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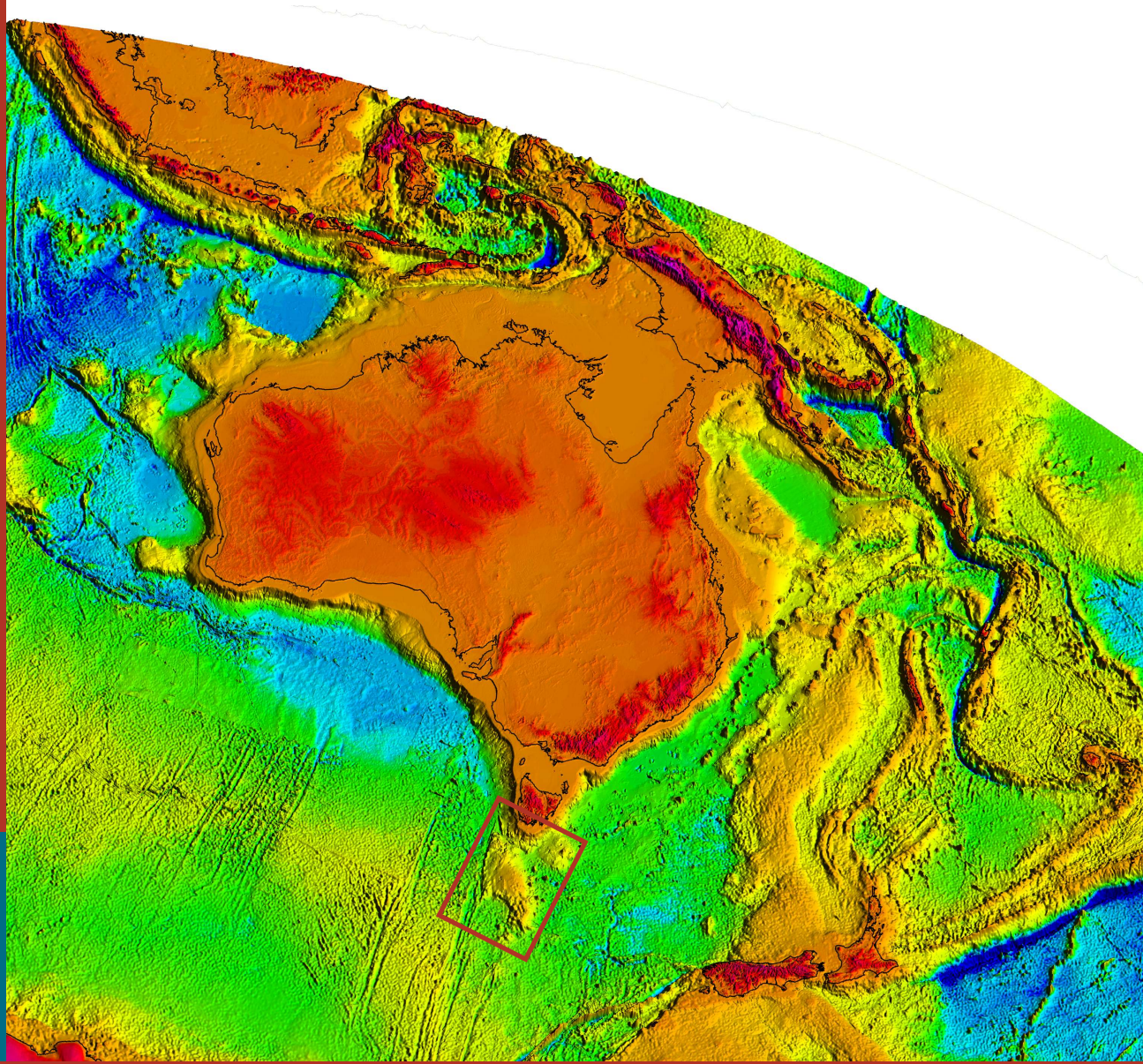
Geological framework of the South Tasman Rise and East Tasman Plateau

P.J. Hill and A.M.G. Moore



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Geological framework of the South Tasman Rise and East Tasman Plateau

by

P.J. Hill and A.M.G. Moore

Geoscience Australia

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ABSTRACT

The South Tasman Rise (STR) and East Tasman Plateau (ETP) are large submerged continental blocks that abut southern Tasmania, and cover an area of ~230,000 km². They are separated from Tasmania by 3000 m deep saddles underlain by transitional crust, but elsewhere are surrounded by oceanic crust of Campanian to Palaeogene age. Since 1994, the region has been the focus of a number of major geoscientific investigations including seismic surveys, seabed swath-mapping, geological sampling and ODP deep-sea drilling. These have led to a greatly improved understanding of the geology and evolution of this remote region.

The STR and ETP evolved in the Late Cretaceous as this part of eastern Gondwana began to fragment, creating a number of microplates. The structural development of the region has been dominated by wrenching associated with the NW-SE Tasmanian-Antarctic Shear Zone (active from early Late Cretaceous to Paleocene), Tasman Basin rifting and breakup (early-mid Late Cretaceous), Paleocene breakup at the southern margin of the STR, and Tertiary STR/Antarctica transform movement along the N-S Tasman Fracture Zone.

The STR comprises two main structural provinces: (i) a complexly-deformed western block with mainly N-S trends and less-developed E-W trends, related to early Tertiary N-S STR-Antarctica wrenching overprinting NW-SE wrenching along the Tasmanian-Antarctic Shear Zone, and (ii) a structurally-simpler eastern block cored by shallow basement beneath the crest of the STR and flanked by narrow NW-SE trending rift basins.

Sedimentary basins on and adjacent to the STR and ETP contain at least 4 km of section consisting of Late Cretaceous to Eocene siliciclastics, overlain by Oligocene and younger pelagic carbonates. The siliciclastics, where drilled, comprise deltaic and shallow marine silty claystones, often rich in organic carbon. The western STR contains numerous small wrench basins comprising the Ninene Basin. Narrow NW-trending rift basins, with at least 3 km of section and 20-25 km wide, flank the central STR basement high. The margins of the oceanic L'Atalante Depression between the STR and ETP are underlain by more than 2 km of post-breakup sediments. On the ETP almost 2 km of post-breakup sediments overlie a probable volcaniclastic rift sequence of similar thickness.

Volcanic activity has been widespread and appears to be related to two main phases, Campanian (initial breakup) and Eocene (mantle plume/lithospheric tensile stress).

The STR/ETP region is a deep-water frontier, prospective for petroleum in the medium to long term. Very little industry exploration has been undertaken so far, but this is likely to change as existing oil and gas fields become depleted, and as technological advances permit drilling and production in deeper water. On the STR, narrow wrench basins with several kilometres of fill lie in water depths as shallow as 1400 m. ODP measurements indicate moderately high terrestrial heat flow in the region (55-72 mW/m²), with gradients of ~50º-60ºC/km in the upper section, suggesting oil maturation at less than 2 km depth. Palaeogene claystones provide a regional seal.

Bottom Simulating seismic Reflector (BSR)-like horizons have been identified over parts of the STR and adjacent areas (Stagg *et al.* 2001), but whether they are indicators of gas hydrates is questionable, and further work is needed to establish the presence of gas hydrates in the region. If proven, gas hydrate accumulations in the upper few hundred metres of the sedimentary section may have long-term resource potential.

Deep-sea ferromanganese nodules and crusts occur in the region. Extensive fields of manganese nodules have been identified in deep water (>2400 m depth) on the STR and adjacent abyssal plains. The nodules are commonly large (5-10 cm diameter), but their metal grades are sub-economic. Thick (to 20 cm) ferromanganese crusts are abundant on rocky substrates, and those recovered from within the oxygen-minimum zone (<2000 m depth) are high in cobalt. Such crusts may be of economic interest in the long term.

Key words: South Tasman Rise, East Tasman Plateau, L'Atalante Depression, Ninene Basin, tectonics, geological structure, sedimentary basin, sediment thickness, volcanics, petroleum, deep-sea minerals, UNCLOS, seismic survey, Ocean Drilling Program, Leg 189.

1. INTRODUCTION

This study of the geological framework of the South Tasman Rise (STR) and East Tasman Plateau (ETP), both located off Tasmania (**Figure 1**; **Plate 1**), was undertaken to assist documentation of critical information required to help define the outer limit of Australia's Continental Shelf under Article 76 of the United Nations Convention on Law of the Sea (UNCLOS 1983; **Appendix 1**), and to provide an understanding of geological processes and potential economic values to underpin promotion of future exploration activities. The ETP lies wholly within the Australian Exclusive Economic Zone (AEEZ), while only the northern half of the STR is within this zone (**Plate 1**). Both the STR and ETP form part of the Australian South-east Marine Region (Hill *et al*. 2001), for which an environmental management plan is currently being developed by the National Oceans Office (Hobart).

The STR and ETP are large submerged landmasses that form the southernmost part of the Australian craton (**Plates 1** & **2**). Together they cover an area of ~230,000 km², about the size of Victoria. The summit area of the STR is a broad dome about 750 m deep. The upper ETP lies mainly in water depths of 3000-2500 m and is topped by a large volcanic guyot, Cascade Seamount, that rises to 650 m below sea level (**Plate 1**). These continental fragments formed between Campanian and Eocene time, as eastern Gondwana broke up and seafloor spreading (**Figure 3**) separated them from Antarctica, the Lord Howe Rise and other continental microplates (Müller *et al.* 2000).

