUSTRALIA

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002.
Geological framework of the Kerguelen Plateau and adjacent ocean basins.
Geoscience Australia Record 2002/05

23/OA/1115

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

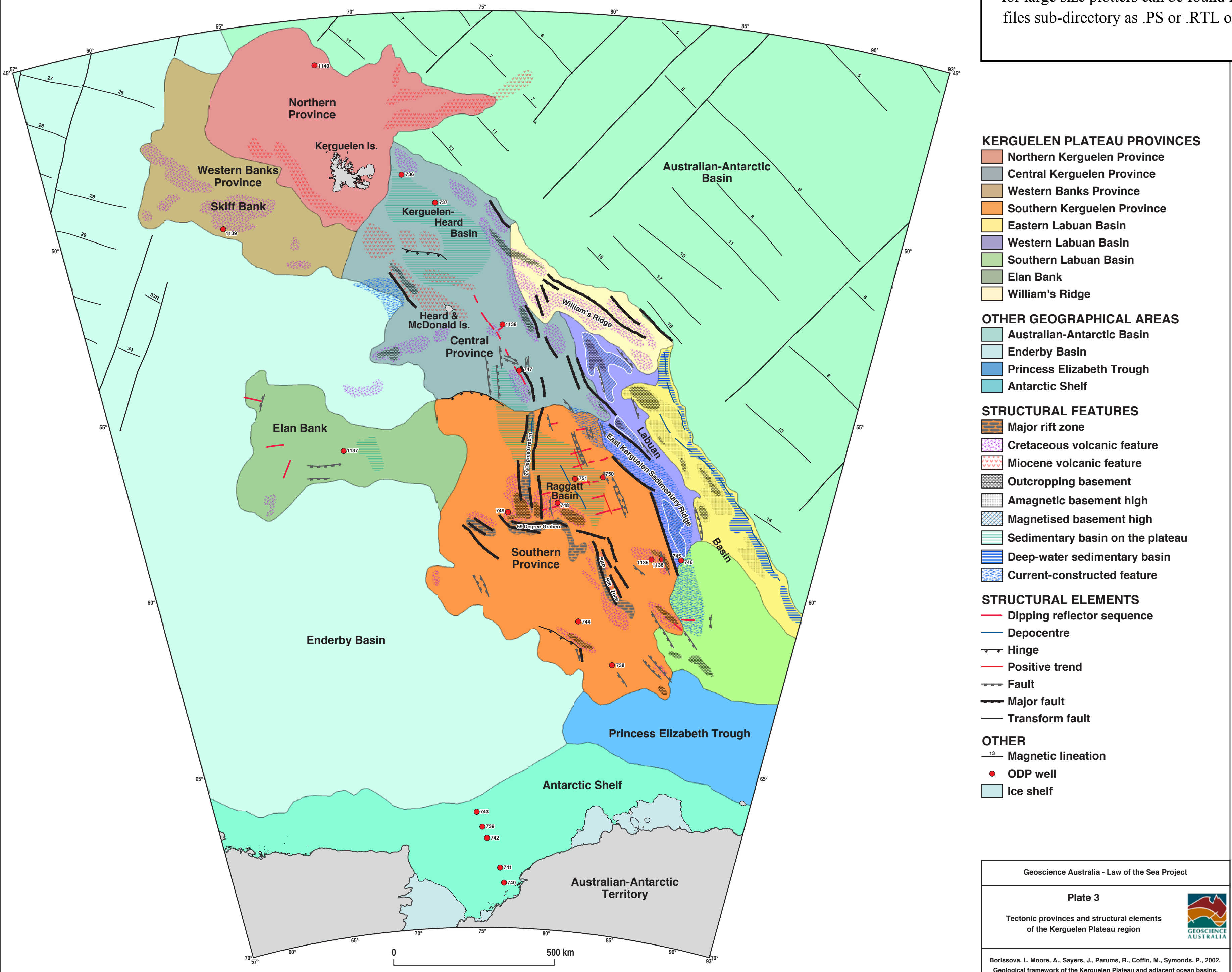

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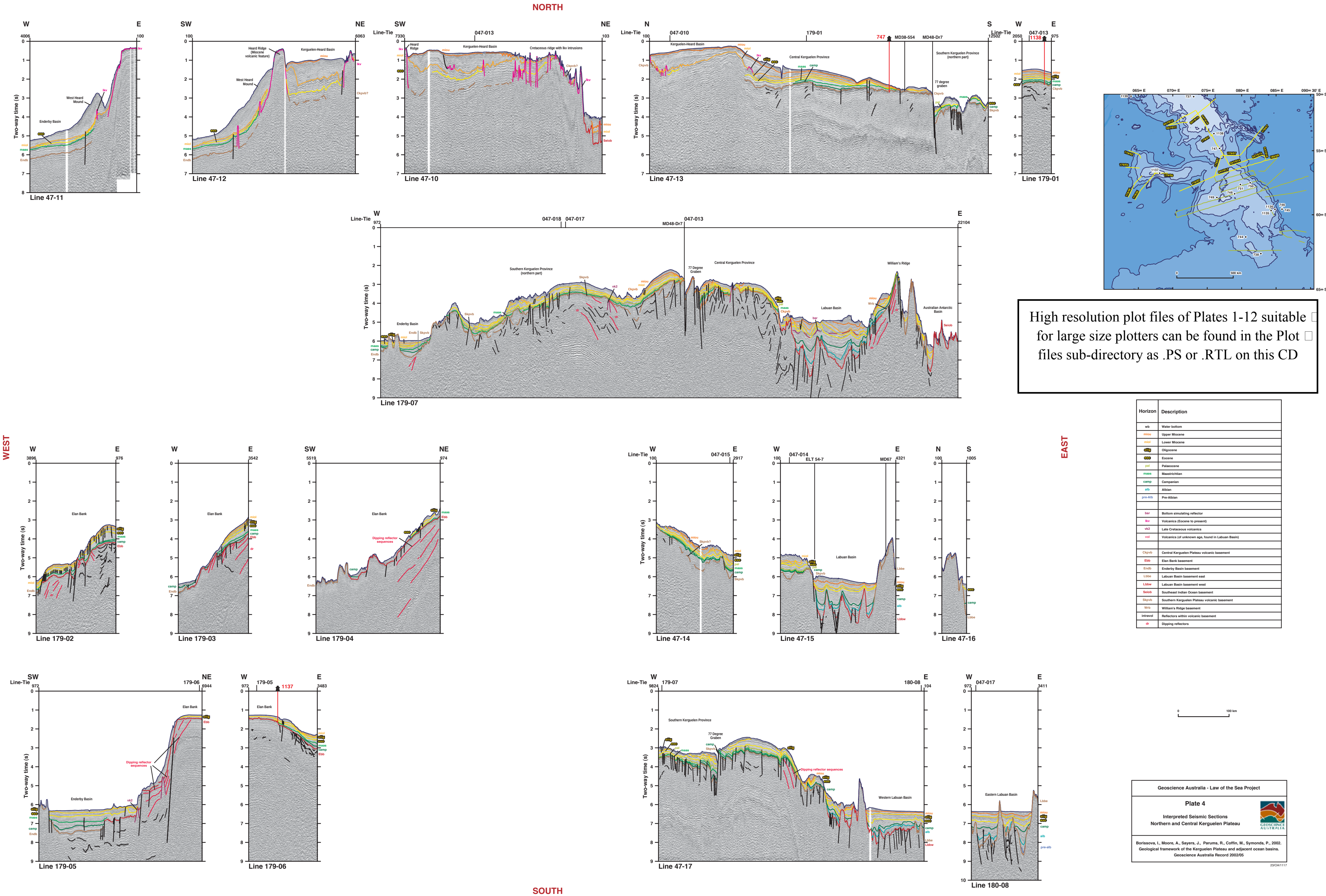
Plate 3

Tectonic provinces and structural elements of the Kerguelen Plateau region

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1116



High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

Horizon	Description
wb	Water bottom
miou	Upper Miocene
miol	Lower Miocene
olig	Oligocene
eoc	Eocene
pal	Palaeocene