Sedimentary basins, containing at least several kilometres of apparently mainly Cretaceous-Cainozoic sediment fill, lie within and on the margins of these plateaus (**Figure 4**; **Plate 5**). Though basin development is extensive, depocentres are generally small and of complex architecture. This is a reflection of the region's complicated tectonic history. Only two of the basins have been named (Exon *et al.* 1997b): the Ninene Basin (**Figure 4**), an extensive series of depocentres beneath the western flank of the STR (covering ~30,000 km²), and the triangular-shaped Toogee Sub-basin that lies at the far northwestern extremity of the STR, adjacent to the southern Sorell Basin.

In terms of petroleum exploration, the STR and ETP are considered remote frontier areas, with only two industry reconnaissance seismic lines shot on the ETP, and no exploration wells drilled. A number of research cruises have focussed on the STR and ETP in recent years, resulting in considerable advances in our understanding of the structure and evolution of this region.

2. PREVIOUS SURVEYS AND STUDIES

Early research cruises in the region were by USNS *Eltanin*, RV *Vema* and RV *Robert D. Conrad*. Conducted in the late 1960s and early 1970s, these reconnaissance geophysical and geological sampling surveys (e.g. Hayes *et al*. 1975, 1976) resulted in the first regional marine geological studies of the southeast Indian Ocean basin (Hayes 1971). Exon (1995) provides a listing of cores taken by the relevant U.S. research institutions. In 1971, as Survey 11 of the Australian Continental Margin Survey, sparker seismic and geopotential data were acquired over a pattern of lines across the northern STR and on the ETP (Cameron & Pinchin 1994). The only industry multichannel seismic lines shot beyond the shelf edge off southern Tasmania were acquired in 1973 by Shell International Petroleum using MV *Petrel*. During this survey, a broad pattern of zigzag lines was shot across the west and east Tasmanian margins.

The first sub-bottom geological information from the STR region was obtained in 1973 with the drilling of several sites during Leg 29 of the Deep Sea Drilling Program (Kennett, Houtz *et al*. 1975a). At Site 281 on the upper southern flank of the STR, the drill bottomed in Palaeozoic mica schist, proving the continental nature of the STR. Both Site 280 (south of the STR) and Site 283 (east of the ETP) were drilled on oceanic crust, shown to be of Paleocene age. At Site 282, on the lower continental slope off western Tasmania, basement comprises pillow basalts of early Palaeogene age.

Scientific exploration activity waned, until in 1985 the German RV *Sonne* completed two research cruises, one geophysical (SO-36B) and the other geological (SO-36C), off the west Tasmanian margin and the STR (Hinz *et al.* 1985). The research program was a cooperative venture between the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and the Australian Bureau of Mineral Resources (BMR). On the STR, nine regional multichannel seismic lines were shot (**Plate 5**) and 19 sampling stations occupied (summarised in Exon *et al*. 1995).

Geoscience survey activity in the region intensified from 1994 onward, with AGSO playing a significant role. Investigations since then have included seabed swath-mapping, reflection seismic surveys, geological sampling and ODP deep-sea drilling. As a result, an extensive grid of multichannel seismic lines now exists over much of the region (**Figure 2**). The swath-mapping has produced detailed images of the seafloor morphology and shallow structure of the central and northern STR, and also the central and southwestern parts of the ETP (**Figures 1** & **2**; **Plate 1**).

The first major multibeam sonar survey in Australian waters, the TASMANTE survey (AGSO Survey 125, Exon *et al.* 1994) in 1994, swath-mapped the northern and central STR and ran a single line across the top of the ETP. Seismic reflection and other geophysical data were also collected on this survey. A follow-up geological sampling cruise in 1995 (AGSO Survey 147, Exon *et al.* 1995) resulted in successful recovery of rocks and sediments from over 70 dredge and core stations in the STR/ETP area.

Also in 1995, a circum-Tasmania deep seismic survey by AGSO (Survey 148/159, Hill *et al.* 1995b) included several lines over the far northwestern tip of the STR. *Marion Dufresne*, in 1997 and as part of the global palaeoclimate IMAGES program, took long piston cores at three widely-separated stations on the margins of the STR. In 1998, a 3900-km regional network of deep seismic lines (AGSO Survey 202, Bernardel 1999) was shot over the STR and ETP as part of AGSO's Law of the Sea Program to support definition of the outer limit of Australia's marine jurisdiction under UNCLOS. In late 1998, during the RV *Sonne* TASQWA expedition (survey SO136; Thiede, Nees *et al.* 1999), a series of sampling stations (mainly gravity and box cores) were occupied along a S-N transect that included the eastern margin of the STR. During this cruise, short site surveys for several proposed Ocean Drilling Program (ODP) sites (under ODP Proposal 485, Exon *et al.* 1996 – later to become Leg 189) were conducted on the STR and ETP by Atlas Hydrosweep multibeam and Parasound sub-bottom profiler.

In early 2000, the AUSTREA surveys (AGSO Survey 222, Hill *et al*. 2000, Hill *et al*. 2001; AGSO Survey 223, Bernardel *et al.* 2000) swath-mapped and acquired seismic profiles over much of the western ETP, the eastern STR and their summit areas. These surveys were commissioned by the National Oceans Office and Environment Australia and were designed to provide data mainly for regional marine planning and management.

They were followed in mid-2000 by Leg 189 of the ODP (Exon *et al.* 2001a,b), during which drill-ship *Joides Resolution* drilled and cored five sites off Tasmania (**Figures 2** & **5**; **Plates 1**, **7** & **8**). Leg 189 was designed to study changes in sedimentation, oceanography and climate caused by Australia's movement northward from Antarctica during the Cainozoic. The sites included three on the STR, with penetration ranging between 246 and 959 m and oldest section of late Paleocene age, and one on the ETP which intersected the K-T boundary and bottomed in Maastrichtian claystones at 766 mbsf (metres below sea floor). At about the same time, the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover, Germany), using *Polar Duke*, shot a number of seismic lines in the poorly-explored southern STR area. An important line was a long E-W transect (D in **Figure 2**) across the southern Rise, and crossing the southernmost ODP site (1171).

In April 2001, RV *Franklin* seismic and geological sampling cruise FR3/01 (AGSO Survey 226; Exon *et al.* 2001c) acquired 1300 km of seismic data off east Tasmania, including the western ETP, and had successful recovery from 15 dredge and gravity core stations in this area.

Table 1 lists all multichannel reflection seismic surveys shot in the STR/ETP region. Shot-point maps for all these surveys, except BMR's 1971 CMS 11 sparker survey, are included in **Plates 5** and **6**.

The main stratigraphic control in the region is provided by the DSDP and ODP sites, plus one offshore well, Cape Sorell-1, drilled in the Strahan Sub-basin off western Tasmania by Amoco Australia Petroleum Company in 1982 (**Figure 2**; Amoco 1982).

Framework studies of the STR include Hinz *et al.* (1985), Willcox (1989), Salge (1989), Exon *et al.* (1997b), Hill *et al.* (in press), while the main reference on the ETP is Exon *et al.* (1997a).

3. REGIONAL GEOLOGICAL AND TECTONIC SETTING

During the Late Jurassic to Early Cretaceous, the area south of Tasmania was located on a bifurcation of the Southern Rift System (Willcox & Stagg 1990; Norvick & Smith 2001). Sediments equivalent to the volcaniclastic Otway and Strzelecki Groups in the Otway, Bass and Gippsland Basins could be expected in deep grabens of the STR (Symonds *et al.* 1996). Strong northwest structural trends, consistent with major strike-slip movements (and inferred local transtension) are observed, and represent a continuation of the wrench pull-apart sub-basins of the Sorell Basin aligned along the west Tasmanian continental margin (Moore *et al.* 1992; Hill *et al.* 1997b). To what degree wrench structures may have developed at this time, and their relationship to later movements along the Tasmanian-Antarctic Shear (see below), is not clear. Though Early Cretaceous depocentres probably developed south of Tasmania, sediments of this age have yet to be recovered from this area.

In southeast Australia, Cenomanian uplift and erosion (O'Sullivan & Kohn 1997) was followed by renewed continental rifting, which by ~83 Ma (Early Campanian) led to synchronous breakup in the Bight Basin (Sayers *et al.* 2001) and southern Tasman Basin (Royer & Rollet 1997; Gaina *et al.* 1998). Seafloor spreading adjacent to the ETP and eastern STR was in a SW-NE direction, with opening between these features forming the L'Atalante Depression (**Figure 3**). Meanwhile, opening in the Great Australian Bight was linked to a major transform shear zone, the Tasmanian-Antarctic Shear (Exon *et al.* 2001b), trending northwest off western Tasmania and intersecting the proto STR.

By the Paleocene, a shift in relative motion between the Antarctic and Australia plates to a more N-S direction (Tikku & Cande 1999) led to onset of seafloor spreading off western Tasmania (Hill *et al.* 1997) and break-off of part of the Antarctic plate (the western STR terrane), which became welded to the eastern STR block, resulting in the present composite STR (Royer & Rollet 1997). At this time, or possibly earlier, seafloor spreading began at the southern margin of the STR (Pyle *et al.* 1995; Cande *et al.* 2000; Norvick & Smith 2001), and ceased soon after in the Tasman Basin (55-50 Ma, Royer & Rollet 1997).