maas	Maastrichtian
camp	Campanian
alb	Albian
pre-Alb	Pre-Albian
bsr	Bottom simulating reflector
lkv	Volcanics (Eocene to present)
vk2	Late Cretaceous volcanics
vol	Volcanics (of unknown age, found in Labuan Basin)
Ckpvb	Central Kerguelen Plateau volcanic basement
Ebb	Elan Bank basement
Endb	Enderby Basin basement
Lbbe	Labuan Basin basement east
Lbbw	Labuan Basin basement west
Seiob	Southeast Indian Ocean basement
Skpvb	Southern Kerguelen Plateau volcanic basement
Wrb	William's Ridge basement
intravol	Reflectors within volcanic basement
dr	Dipping reflectors

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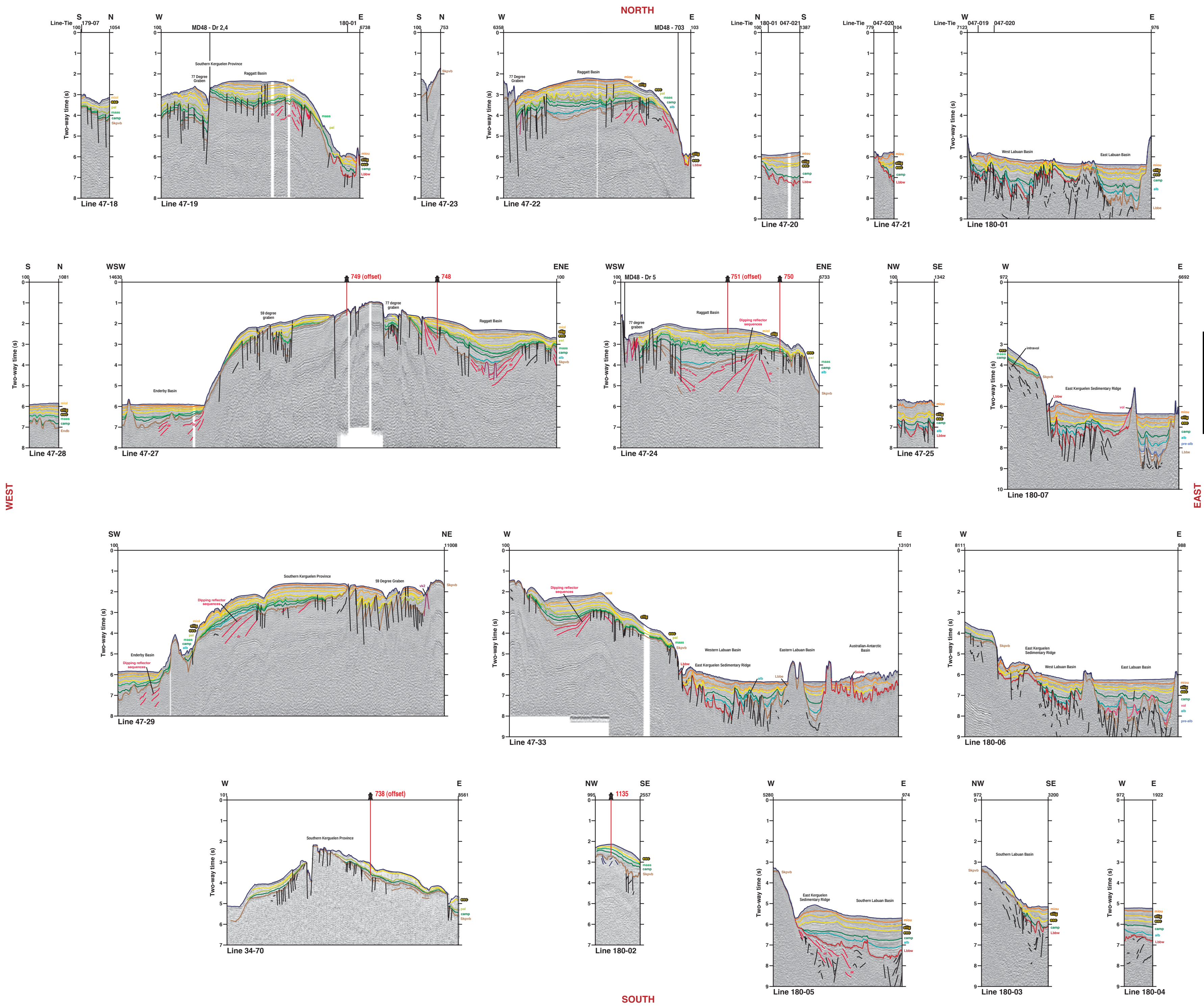
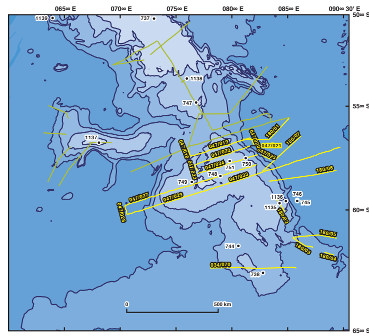
Plate 4