Though the continental fragmentation in the STR region up to this time is broadly understood, consensus on the details of plate reconstruction and kinematics remains elusive, as shown by comparison of recent reconstruction models (e.g. Müller *et al.* 2000 and Norvick & Smith 2001).

Fast N-S seafloor spreading in the Southern Ocean, commencing at ~43 Ma, led to separation of the STR from Antarctica along the Tasman Fracture Zone, producing a major 500-km long escarpment along the western STR (**Figure 1**; **Plate 1**). The STR and Antarctica cleared each other at the southwestern tip of the STR at ~33 Ma, resulting in the opening of the Tasmanian Gateway (Exon *et al.* 2001a), which had profound effects on regional sedimentation. The Southeast Indian Ridge (SEIR) cleared the STR's southwest tip at ~23 Ma (Early Miocene).

4. GEOMORPHOLOGY, SEABED SAMPLING AND GEOLOGY

The STR and ETP region is one of spectacular morphology and relief (**Figure 1**; **Plate 1**), having been shaped by the processes of plate tectonics, both passive and transform continental margin development, and volcanism. New high-resolution bathymetry and backscatter swath images now available over much of the region provide a wealth of information on structural detail and nature of the seabed (Hill *et al.* 1995a; Exon *et al.* 1996; Hill *et al.* 1997a; Exon & Hill 1999, Hill *et al*. 2001).

Extensive early Tertiary volcanism has significantly modified the submarine landscape, creating large volcanoes 2 km high. These are located in the deeper water areas on and adjacent to the oceanic basins (off the ETP and in the L'Atalante Depression; **Plate 1**) and on the extremely thin continental crust of the South Tasman Saddle between Tasmania and the STR. Volcanism also covered large areas with volcanic cones and lava fields (Hill *et al*. 2001), particularly just south of Tasmania, on the continental slope and in the South Tasman Saddle. Extensive volcanic terrain is also located on the summit area of the STR, and at the far southeast tip. Bedrock exposures are also common in some parts of the region. These include the western edge of the STR (adjacent to the Tasman Fracture Zone), the Lowreenne Massif (at the northwestern corner of the STR), and the summit area of the STR (Hill *et al*. 2001).

The abyssal region west and southwest of the STR (along and west of the Tasman Fracture Zone) is floored by oceanic basalts, with only patchy thin sediment cover in places (**Figure 4**; **Plate 5**). Multibeam swaths in this area show well-developed seafloor spreading fabric (Exon & Hill 1999; **Plate 1**) and high backscatter, while seismic profiles show a rough basement surface with little or no sediment cover. In contrast, the floor of the L'Atalante Depression and abyssal areas adjacent to the ETP are relatively flat and thickly sedimented (**Figures 4** & **12**).

Geological sampling (e.g. Hinz *et al*. 1985; Exon *et al.* 1995; **Plate 2**) has shown the STR and ETP to be geologically complex continental blocks, cored by gneisses, granites and metasediments, some of them similar to the Palaeozoic basement rocks of Tasmania (Berry *et al.* 1997). The oldest datable sediments recovered by dredging from the STR and ETP are Middle Eocene immature, poorly-sorted sandstones and mudstones (Exon *et al.* 1995). However, the presence of Early Cretaceous palynomorphs in some of the Eocene samples (Truswell 1997) suggests that Early Cretaceous non-marine synrift sediments have been reworked and may be located nearby. Gravity coring at several sites on the southeast Tasmanian mid continental slope off Storm Bay recovered the oldest (post-Triassic) sediments so far sampled in the region - late Campanian sandstones and siltstones (Harris *et al.* 1999).

Nature and Age of Volcanics

Volcanics dredged in the region generally exhibit strong seafloor weathering and alteration, and have mostly been unsuitable for radiometric dating. Alkali olivine basalts from the Cascade Seamount are well preserved and give an age of ~36-40 Ma, consistent with biostratigraphic evidence (Quilty 1997). These basalts are considered to be of intraplate hot-spot origin (Crawford *et al.* 1997), with Cascade Seamount forming part of the Balleny chain (Lanyon *et al.* 1993; Sutherland 1994). Basalts dredged from seamounts in the L'Atalante Depression, and also from the STR, show strong affinities with those of the Cascade Seamount (Crawford *et al.* 1997) implying a similar origin and possibly similar age.

Though located farther north, off northeast Tasmania, St Helens Hill is a volcanic cone with morphological similarities to the many cones mapped off southern Tasmania. An olivine basalt pebble dredged (Hill 1999) from this 450-m high edifice gave an Ar-Ar age of 45-50 Ma (analysis by D. Phillips, RSES, Australian National University). The only other age of volcanic rocks from offshore in the region comes from basalt at the base of DSDP Site 280, located on oceanic crust just south of the STR (**Figures 2** & **4**). Pyle *et al.* 1995 showed the basalts to be of typical mid-ocean ridge composition (N-MORB), with an Ar-Ar age of 64 Ma, indicating that seafloor spreading started here in the Paleocene, or earlier.

5. STRATIGRAPHY AND SEISMIC HORIZONS

Regional Stratigraphic Correlation

Stratigraphic control from drilling in the region is provided by four sites of DSDP Leg 29 (Kennett, Houtz *et al.* 1975a), five sites of the recent ODP Leg 189 (Exon *et al.* 2001b), and the Cape Sorell-1 petroleum exploration well off western Tasmania (**Figures 2** & **5**; **Plates 7** & **8**; **Table 2**). All drill-holes are tied to the seismic grid (**Figure 2**). Geological sampling of seabed outcrops (Hinz *et al*. 1985; Exon *et al.* 1995; Harris *et al.* 1999) provides additional control on seismic stratigraphy.

Figure 5 summarises the drill-hole chronostratigraphy, and correlations with regional tectonic and oceanographic events. The layout is roughly from the northwest to the southeast. Details of the regional stratigraphy and petroleum implications, particularly in the light of the new Leg 189 results, are provided by Exon *et al*. (in press).

DSDP Leg 29 was the first major coring activity around the STR. Site 280 was drilled on oceanic crust bordering the STR in the south, and Site 281 was drilled near the bathymetric crest, while Site 283 was drilled in the oceanic Tasman Basin to the east of the ETP.

Drilling at DSDP Site 280 (**Plate 8**) intersected marine sediments on oceanic crust southwest of the STR, and bottomed in an intrusive basalt. It penetrated a veneer of Late Miocene to Late Pleistocene clay and ooze underlain, beneath a sampling gap, by 55 m of siliceous Early Oligocene sandy silt, and 428 m of Middle Eocene to Early Oligocene sandy silt, containing chert in the upper 100 m, and glauconite and manganese micronodules below that depth. The lower 200 m is rich in organic carbon (0.6-2.2%). All sediments are presumed to be abyssal types. DSDP Site 281 (**Plate 8**) was drilled on the STR southwest of its culmination, and bottomed in a quartz-mica-chlorite semischist, created by very low-grade regional metamorphism of sediments (Ovenshine *et al.* 1975). Two whole-rock K-Ar ages were 306±10 Ma (Late Carboniferous). These were the first continental basement rocks recovered from the STR. The hole intersected 36 m of Plio-Pleistocene foram-nanno ooze, 79 m of Miocene foram-nanno ooze, and 3 m of Late Oligocene glauconite-rich detrital sand. Below a major hiatus, it drilled about 33.5 m of shallow-marine late Eocene sediment including an upper 28.5 m of grayish-olive sandy silt and silty clay, a middle 3 m of detrital sand and nanno chalk, and 2 m of basal conglomerate. DSDP Site 283 (**Plate 8**) was drilled on the abyssal plain of the Tasman oceanic basin about 200 km east of the East Tasman Plateau. It penetrated 13 m of Plio-Pleistocene zeolitic clay, 163 m of Late Eocene siliceous ooze, 139 m of Middle Eocene silty clay, and 273 m of Paleocene silty clay with chert, before bottoming in 4 m of pillow basalt.

The oldest sediments drilled on the STR are from the base of ODP Site 1171 (959 mbsf) and consist of late Paleocene (58 Ma) organic silty claystones (**Plate 8**). On the ETP, Site 1172 drilled to 766 mbsf obtained dark, organic-rich, silty claystones of Maastrichtian age (**Plate 8**). The most prominent regional unconformity is at the Eocene-Oligocene boundary (~33 Ma), and corresponds to a dramatic change in sedimentation patterns associated with the opening of the Tasmanian Gateway (Kennett, Houtz *et al.* 1975b; Exon *et al.* 2001a). The unconformity (‘clearance hiatus’) is marked by deposition of glauconitic units, and generally separates underlying Maastrichtian-Eocene siliciclastic deltaic/shallow marine sequences from overlying pelagic carbonates (**Figure 5**).

Composite Logs

The lithostratigraphy of the DSDP and ODP bores is displayed, together with selected wireline logs and the results of sedimentological studies, on **Plates 7** & **8**. Some wireline logs are missing or incomplete (e.g. at ODP 1169 and 1170) because of adverse logging conditions at the sites.

The largely Neogene carbonate succession is characterised by the low gamma-ray log response and the high values of the calcium carbonate log. The sand log shows significant values only in the Palaeogene succession, reflecting, like the gamma log, the terrigenous content of the older succession, and its absence in the Neogene. The total organic carbon (TOC) log shows low values in the carbonate succession, reflecting the open-ocean environment of the Neogene, which was not conducive to the preservation of organic matter, and higher values in the clastic succession, reflecting the more restricted circulation and less oxygenated environment of the Australo-Antarctic Gulf during the Cretaceous and early Tertiary.