Interpreted Seismic Sections
Northern and Central Kerguelen Plateau

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1117





High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

Horizon	Description
wb	Water bottom
miou	Upper Miocene
miol	Lower Miocene
olig	Oligocene
eoc	Eocene
pal	Palaeocene
maas	Maastrichtian
camp	Campanian
alb	Albian
pre-Alb	Pre-Albian
bsr	Bottom simulating reflector
lkv	Volcanics (Eocene to present)
vk2	Late Cretaceous volcanics
vol	Volcanics (of unknown age, found in Labuan Basin)
Ckpvb	Central Kerguelen Plateau volcanic basement
Ebb	Elan Bank basement
Endb	Enderby Basin basement
Lbbe	Labuan Basin basement east
Lbbw	Labuan Basin basement west
Seiob	Southeast Indian Ocean basement
Skpvb	Southern Kerguelen Plateau volcanic basement
Wrb	William's Ridge basement
intravol	Reflectors within volcanic basement
dr	Dipping reflectors

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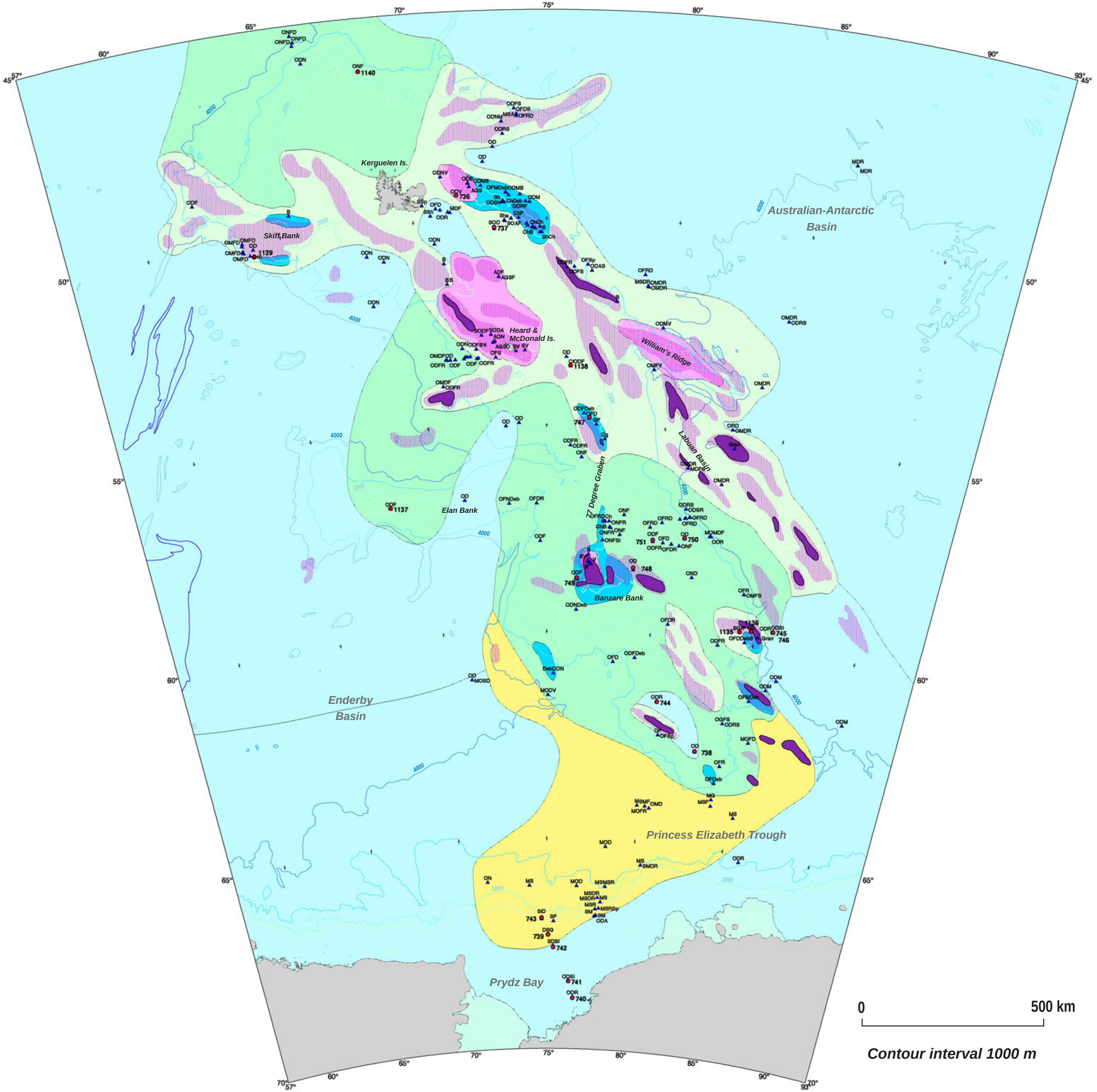
Plate 5