Australo-Antarctic Gulf Succession (Cretaceous–Late Eocene)

This succession is found on the western side of the emergent STR. It is most fully developed in the Sorell Basin and the Ninene Basin. It is not found in the east, where sediments of this

age were deposited in the environment of the Tasman Basin. The Australo-Antarctic Gulf succession consists primarily of Palaeogene detrital sediments (drilled and cored from the STR by DSDP and ODP, and dredged during sampling cruises) and inferred Cretaceous detrital sediments. Seismic profiles indicate that this is part of a Palaeogene, and probably Late Cretaceous, prograded sequence that, in basinal areas, averages 1000-2000 m thick and reaches a maximum thickness close to 5000 m in some of the numerous small depocentres.

Most of the dredged samples from a dozen stations (Exon *et al*. 1995) are immature poorly sorted sandstones and mudstones. Most lithologies are massive and bioturbated, but some are laminated, and one is varved (DR14/A6).

Truswell (1997), after palynological examination of two dredge hauls from the Toogee Ridge area, suggests that much of the sequence was laid down in cool shallow seas, and that part at least is of Middle Eocene age. She also found that, as in all Tertiary sediments from southeast Australia, reworked Early Permian and Early Cretaceous palynomorphs are common. This suggests that Early Cretaceous sediments were being eroded in the vicinity in the Eocene, but the Early Permian palynomorphs could have been recycled through the Early Cretaceous sediments.

DSDP Site 281, on the central STR (Kennett, Houtz *et al*. 1975a), penetrated Late Eocene shallow-marine sediments above basement. The sediments consist largely of greyish-olive, glauconite-bearing silty sand to silty clay, with benthic forams, radiolarians, diatoms and sponge spicules. Similar mudstones, of probable Eocene age, were recovered by RV *Sonne* (Hinz *et al*. 1985) in two dredges and four cores. These mudstones are zeolitic and highly bioturbated, with little evidence of bedding, and contain poorly preserved radiolarians and arenaceous forams. They contain glauconitic sand and are partly silicified or finely bedded.

This, and the seismic evidence, suggests that the Eocene sediments sampled are part of a marine deltaic sequence that was laid down in depocentres forming as rifting developed between Australia and Antarctica, from Late Cretaceous to Late Eocene times. ODP 1170 on the southeastern side of the western STR drilled Eocene detrital sediments, and ODP 1171, south of the central STR, drilled Eocene and Paleocene clastics. However, despite the palaeoenvironments being similar to those at sites farther north, plate reconstructions (e.g. Exon *et al.* 2001b) show that Site 1171 was closer to the developing Pacific Ocean than to the Australo-Antarctic Gulf.

Eocene-Oligocene Regional Hiatus - the ‘Clearance Hiatus’

The Late Eocene to Oligocene regional hiatus marks the opening of the Tasmania seaway between the Australian and Antarctic continents, at ~33.5 Ma, when the Antarctic continental margin cleared the Australian margin at the southwestern end of the STR during the episode of rapid seafloor spreading between Australia and Antarctica that began in the mid Eocene. The clearance created a deep-water passage from the Indian Ocean into the southern Pacific Ocean, ending isolation of the Australo-Antarctic Gulf. Instead of being a semi-enclosed sea with restricted circulation, blocked at its eastern extremity by the STR, it became a part of the new Southern Ocean, and a passage for the circum-Antarctic flow of oceanic water. Strong currents were initiated, which inhibited or prevented the deposition of sediments especially on the western and southern flanks of the STR, and may even have caused erosion of soft sediments. The effects can be seen in the stratigraphic diagrams (**Figure 5**; **Plates 7** & **8**). The hiatus is not so pronounced to the north, on the west Tasmanian margin, which is far from the site of the opening seaway, hence not exposed to the maximum current activity during the opening. It is present on the STR, and especially at DSDP Site 280, which is close to the

gateway. It is much less evident at ODP 1172 on the ETP, which lies adjacent to the Tasman Basin, down-current from the seaway.

The 'clearance hiatus' marks a change in the stratigraphy of the western areas especially. The succession beneath is dominated by clastics deposited in relatively shallow water; the succession above is dominated by deep-sea carbonates.

Southern Ocean Succession, Oligocene-Recent

Late Oligocene and younger sediments are widespread on both STR and ETP (**Plate 6**), and have been dredged, cored and drilled. They overlie the regional early Oligocene hiatus ('clearance hiatus') cut by the circum-Antarctic current that first came into existence when Australia and Antarctica completely separated (Kennett, Houtz *et al*. 1975b). Sediments recovered include a late Oligocene sequence that is detrital in some places and calcareous (biogenic) in others, Miocene and Plio-Pleistocene deepwater foram-nanno ooze, and some Pleistocene foram sand. The seismic profiles indicate that the post-clearance succession is typically 200-500 m thick in basinal areas (**Plates 6**, **9-11**).

At DSDP Site 281 (Kennett, Houtz *et al*. 1975a) the succession begins with a thin Late Oligocene shallow-marine, glauconite-rich detrital sand. It is unconformably overlain by Miocene foram-nanno ooze, and Plio-Pleistocene foram-nanno ooze. Micritic chalk and limestone have been dredged from areas of basement outcrop on the northern Rise (Exon *et al*. 1995), where sedimentation rates were low. They contain foraminifera, fish bones, quartz and lithic grains. X-ray diffraction analyses (DR11/C1 & C2) show that calcite and apatite are abundant. The limestones are believed to have been altered variably at the sea bed by phosphate-rich bottom waters of the oxygen-minimum zone.

Quaternary cores of calcareous ooze and foram sand record the changes in sedimentation controlled by climatic and current changes (Connell & Sikes 1997). Where measured, sedimentation rates are 2-5 mm per thousand years.

Seismic Stratigraphy

A preliminary regional seismic stratigraphy (**Figures 10-12**) has been devised to map sedimentary units and sequences on and adjacent to the STR and ETP. It is based on correlation of seismic horizons with drill-hole and sampling stratigraphy, and established tectonic control such as the ages of breakup and formation of oceanic crust. Eleven sub-bottom horizons, generally coinciding with mega-sequence boundaries, have been defined.

6. POST-LATE CRETACEOUS SEDIMENTATION AND PALAEOGEOGRAPHY

Sampling and ODP drilling (Exon *et al.* 2001b) in the STR/ETP region show that prior to the late Eocene, siliciclastic sediments (mainly silty claystones) were being deposited in a relatively warm sea on broad, tranquil shelves in a deltaic environment. Deposition was rapid with sediment supply keeping pace with subsidence and compaction. By the late Eocene, the land bridge between Tasmania and Antarctica had narrowed and began to subside allowing cool surface currents to start sweeping around Antarctica from the west. Glauconitic siltstones were deposited as condensed sequences.

By the early Oligocene, the Tasmanian Gateway had opened, intensifying circum-Antarctic circulation and cutting off warm currents from the tropics (Kennett, Houtz *et al.* 1975b; Exon *et al.* 2001a). Siliciclastic sedimentation ceased and was replaced by biogenic carbonate deposition that could not match subsidence, causing the STR and ETP to sink well below sea level. Hills on the summit area of the STR and the top of the Cascade Seamount would have been the last land areas, forming islands, before being inundated.

Modern sediments are now entirely deep-sea pelagic carbonates (foraminiferal and nanno-fossil oozes). Sediment-bare Oligocene-Neogene oceanic sea floor west of the STR (**Plate 6**), winnowed coarse foraminiferal sands on the summit area, and thick sediment drifts on its eastern side (**Figure 11**) are evidence of the strong easterly-flowing bottom currents that have been active here and continue to sweep this region.

Subsidence History

Deep drilling (766-958 m penetration) at four of the ODP Leg 189 sites permits construction of subsidence curves dating back at least to the late Eocene, and as far back as the Maastrichtian in the case of site 1172. Subsidence plots (**Figures 6-9**) were produced using WinBury V2.81 geohistory modelling software, microfossil and palaeomagnetic age control, and palaeodepth control from benthic forams and other microfossils. It should be noted that palaeodepths are not well constrained for the Neogene when the seafloor was lower bathyal or deeper. An exponentially-decreasing sag is inferred for the late Neogene because of the apparent relative tectonic quiescence during this period.

All plots show a rapid deepening in the Late Eocene. Off western Tasmania (1168) it apparently occurred at ~34 Ma, on the STR (1170 & 1171) at ~36 Ma, and on the ETP (1172) at ~35 Ma. All sites record an onset of rapid tectonic subsidence in the mid-Late Eocene. This appears to be related to the mid-Eocene start of rapid seafloor spreading in the southeast Indian Ocean, with regional tensile lithospheric stress (stretching and thinning) causing a general collapse of continental margins. The rate of tectonic subsidence peaked in the Oligocene, being highest off western Tasmania (~160 m/Ma), ~110-120 m/Ma on the STR, and lowest on the ETP (~90 m/Ma).

7. STRUCTURE AND BASIN ARCHITECTURE

Structural and sediment thickness maps of the region (**Figures 3-4**; **Plates 3-6**) are based on the integrated interpretation of about 15,000 km of seismic data (**Figure 2**), satellite gravity and seabed swath images (bathymetry and backscatter).

The main crustal structures, including rift basins and features such as large volcanoes, are well portrayed in the gravity imagery, particularly when combined with seabed relief imagery (**Figure 3**, **Plate 3**). The prominent NW-SE structural trend along the spine of the STR, and extending along the west Tasmanian margin, is a relic of the Tasmanian-Antarctic Shear, active in the Late Cretaceous to early Tertiary. A marked change in structural style occurs across the STR trend between 146°E and 147°E (Exon *et al.* 1996; Royer & Rollet 1997), from a structurally complex western block to a less complex eastern block. The more complex nature of the western terrain is related to deformation within the Tasmanian-Antarctic Shear during its transfer from the Antarctic to the Australian plate in the Paleocene, and then by N-S wrenching associated with transform movement along the Tasman Fracture Zone. The E-W Tertiary seafloor spreading fabric, truncated against the Tasman Fracture Zone west of the STR, is well expressed in the imagery (**Figure 3**; **Plates 1** & **3**).

The Tasman Sea part of the region, including the eastern STR, L'Atalante Depression and ETP, exhibits mainly NW-SE and NE-SW structural trends, consistent with the Tasman rift and spreading directions, respectively. The L'Atalante Depression is floored by sedimented oceanic crust. Arms of oceanic crust extend partly beneath the East and South Tasman Saddles (**Figure 3**; **Plate 3**). The seismic data indicate that the saddles are probably mostly underlain by highly extended continental crust but it is difficult to be certain because of the extensive volcanism in these troughs (Profile A, **Figure 10** & **Plate 9**; Profile F, **Figure 12** & **Plate 11**). The crust in these places is best referred to as transitional.

There is some uncertainty as to the southeastern extent of the continental STR. On the basis of morphology and some seismic data, it clearly extends to at least 50.0ºS (**Plates 1** & **5**). Just to the south and adjacent to Balleny Fracture Zone lies an elevated crustal block that is about 100 km across, and separated from the main part of the STR by a 4000 m deep passage (**Plate 2**). The summit of this block, located at ~50º 40'S 150º 05'E, lies at a relatively shallow depth of ~2300 m below sea level. A single AGSO seismic profile (202-10) across the western margin of this block shows at least 1.2 s two-way time (twt) of sedimentary section. Contorted strata in parts of the deeper section suggest past volcanic activity. Reflectors are present to sub-bottom depths of more than several seconds twt, and could represent a thick deformed sedimentary section containing igneous flows and intrusions. This block probably separated from the STR at about the time of breakup, and could be a thinned continental fragment of the STR or a crustal build-up formed by extensive late rift/breakup volcanism. Another possible continental fragment, albeit much smaller, may be present at the southwest margin of the STR. A 90-km long, NNW-trending ridge (centred at ~48º 25'S 145º 25'E; **Plates 1** & **3**) may represent a sliver of continental crust detached during transform movement on the Tasman Fracture Zone.

Relatively thick sedimentary basins with more than 2 s twt of section have developed over much of the region (**Figure 4**; **Plate 5**), including the western STR (Ninene Basin and Toogee Sub-basin), the flanks of the central STR, the margins of the L'Atalante Depression, and on the ETP. Beneath the western STR individual depocentres are relatively small (mainly less than 25 km across) and often rhomboid in shape, while on the flanks of the central STR the basins are deep and narrow (20-25 km wide) and trend NW-SE. Areas of shallow basement (mainly less than 300 m of cover) are associated with the summit area of the STR, oceanic crust west of the STR, and the blocky terrain (Lowreenne Massif) immediately south of the Toogee Sub-basin. This latter terrain could also include fault blocks of older sediments (?Early Cretaceous). In some areas such as the South Tasman Saddle, parts of the ETP and East Tasman Saddle, and the southeastern margin of the STR, potentially deep sedimentary section is masked in the seismic profiles by volcanics.

Additional useful structural information comes from magnetic anomaly imagery of the region (**Plate 4**). Data used in compiling this image include closely-spaced aeromagnetic data over Tasmania and some adjacent offshore areas. However, over the STR and ETP the image is based solely on ship trackline data, largely profiles acquired on the TASMANTE survey (Sheet 8 in Hill *et al*. 1997a). Interpretation is limited by the sparse coverage over parts of the region, and because the data are not corrected for diurnal and magnetic storm fluctuations – though levelling adjustments have been made based on profile ties (Petkovic *et al*. 2001). Nevertheless, many of the major structural boundaries mapped on the basis of the seismic and gravity data are well expressed in the magnetics imagery. For example, the northern boundary of the western STR terrane (adjacent to the South Tasman Saddle) coincides with truncation of three major N-S trending magnetic highs. The Tasman Fracture Zone, a fundamental structure marking the COB of the western STR, is also expressed as a major discontinuity in

the magnetic imagery. In the southwest of the STR, N-S and NNW-trending basement structures are replicated in the magnetics imagery. The larger depocentres are mostly associated with magnetic lows.

Representative Cross-sections

Key interpreted seismic profiles across the STR/ETP region (A-F, **Figure 2**; **Figures 10-12** & **Plates 9-11**) show structural and basin development in more detail.

Profile A, northwest STR (**Figures 2** & **10**; **Plate 9**)
This profile extends from the Tasman Fracture Zone to the South Tasman Saddle, and shows a series of large-displacement fault blocks and sediment-filled graben of the northern Ninene Basin. The graben contain 2 km or more of section, with wrench deformation extending to the mid Eocene horizon. A high, very steep escarpment on an uplifted, ?transpressional continental basement block marks the Tasman Fracture Zone. ?Late Eocene volcanics intrude the Ninene Basin section. The South Tasman Saddle is floored by ?Eocene volcanics. There is very little sediment cover evident here and any deeper section is obscured by the volcanics.

Profile B, mid northern STR (**Figures 2** & **10**; **Plate 9**)
ODP Site 1170 is located in a 2-3 km deep, 50 km wide graben of the Ninene Basin. A strong erosional mid-Eocene unconformity and large throw on the eastern bounding fault (displacing the Eocene shallow marine sequence) indicate major tectonic activity at about this time. Paleocene movements are also evident in this and other smaller graben beneath the central and eastern STR.

Profile C, central STR (**Figures 2** & **11**; **Plate 10**)
A deep (3-4 km) rift basin lies on the western flank of the STR summit area. Sediments in the graben record episodes of Paleocene-Eocene tectonism. No major basin development has occurred on the central STR culmination, although there are a few small rift structures. Here basement is mostly exposed or covered by no more than a veneer of post Oligocene pelagic carbonates. A cluster of large ?Eocene hot-spot volcanoes straddles the continent-ocean boundary (COB). A well-stratified 2 km thick pile of Campanian-Cainozoic sediments overlies Tasman Basin oceanic crust east of the STR margin. Exceptionally thick (~800 m) Oligocene-Neogene pelagic drifts have accumulated on the lower slope of the STR, deposited here by the easterly-flowing Antarctic Circumpolar Current in the lee of the STR.

Profile D, southern STR (**Figures 2** & **11**; **Plate 10**)
ODP Site 1171 is located in the westmost of two deep graben beneath the southwest flank of the southern STR. The sediments record significant Paleocene tectonic movement, with some movement continuing into the Eocene. The basal sediments on oceanic crust south of the STR are Paleocene or older, indicating that breakup on this margin occurred in the Paleocene or earlier. This is consistent with the magnetic anomaly interpretation of Royer & Rollet (1997) that puts DSDP Site 280 (just south of the COB) on crust as old as chron 25/26 (~58 Ma), and also more recent evidence from east of the Balleny Fracture Zone (Cande *et al.* 1996; Cande *et al.* 2000) that puts the onset of spreading as early as chron 27 (~61 Ma).

Profile D shows slumping of Eocene and younger sediments on the steep lower slope of the western margin. ?Eocene volcanics occur within the section beneath the Tasman Basin flank of the southern STR.

Profile E, L'Atalante Depression (**Figures 2** & **12**; **Plate 11**)

About 2 km of Campanian-Cainozoic section has been deposited on the lower continental slopes of the STR and ETP and on adjacent oceanic crust within the L'Atalante Depression. The Eocene sequences prograde strongly into the Depression. A 2 km high ?Eocene basaltic hot-spot volcano has erupted through Campanian-Maastrichtian oceanic crust towards the middle of the L'Atalante Depression. The sedimentary section beneath the ETP has also been disrupted by hot-spot volcanism, in this case volcanism associated with the mid-Late Eocene Cascade Seamount.

Profile F, ETP (**Figures 2** & **12**; **Plate 11**)

The ETP is underlain by about 2 km of post-breakup section (Campanian and younger), and the adjacent East Tasman Saddle contains a similar but slightly thicker succession. The sedimentary section on oceanic crust east of the ETP is also about 2 km thick. On the ETP the post-breakup section appears to be underlain by ?volcaniclastic synrift basins of similar thickness. Dredging of granite from the steep escarpment at the COB and also from the steep upper Tasmanian continental slope indicates that basement in this area is probably largely granitic rocks. Volcanics associated with the Cascade Seamount occur within the Eocene and older sediments. Volcanics also appear to lie at the breakup unconformity on the ETP.

Deep Crustal Structure

Gravity modelling along three *Sonne* profiles across the mid northwestern STR (Kessler 1996) indicates a crustal thickness of 20 km beneath the crest, decreasing to 10-12 km on the flanks. Kessler (1996) also modelled eight magnetic profiles distributed over much of the STR and found that the observed anomalies (ranging between ±300 nT) were mainly sourced by magnetic bodies within basement to a depth of ~12 km below sea level.