Interpreted Seismic Sections
Southern Kerguelen Plateau

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1118

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD



- ODP wells
- Geological sampling sites (dredges and cores)

Surface sediment types

- Nannofossil ooze with silt and/or sand
- Ooze and silt with rare nannofossils
- Sediments with volcanogenic component
- Sediments with significant clastic component
- Siliceous (diatom) ooze
- Siliceous and calcareous ooze
- Silt and sand - terrigeneous origin
- Basement highs and ridges
- Outcrop

Sediment code	Sediment type
O	Ooze
M	Mud
D	Diatoms
F	Foraminifera
R	Radiolaria
A	Volcanic ash
S	Sand
Sp	Spicules
G	Gravel
N	Nannofossils
V	Volcanic debris
Si	Silt
Met	Metasediment
Gr	Granules
P	Pebbles
C	Clastic sediments
Cl	Clay
B	Basalts
Ch	Cherts
Cg	Conglomerate
Gran	Granite
Deb	Debris
Sh	Shells
Sha	Shale
Lime	Limestone

0 500 km

Contour interval 1000 m

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Plate 6

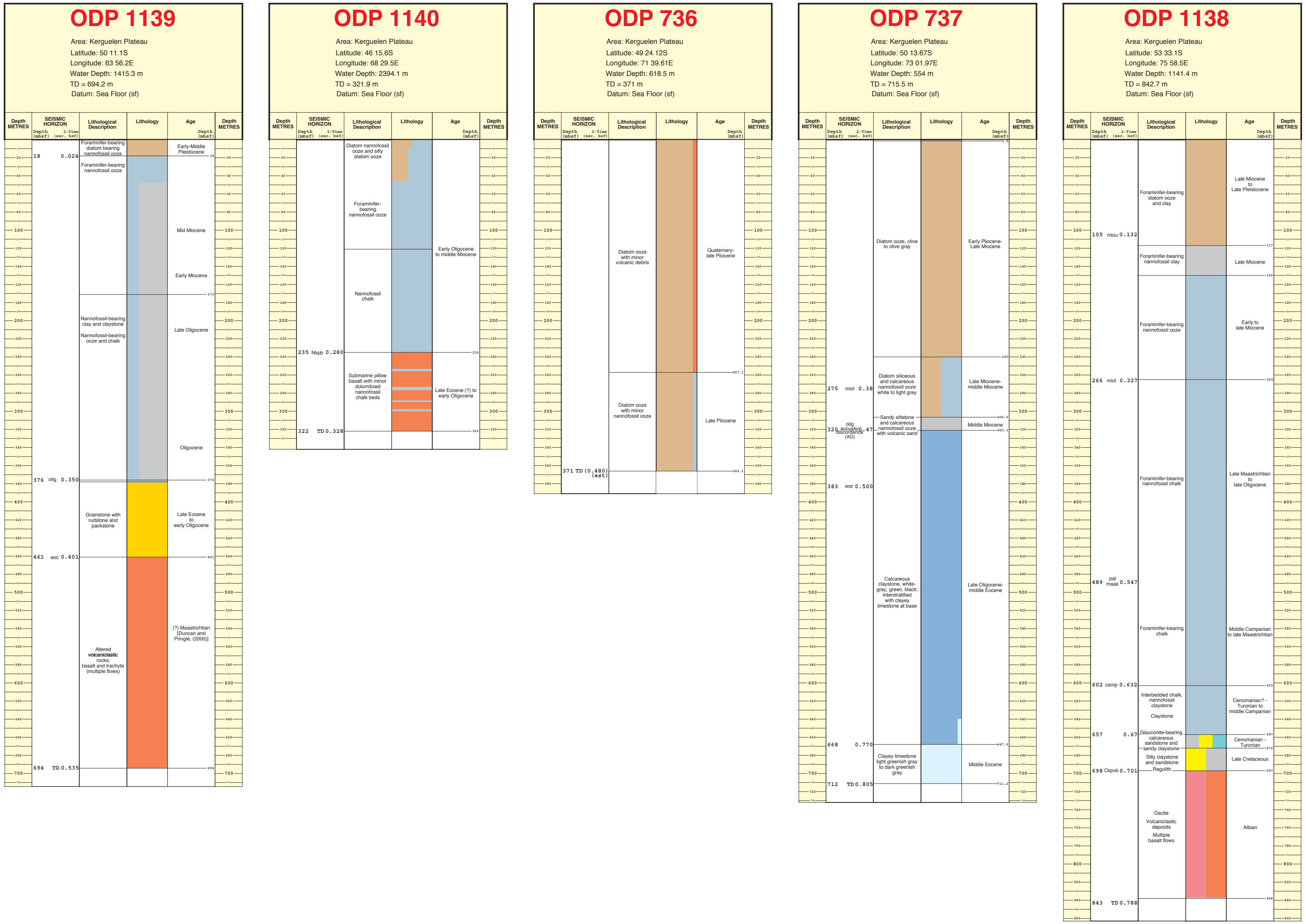
Surface sediment types
in the Kerguelen Plateau region