Pre-1973, a number of sonobuoy refraction recordings were made in the STR-ETP region during voyages of *Eltanin* (Houtz 1975). However, these only provide relatively shallow (<1 km depth) velocity information and are of limited use in understanding mid-deep crustal structure. Ten sonobuoys were successfully deployed on AGSO's LOS Survey 202 (Bernardel 1999), but these data have not been processed and interpreted.

8. TECTONO-STRATIGRAPHIC EVOLUTION

Basin development south of Tasmania probably dates back to the latest Jurassic-Early Cretaceous when this area was presumably developed as an arm of the Southern Rift System that initiated the Bight, Otway, Bass and Gippsland basins. At present, no sediments of this age have been identified, but palynology indicates the presence of such reworked sediments and seismic stratigraphy implies that the basal fill of the deep rifts is Late Cretaceous or older.

The main phase of basin development occurred post-Cenomanian. In the east, this was the direct result of the rifting that led to the formation of the Tasman Basin, while in the west it was related to wrenching as the NW-SE sinistral Tasmanian-Antarctic Shear Zone became active during extension in the Great Australian Bight. Seafloor spreading in the southern Tasman Basin began in the Early Campanian adjacent to the eastern STR and ETP, at the same time that spreading commenced in the central Bight. The L'Atalante Depression opened first, separating the STR and ETP, but then failed several million years later as the locus of spreading jumped east and to the north of the ETP, leading to the main phase of SW-NE Tasman opening. The East Tasman Saddle was a short-lived transform zone between

Tasmania and the ETP during the initial breakup phase. Up to the Paleocene, the structural development of the STR was controlled by two tectonic stress regimes: NW-SE strike-slip movements associated with the Tasmanian-Antarctic Shear to the west and extension to the east (Tasman rifting and spreading). The resulting transtension produced the deep, narrow rifts co-aligned with the main NW-SE-oriented spine of the STR (**Figures 3-4**). The structural style beneath the eastern margin of the STR and the ETP is mainly normal faulting, consistent with Tasman passive margin development.

There was a dramatic change in the tectonics of the region post-Maastrichtian, as relative plate motions began to change. The relative movement between Australia and Antarctica became more N-S, and the western STR, which until then had been part of the Antarctic plate, broke off and remained fused to what is now the eastern STR. During this change and subsequent strike-slip tectonism sub-parallel to the Tasman Fracture Zone, the western STR terrane experienced major deformation, associated wrenching and block rotation. Seafloor spreading south of the STR began in the Paleocene, as spreading in the Tasman Basin slowed and then shut down.

With development of fast N-S seafloor spreading between Australia and Antarctica in the Middle Eocene, the continental margin in the region behaved largely as a maturing passive margin, except for continuing deformation along the Tasman transform margin that affected the western STR. By 33 Ma (Eocene-Oligocene boundary), the continents had cleared each other, and by ~23 Ma (Early Miocene), the Southeast Indian Ridge had passed by the southwestern tip of the STR, marking the end of wrenching in the region.

Volcanism has been widespread in the STR/ETP region, and appears to be related to two main phases: (i) ~Campanian, related to initial breakup, and (ii) Eocene, related to transit over the Balleny mantle plume with possibly enhancement by regional tensile stress in the lithosphere associated with the onset of fast spreading. The Eocene volcanics comprise a number of large isolated basaltic seamounts, 1000-2000 m high, mainly in the L'Atalante Depression, but also on the ETP (Cascade Seamount) and in the South Tasman Saddle (**Plate 1**; Hill *et al.* 2001). Small volcanic cones up to several hundred metres high, and associated flows, are common in the region. In some places the seafloor is dominated by volcanics, notably in the South Tasman and East Tasman Saddles, and on the summit area and the far southeastern tip of the STR.

9. RESOURCE POTENTIAL

Petroleum

The STR contains deep wrench and extensional basins with at least several km of sedimentary section (up to 6 km of fill according to Willcox (1989)), but they lie in deep water on the flanks of this continental block, and so their prospectivity is reduced. Nevertheless, drilling and development technology has kept up with the global trend to explore deeper and deeper fields, with 1500 m water depths now not considered exceptional (Thomas 2000). Though the Ninene Basin and larger sub-basins on the STR are mainly located at depths of 2-3 km, some of the deep depocentres on the flanks of the central STR high lie in water depths of only ~1400 m (**Plate 5**). Thus the STR is considered to have at least medium to long term petroleum potential.

Overall, the sub-basins west and south of Tasmania resemble in size and tectonic setting the productive Californian basins that formed likewise under a strike-slip stress regime on a

continental plate boundary (Mero *et al.* 1992), although the sense of strike-slip is opposite (sinistral), and the congruent boundary in Tasmania is not oceanic but continental (Antarctica). The only offshore petroleum exploration well in the region, Cape Sorell-l (**Figure 1**), was drilled off western Tasmania in the Strahan Sub-basin, a pull-apart depocentre (**Plate 5**) within the Tasmanian-Antarctic Shear off western Tasmania. Oil and gas shows were recorded below ~3000 m depth in a 400 m thick latest Cretaceous interval consisting of clastics (shales, sandstones and conglomerates) and coals (**Plate 7**). Nearby, seismic profiles show flat-spots in the section (Hill *et al.* 1997b), providing further evidence that hydrocarbons have been generated.

Exon *et al.* (in press) summarise the evidence of petroleum potential from ODP Leg 189. Total organic carbon (TOC) logged in Leg 189 wells is shown on the composite logs (Plates 7-8). Organic matter is generally absent from the Neogene carbonate-dominated succession on the STR and surrounding region, reflecting the well-ventilated Southern Ocean environment of deposition. Clearly, adequate hydrocarbon source material is absent. Also, the Neogene succession, being generally much less than 1 km thick, does not approach maturity for hydrocarbons.

Beneath the regional Eocene-Oligocene 'clearance hiatus', darker sediment colours on the western South Tasman Rise, and abundant organic matter on the west Tasmanian margin, indicate poor ventilation of the Australo-Antarctic Gulf in the Middle and Late Eocene. Anoxic to sub-oxic conditions occurred in the 'sheltered troughs' of the west Tasmanian margin (Exon *et al.* 2001b). TOC mainly ranges from 0.5 to 2% in the older siliciclastic succession, except at Site 1170 where it rises to 3% near the bottom of the hole (Middle Eocene) and at Site 1168 on the west Tasmanian margin, where it rises to more than 5% in Late Eocene sediments and is almost entirely terrestrial in origin. These are the highest organic carbon contents observed on Leg 189, and probably reflect the site location well within the restricted Australo-Antarctic Gulf. Whiticar *et al*. (1985) noted that Middle Eocene mudstones from DSDP Site 280 are potential source rocks.

On *Sonne* Cruise SO-36C, fourteen Quaternary cores taken on the northern STR were examined for hydrocarbons (Whiticar *et al*. 1985). Seventeen samples were degassed using a vacuum/acid technique that strips gas from minerals as well as sampling headspace gas. The highest values came from the eastern basin, near the outermost basement high. Average values were relatively low at 80 ppb for total hydrocarbons, 34 ppb methane, 13 ppb ethane, and 16 ppb pentane. Maximum values were 402 ppb for total hydrocarbons, 175 ppb methane, 65 ppb ethane, and 34 ppb pentane. The authors conclude that these hydrocarbons are thermogenic, and derived from deep source rocks.

Headspace gases at all sites on Leg 189 appear to be dominantly biogenic (Exon *et al.* 2001b), although thermogenic inputs were observed at the base of most holes. T_{max} values obtained by Rock Eval pyrolysis suggest that organic matter is immature generally, although values characteristic of the 'oil window' occur towards the bottom of the deeper holes.

Temperature measurements made during Leg 189 indicate geothermal gradients of ~50-60°C/km (Exon *et al*. 2001b). None of the DSDP and ODP holes in the region were deeper than a kilometre (the deepest was ODP 1171 at 959 m), and only thermally immature to marginally mature successions were drilled. At ODP Site 1172, on the East Tasman Plateau, apparent bitumen traces may indicate the beginning of migration of hydrocarbons from below the base of the hole, i.e. from the Mesozoic, probably Cretaceous, succession.

Gas Hydrates

Gas hydrates (water clathrates of natural gas) are crystallised gas and water that form in deep-sea sediments under conditions of high pressure and low temperature. In most cases the gas is methane, but some hydrates have been recovered with high concentrations of carbon dioxide, hydrogen sulphide and heavier hydrocarbons. Gas saturation is required for the hydrates to form. It is estimated that gas hydrates globally contain about twice the organic carbon of all fossil fuels combined (Kvenvolden 1998). Thus gas hydrates are an important potential future energy resource, albeit long-term since methods of efficient recovery or *in situ* conversion remain to be devised.

Most gas hydrate occurrences are inferred from marine seismic reflection profiles, based on an anomalous bottom-simulating reflector (BSR). This BSR represents the base of the gas hydrate stability zone, and commonly lies at sub-bottom depths of ~500-600 m. It is often best recognised where it cuts across dipping sedimentary strata.

The presence of BSRs within small sedimentary basins on the STR, and also beneath the L'Atalante Depression, has recently been reported (Stagg *et al.* 2000). However, some doubt exists as to whether these local reflectors are really indicative of gas hydrates. The 'BSR's are of limited extent, and are generally not strongly bottom-simulating. Nor is there clear correlation between their sub-bottom depth and basement topography, which would be expected for a geothermal effect. The 'BSR' examples are of varying depth below the sea floor (mainly in the range 400-700 ms), and are reported as outcropping in some locations. The reflectors could be interpreted as unconformities or as diagenetic horizons. The profile example shown as being on line 202-12 in the L'Atalante Depression (Figure 3 in Stagg *et al.* 2000) is actually on and at the end of line 202-01, well onto oceanic crust of the Tasman Basin east of the ETP.

The results of ODP Leg 189 drilled in 2000 (Exon *et al.* 2001b) cast further doubt on the existence of extensive gas hydrates on the STR and ETP. The geochemistry shows no compelling evidence of gas hydrates at the sites, with gas hydrates ruled out on the ETP (Site 1172) because of the very low methane concentrations recorded. At the two deeper sites (1170, 1171) on the STR, moderately high levels of methane were recorded at intervals below 480 mbsf, but mainly below the predicted methane hydrate stability zone. In addition, chloride concentrations in this zone were close to that of sea-water and not anomalously low as would be expected in a gas hydrate layer.

Seabed Mineral Resources

The main deep-sea mineral deposits that may be of long term commercial mining interest are metal-rich ferromanganese crusts and nodules. The main metals of economic interest in such deposits are Co, Cu and Ni.

The most comprehensive study of the ferromanganese deposits in the region has been that by Exon (1997) drawing also on an earlier study of Bolton *et al.* (1988). Unusually thick ferromanganese crusts, up to 20 cm thick, are present on rocky outcrops off western Tasmania and on the STR in water depths of 1500-4500 m. Those from within the oxygen-minimum zone (<2000 m) average 0.8% Co, which compares very favourably with other locations in the world that are highly prospective (e.g. Marshall Islands). However, the highest Co contents are from crusts only 2-4 cm thick, as compared to a suggested cut-off thickness of 4 cm. Exon (1997) recommends that further prospecting for Co-rich crusts should concentrate

on outcrops in water depths of 1000-2000 m on the eastern STR and southern Tasmanian margin.

Manganese nodule fields are common on the abyssal plains off Tasmania and the STR, and also occur in deep water on the STR (shallowest recovery was at 2400 m). Nodules dredged from the STR were commonly from areas of rocky outcrop, and were mostly smooth and very large (5-10 cm diameter). Though apparently abundant, the nodules from both the STR and adjacent abyssal areas are of low metal grade (averaging 0.14% Cu, 0.26% Ni, 0.20% Co) and are presently not of economic interest (Exon 1997).

Swath backscatter images and relief maps (Hill *et al.* 2001) indicate areas of rocky seabed where nodules and crusts are likely to be present. High backscatter intensity from much of the abyssal seafloor adjacent to the southern STR suggests the presence of extensive manganese nodule pavements, exposed or perhaps covered by up to several metres of pelagic sediment. Though not of direct commercial/mining interest because of the apparent low metal grades, knowledge of the distribution of these deposits is nevertheless of importance for regional marine planning and environmental management.

10. SUMMARY AND CONCLUSIONS

Plate reconstructions show that rifting and basin development in the STR/ETP region may have begun in the Late Jurassic-Early Cretaceous as an arm of the Southern Rift System, the extensional phase that initiated the Bight, Otway, Bass and Gippsland Basins. The main period of basin development took place post-Cenomanian, however. On the western and central STR the dominant influence was sinistral strike-slip movement along the NW-SE–oriented Tasmanian-Antarctic Shear Zone. This shear zone, active from early Late Cretaceous-Paleocene, resulted in the formation of a string of wrench basins from the northern Sorell Basin to the southern STR. At the same time, the ETP rifted off southeast Tasmania and separated from the eastern STR during passive margin development, with breakup in the Campanian. With relative Australia-Antarctic movement becoming more N-S in the Paleocene, the western STR terrane was left attached to the Australian plate and seafloor spreading began south of the STR. Continental strike-slip continued along the Tasman Fracture Zone during the Palaeogene, inducing wrench structures of largely N-S orientation in the western STR.

Opening of the Tasmanian Gateway in the early Oligocene, together with regional tectonic subsidence, led to development of circum-Antarctic oceanic circulation, thermal isolation of Antarctica, and global cooling. The supply of siliciclastic sediments dwindled, and as the STR and ETP sank, deposition was almost entirely of biogenic carbonates (foraminiferal/nanno-fossil oozes).

Basaltic volcanism, probably mainly of Eocene age, was widespread and locally intense in the region. There is also seismic evidence on the ETP for volcanism associated with Tasman breakup (Campanian), and for similar but later (Paleocene) activity at the southern STR leading to Southern Ocean breakup.

Basins on and adjacent to the STR and ETP contain at least 4 km of sedimentary section, consisting mainly of Late Cretaceous-Eocene siliciclastics and Oligocene and younger pelagic carbonates. The pelagic carbonates above the strong regional Eocene/Oligocene unconformity (clearance hiatus) are generally less than a few hundred metres thick, but on the lower eastern margin of the STR they have accumulated as current-controlled drifts to a thickness of almost

1 km. Drilling and geological sampling indicate that the underlying siliciclastic sediments comprise deltaic and shallow marine silty claystones that are commonly high in total organic carbon (TOC to 5%).

The western STR is a complex of numerous small wrench basins, constituting the Ninene Basin in the central area and the Toogee Sub-basin in the far north. The summit area of the central STR is a basement block with little sediment cover, although deep rift basins in water depths of 1400-2000 m flank the basement block. These NW-trending rifts are 3-4 km deep and typically 20-25 km wide. They are considered to have medium to long term petroleum potential.

The margins of the partially oceanic L'Atalante Depression are underlain by a post-breakup succession more than 2 km thick. On the ETP the post-breakup sediments are also almost 2 km thick, and appear to be underlain by a volcaniclastic rift sequence of similar thickness. Though petroleum potential exists on the ETP, the extreme water depths (>2600 m, excluding Cascade Seamount) and extensive Eocene volcanism reduce prospectivity to a marginal level.

Claims of BSRs and potential gas hydrates on and adjacent to the STR need to be further investigated. The evidence for gas hydrates is not compelling at present. Other potential resources in the area are ferromanganese nodules and crusts. Though extensive nodule fields exist, their low metal grades makes them sub-economic (vast fields in the central Pacific with significantly higher metal content are yet to be exploited). Cobalt-rich crusts in water depths of less that ~2000 m could be of commercial interest in the long term.

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TABLES

Table 1. Summary of multichannel reflection seismic surveys in the South Tasman Rise/East Tasman Plateau region.

Year	Survey/vessel	Area	Energy Source	Reference
1971	BMR CMS 11	Northern STR	Sparker	Cameron & Pinchin 1994
1973	Shell *Petrel* (N)	West & east Tasmanian margin	Airguns	BMR P(SL)A 72/30
1985	BGR/BMR *Sonne* SO-36B	West Tasmanian margin & STR	Airguns	Hinz *et al.* 1985
1994	TASMANTE, AGSO Survey 125 (*L'Atalante*)	ETP, STR, west Tasmanian margin	GI-(air)guns	Exon *et al.* 1994
1995	TASGO, AGSO Survey 148/159 (*Rig Seismic*)	Tasmanian margin, northern STR	Airguns	Hill *et al.* 1995b
1998	AGSO Survey 202 (*Rig Seismic*), LOS	STR & ETP	Airguns	Bernardel *et al.* 1999
1999/ 2000	AUSTREA-1, AGSO Survey 222 (*L'Atalante*)	Tasmanian margin	GI-(air)guns	Hill *et al.* 2000, 2001
2000	AUSTREA-2, AGSO Survey 223 (*L'Atalante*)	ETP, western STR	GI-(air)guns	Bernardel *et al.* 2000
2000	BGR *Polar Duke* (PD00)	Southern STR	Airguns	-
2001	*Franklin* FR3/01, AGSO Survey 226	East Tasmanian margin	GI-(air)guns	Exon *et al.* 2001c

Table 2. Summary of deep-sea drill sites (DSDP and ODP) and exploration wells off western Tasmania and in the South Tasman Rise/East Tasman Plateau region.

Site	Latitude S Longitude E	Water depth (m)	Penet-ration (m)	Maximum age of sediments	Basement type
DSDP 280[1]	48° 57.44' 147° 14.08'	4176	524	Middle Eocene	Intrusive basalt
DSDP 281[1]	47° 59.84' 147° 45.85'	1591	169	Late Eocene	Palaeozoic (?Late Carboniferous) mica-schist
DSDP 282[1]	42° 14.76' 143° 29.18'	4202	310	Late Eocene	Pillow basalt
DSDP 283[1]	43° 54.60' 154° 16.96'	4729	592	Paleocene	Altered basalt
ODP 1168[2]	42° 36.57' 144° 24.76'	2464	883.5	Late Eocene	
ODP 1169[2]	47° 03.92' 145° 14.21'	3568	246.3	Middle Miocene	
ODP 1170[2]	47° 09.03' 146° 02.98'	2705	779.8	Middle Eocene	
ODP 1171[2]	48° 30.00' 149° 06.70'	2148	958.8	Late Paleocene	
ODP 1172[2]	43° 57.57' 149° 55.70'	2622	766.5	Maastrichtian	
Cape Sorell-1[3]	42° 08.16' 145° 01.76'	94	3412	Maastrichtian-Campanian	

References: [1] Kennett, Houtz *et al.* (1975a)
[2] Exon *et al.* (2001b)
[3] Amoco (1982)

APPENDICES

Appendix 1.
United Nations Convention on the Law of the Sea (UNCLOS) 1982, Article 76

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.