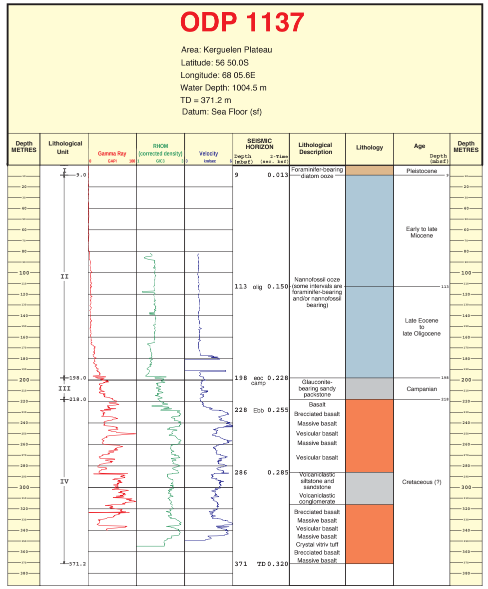
Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002.
Geological framework of the Kerguelen Plateau and adjacent ocean basins.
Geoscience Australia Record 2002/05

23/OA/1326

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

Well Composites - Skiff Bank, Northern and Central Kerguelen Plateau and Elan Bank.





LITHOLOGY LEGEND

- Diatom ooze
- Nannofossil ooze
- Nannofossil chalk
- Volcaniclastic
- Calcareous claystone
- Volcanic rock
- Conglomerate
- Sandstone
- Claystone
- Glauconite
- Limestone
- Dacite
- Interbedded chalk and clay
- Diatomite
- Zeolitic sand
- Regolith
- Packstone
- Foraminiferal ooze
- Calcareous

References

Barron, Larson et al, 1989
Barron, Larson et al, 1991
Coffin et al, 1990
Coffin, Frey, Wallace et al 2000
Duncan and Pringle, 2000
Fritsch et al 1992
Munschy et al 1994
Munschy, Rotstein et al 1993
Pringle and Duncan, 2000
Schlich, Wise et al, 1989
Wise, Schlich et al, 1992
Geological timescale, AGSO, 1999
Cande and Kent, 1995
Nicolaysen et al, 2001
Weis et al, 2001

Compiled by A. Moore and P. Butler, June 2000.

23/OA/1112

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Plate 7

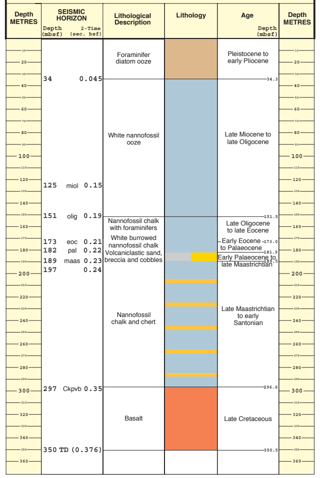
Composite logs for ODP Sites 1139, 1140, 736, 737, 1138, 1137

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

Well Composites - Central and Southern Kerguelen Plateau.

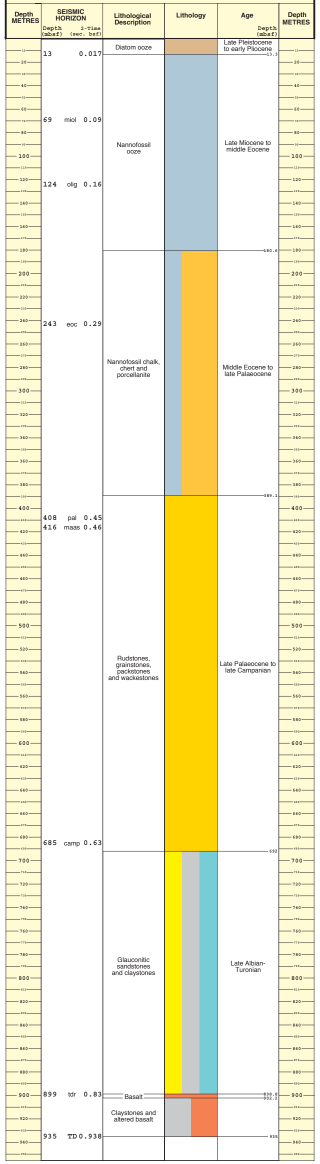
ODP 747

Area: Kerguelen Plateau
Latitude: 54 48.68S
Longitude: 76 47.64E
Water Depth: 1695 m
TD = 350.5 m
Datum: Sea Floor (sf)



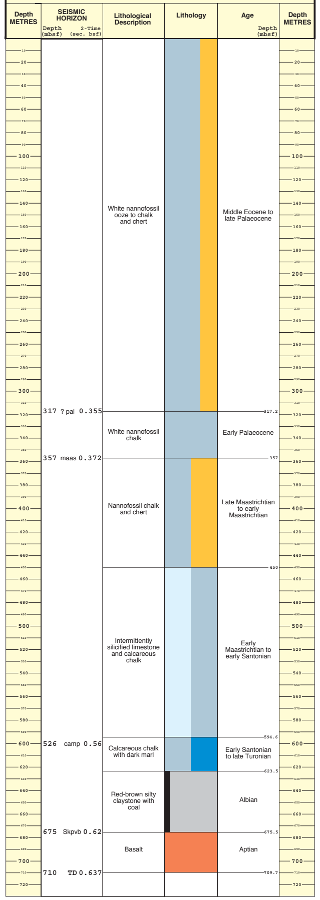
ODP 748

Area: Kerguelen Plateau
Latitude: 58 26.45S
Longitude: 78 58.89E
Water Depth: 1277 m
TD = 935 m
Datum: Sea Floor (sf)



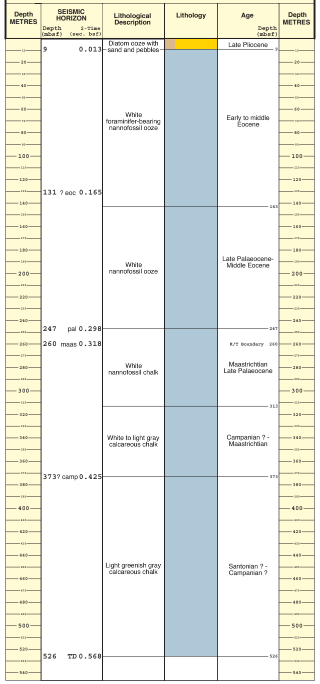
ODP 750

Area: Kerguelen Plateau
Latitude: 57 35.54S
Longitude: 81 14.42E
Water Depth: 2030.5 m
TD = 709.7 m
Datum: Sea Floor (sf)



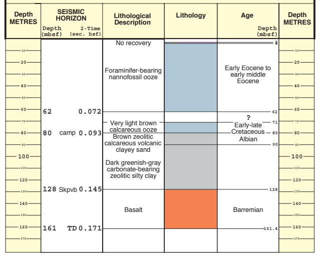
ODP 1135

Area: Kerguelen Plateau
Latitude: 59 42.0S
Longitude: 84 16.4E
Water Depth: 1566.6 m
TD = 526 m
Datum: Sea Floor (sf)



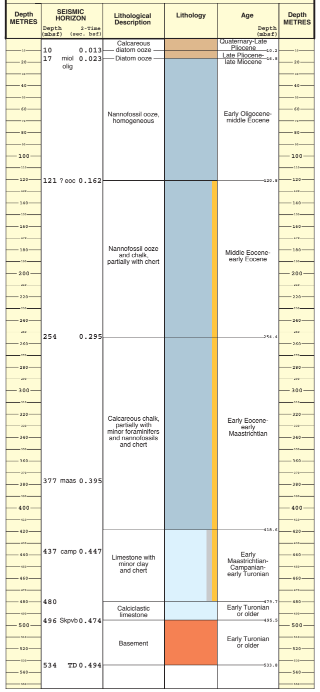
ODP 1136

Area: Kerguelen Plateau
Latitude: 59 39.1S
Longitude: 84 50.1E
Water Depth: 1930.6 m
TD = 161.4 m
Datum: Sea Floor (sf)



ODP 738

Area: Kerguelen Plateau
Latitude: 62 42.54S
Longitude: 82 47.25E
Water Depth: 2242.2 m
TD = 533.8 m
Datum: Sea Floor (sf)



LITHOLOGY LEGEND

References

Barron, Larson et al., 1989
Barron, Larson et al., 1991
Coffin et al., 1990
Coffin, Frey, Wallace et al 2000
Duncan and Pringle, 2000
Fritsch et al 1992
Munschy et al 1994
Munschy, Rotstein et al 1993
Pringle and Duncan, 2000
Schlich, Wise et al, 1989
Wise, Schlich et al, 1992
Geological timescale, AGSO, 1999
Cande and Kent, 1995
Nicolaysen et al, 2001
Weis et al, 2001

Compiled by A. Moore and P. Butler, June 2000.

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

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Plate 8

Composite logs for ODP Sites 747, 748, 750, 1135, 1136, 738

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

KERGUELEN PLATEAU

STRATIGRAPHY, SEALEVEL, TECTONIC EVENTS AND SEISMIC HORIZONS

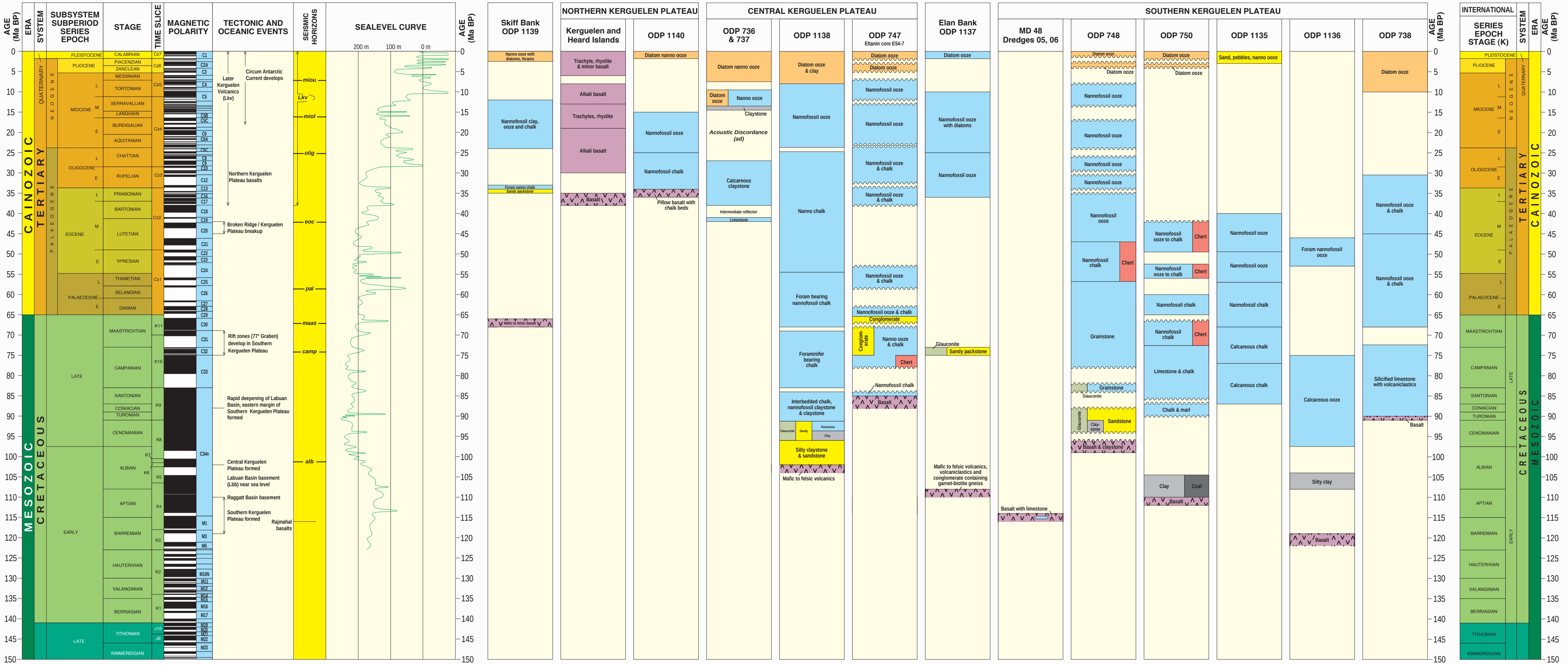


Chart stratigraphy: Aidan Moore

Digital compilation: Neville Montgomerie

Sediment type

- Cold water biogenic
- Marine
- Terrestrial
- Igneous

References

Barron, Larson et al, 1989
Barron, Larson et al, 1991
Coffin et al, 1990
Coffin, Frey et al, 2000
Duncan and Pringle, 2000
Fritsch et al, 1992
Leclaire, Bassias, et al, 1987
Munschy and Schlich, 1987
Munschy et al, 1994
Munschy, Rotstein et al, 1993
Pringle and Duncan, 2000
Schlich, Wise et al, 1989
Wise, Schlich et al, 1992
Geological timescale, AGSO, 1999
Cande & Kent, 1995
Nicolaysen et al, 2001
Weis et al, 2001

23/OA/1113

Geoscience Australia - Law of the Sea Project

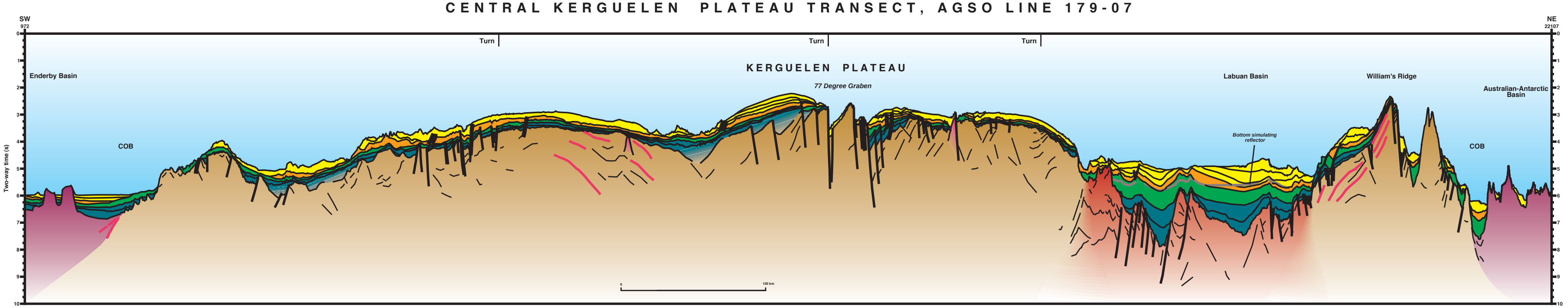
Plate 9

Composite chronostratigraphic chart of the Kerguelen Plateau, showing stratigraphy, sea level, tectonic and oceanic events and seismic horizons

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

CENTRAL KERGUELEN PLATEAU TRANSECT, AGSO LINE 179-07



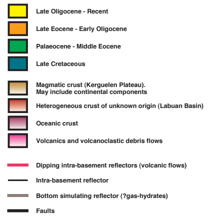


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Plate 10

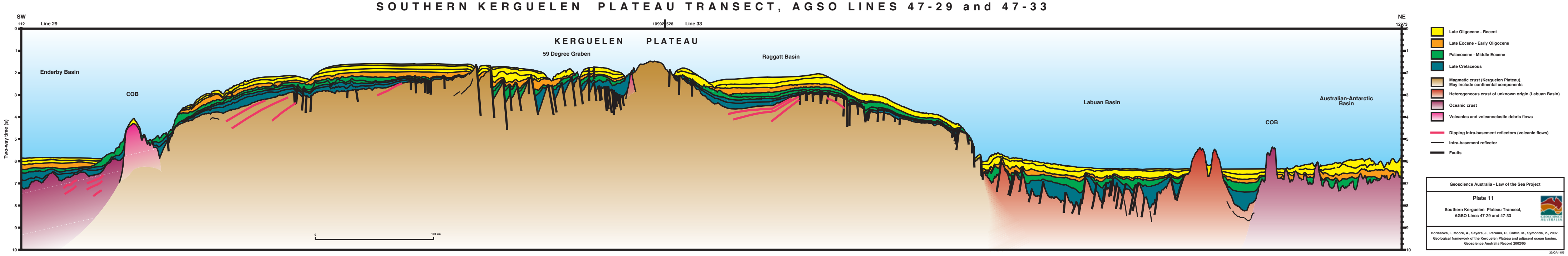
Central Kerguelen Plateau Transect, AGSO Line 179-07

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1154

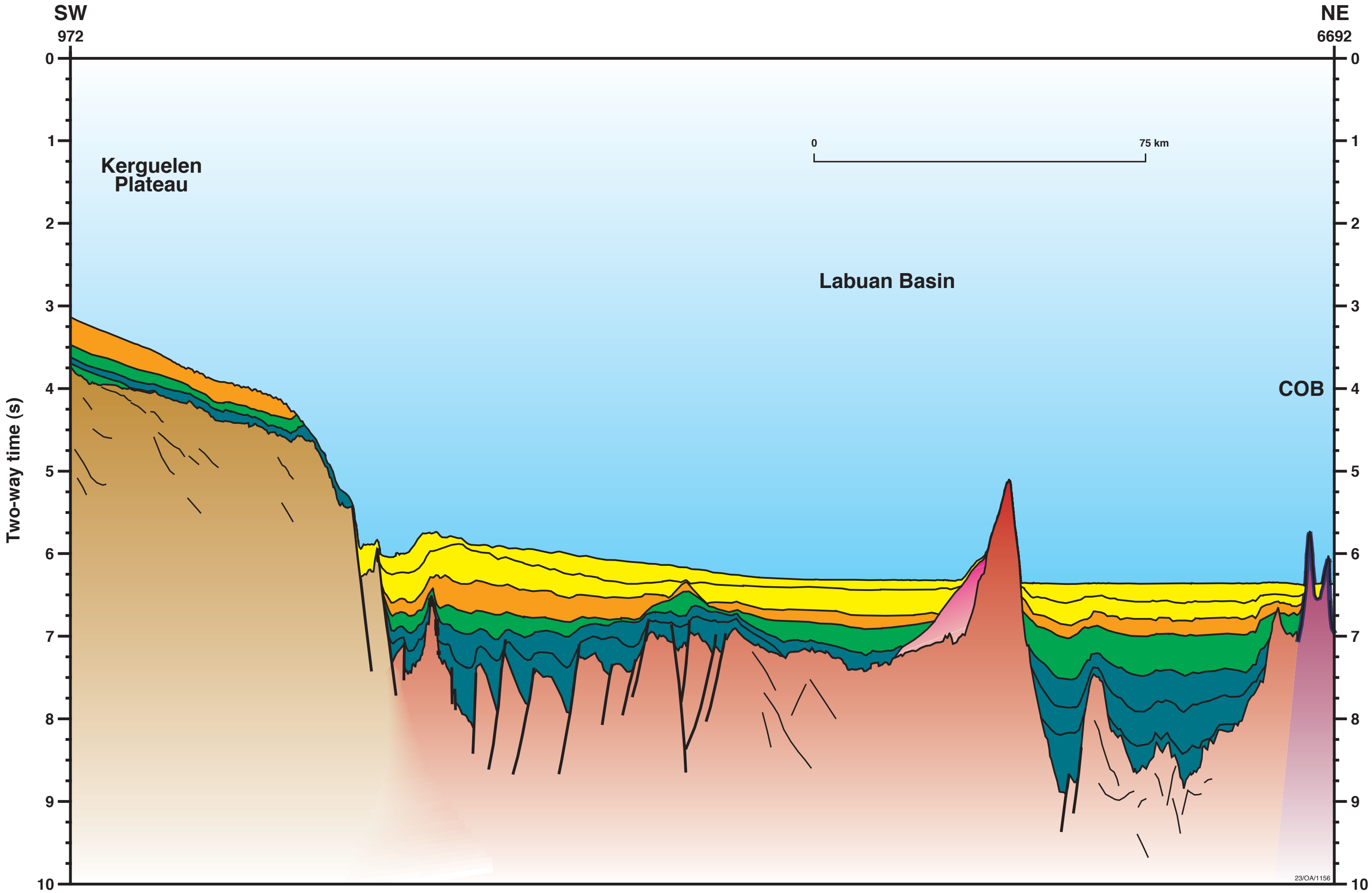
High resolution plot files of Plates 1-12 suitable
for large size plotters can be found in the Plot
files sub-directory as .PS or .RTL on this CD

SOUTHERN KERGUELEN PLATEAU TRANSECT, AGSO LINES 47-29 and 47-33



High resolution plot files of Plates 1-12 suitable for large size plotters can be found in the Plot files sub-directory as .PS or .RTL on this CD

LABUAN BASIN TRANSECT, AGSO LINE 180-07



- Late Oligocene - Recent
- Late Eocene - Early Oligocene
- Palaeocene - Middle Eocene
- Late Cretaceous
- Magmatic crust (Kerguelen Plateau). May include continental components
- Heterogeneous crust of unknown origin (Labuan Basin)
- Oceanic crust
- Volcanics and volcanoclastic debris flows
- Intra-basement reflector
- Faults

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Plate 12

Labuan Basin Transect,
AGSO Line 180-07

GEOSCIENCE AUSTRALIA

Borissova, I., Moore, A., Sayers, J., Parums, R., Coffin, M., Symonds, P., 2002. Geological framework of the Kerguelen Plateau and adjacent ocean basins. Geoscience Australia Record 2002/05

23/OA/1156

Instructions for the CD-ROM

GEOLOGICAL FRAMEWORK OF THE KERGUELEN PLATEAU AND ADJACENT OCEAN BASINS

This CD-ROM contains the above-titled document as GeoscienceAustraliaRecord2002_05.pdf

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

Once the reader is installed, go to the Record directory, double click on the GeoscienceAustraliaRecord2002_05.pdf to launch the document.

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

Directories on this CD

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

Plot files directory:
With sub-directories of Postscript (.PS) and Raster Transfer Language (.RTL) of the Plates used in this Record. Suitable for plotting to large format plotters.

Record directory:
GeoscienceAustraliaRecord2002_05.pdf