Informal Terms Relating to UNCLOS Article 76

Application of Article 76 of United Nations Convention on the Law of the Sea (UNCLOS) raises several concepts and terms which will be referred to frequently in interpretations of seismic/bathymetric survey lines for the purposes of 'legal' Continental Shelf (CS) definition. Following are simplified definitions of the more important terms that we commonly use. Some aspects of the application of Article 76 remain unclear, and will only be resolved following further deliberation by the Commission on the Limits of the Continental Shelf.

Firstly, a *Hedberg arc* may be drawn, with a radius of 60 nautical miles, from an interpreted foot-of-slope (FoS) position. The location at which this arc intersects the seaward extension of the survey line is called the *Hedberg point.* With a series of FoS positions established around a continental margin, at a spacing of less than 120 nautical miles, a series of intersecting Hedberg arcs may then be constructed. Clearly, as the spacing between survey lines (and therefore, the FoS positions) decreases, the envelope of the intersecting Hedberg arcs approaches a 60 nautical mile buffered locus of the FoS, except in some cases where the latter contains embayments. This is part of the reason for AGSO's 'safe minimum' approach, where we aim to space survey lines ~30 nautical miles apart, where logistically possible. The final outcome, the true *Hedberg Line* (the informal name for the line that defines the outer edge of the 'legal' continental margin, as contained in Article 76, paragraph 4(a)(ii), of UNCLOS), is constructed by joining selected points on the Hedberg arcs by straight lines, not more than 60 nautical miles long. This would normally be done in a manner so as to maximise the size of the enclosed 'legal' continental margin. This true Hedberg Line will normally only intersect the survey line at the Hedberg point where the locus of the FoS points is a straight line. Such situations are unusual in the context of CS beyond 200 nautical mile, since it is normally associated with irregularly shaped marginal plateaus.

Secondly, a *Sediment Thickness point* may be determined, by interpretation of a seismic survey line (or possibly by drilling), where the 1% sediment thickness criterion is satisfied. That is, the point at which the thickness of sedimentary rocks is at least 1% of the shortest distance from such point to the FoS. In contrast to the Hedberg arc, this is strictly a single point, which may be joined to adjacent Sediment Thickness points to form the *Sediment Thickness Line* (the informal name for the line that defines the outer edge of the 'legal'

continental margin, as contained in Article 76, paragraph 4(a)(i), of UNCLOS), or to selected points on Hedberg arcs, again by straight lines, not more than 60 nautical miles in length.

Finally, the fixed points (not more than 60 nautical miles apart) comprising the line which defines the outer limits of the CS, may not lie beyond one or other of two cut-offs. The first cut-off is 350 nautical miles from the baseline (informally called the *350 nautical mile cut-off line*), and the second is 100 nautical miles beyond the 2500 m isobath (informally called the *isobath cut-off line*). The former is purely a geometrical construction from the Territorial Sea baselines, whereas the latter depends on definition of the 2500 m isobath.

LIST of FIGURES

Figure 1 3-D view of the sea floor off southern Tasmania, including the South Tasman Rise (STR) and East Tasman Plateau (ETP). The summit area of the STR is about 750 m deep, while the ETP lies mainly at 3000 m depth and is surmounted by the Cascade Seamount that rises steeply to 650 m below sea level. The steep escarpment of the Tasman Fracture Zone, which forms the western margin of the STR, is up to 2 km high in places.

Figure 2 Multichannel airgun seismic survey coverage (thin white lines) overlain on hill-shaded topographic image of the STR/ETP region. The thick pink lines are interpreted key seismic profiles (see Figures 10-12 & Plates 9-11). Locations of deep-sea drill sites, DSDP (brown dots) and ODP (red dots), are indicated, as is petroleum well Cape Sorell-1.

Figure 3 Image of shaded topographic relief on free-air gravity anomaly, showing the main structural elements of the STR/ETP region. The gravity data are derived from satellite altimeter measurements (grid V9.2, Sandwell & Smith 1997). Gravity anomaly values range from –100 mGal (purple) to +120 mGal (vivid pink). Structures are continental faults (black lines), transform faults (thick dotted blue lines) and continent-ocean boundary (COB, thick dotted green lines). The linear Tasman Fracture Zone and adjacent E-W oriented spreading fabric record the relative N-S Tertiary transform motion between the STR and Antarctica. Basinal areas and rifts within basement are commonly expressed as local gravity lows because of their low-density fill.

Figure 4 Minimum sediment thickness (seismic two-way time) and structure map of the STR/ETP region. The western STR is of high structural complexity and contains numerous small depocentres of the Ninene Basin. The Toogee Sub-basin, at the extreme northwestern tip of the STR, is a local wrench basin with more than 2 km of deformed fill. Narrow rift basins on the flanks of the central STR and on the ETP contain 3 km or more of section. The margins of the L'Atalante Depression lie in deep water (3-4 km), but are underlain by thick sediment accumulations (at least 2-3 km of Late Cretaceous and younger). Extensive volcanic activity, particularly in parts of the South Tasman Saddle and on the eastern margin of the STR, has obscured evidence of basin development at depth in the seismic sections.

Figure 5 Regional stratigraphic diagram based on deep-sea drilling (DSDP and ODP) and the only deep exploration well in the area, Cape Sorell-1.

Figure 6 Geohistory plot, ODP Site 1168 (west Tasmanian margin).

Figure 7 Geohistory plot, ODP Site 1170 (western STR).

Figure 8 Geohistory plot, ODP Site 1171 (southern STR).

Figure 9 Geohistory plot, ODP Site 1172 (ETP).

Figure 10 Key interpreted seismic profiles across the northern STR. Lines SO36-62 (A), SO36-58 (B). Locations shown in Figure 2.

Figure 11 Key interpreted seismic profiles across the central and southern STR. Lines 202-2 (C), PD00-5 (D). Locations shown in Figure 2.

Figure 12 Key interpreted seismic profiles across the L'Atalante Depression and ETP. Lines 202-12 (E), 226-4 & 202-1 (F). Locations shown in Figure 2.

LIST of PLATES

Full-scale colour images on CD-ROM (back pocket); reduced (A4) greyscale versions towards back of hardcopy report.

Plate 1 Seafloor topography (hill-shaded relief) and topographic features of the STR/ETP region from 42°S to 51.5°S, ODP drill sites and Australian Exclusive Economic Zone (AEEZ). Bathymetry grid (Petkovic *et al.* 2001) based on swath and trackline data in AGSO's data base and predicted bathymetry from satellite data (Smith & Sandwell 1997) in areas of sparse coverage.

Plate 2 Geological sampling stations and summary lithological descriptions, on topographic contour base map: 42°S-51.5°S

Plate 3 Basin structure and tectonic elements on base map of satellite gravity (Sandwell & Smith 1997) and seabed relief, covering the STR/ETP region, 42°S-51.5°S.

Plate 4 Magnetic anomaly map and geological structures of the STR/ETP region, 42°S-51.5°S. The magnetic grid (Petkovic *et al.* 2001) used to produce the image is based on levelled shipboard data and aeromagnetic surveys on and adjacent to Tasmania. To compensate for the varying source depths (shallow onshore and nearshore, deep over abyssal areas) and to enhance regional structures, a 7x7 low-pass filter has been applied to the 1100-m grid.

Plate 5 Sediment thickness (minimum), basin structure and tectonic elements of the STR/ETP region, 42°S-51.5°S. Also shown are geological sampling sites with facies, DSDP and ODP drill sites, and multichannel seismic lines (shot-point annotated).

Plate 6 Isopach (twt) map of post-'clearance hiatus' succession of the STR/ETP region, 42°S-51.5°S, Oligocene to Quaternary. Also shown are geological sampling sites with facies, DSDP and ODP drill sites, and multichannel seismic lines (shot-point annotated). The faults shown are as in Plate 5, and mainly represent underlying basement faults. They are shown for reference only. The post-Eocene section is relatively unfaulted.

Plate 7 Well composite data, west Tasmanian margin and western STR (Cape Sorell-1, DSDP 282, ODP 1168, ODP 1169, ODP 1170).

Plate 8 Well composite data, southern STR and ETP (DSDP 280, DSDP 281, ODP 1171, ODP 1172, DSDP 283).

Plate 9 Detail of key interpreted seismic profiles, northern STR.

Plate 10 Detail of key interpreted seismic profiles, central and southern STR.

Plate 11 Detail of key interpreted seismic profiles, L'Atalante Depression and ETP.

Plotfile Table for Plates

Plotfile Name (.ps)	Total Size (bytes)	Dimensions (cm)
Plate 1	86591667	86 wide, 108 high
Plate 2	138818254	88 wide, 112 high
Plate 3	87002888	86 wide, 108 high
Plate 4	87002888	86 wide, 108 high
Plate 5	144219101	88 wide, 112 high
Plate 6	144158145	88 wide, 112 high
Plate 7	4321672	197 wide, 87 high
Plate 8	3007625	146 wide, 89 high
Plate 9 part A	2533212	58 wide, 30 high
Plate 9 part B	2600507	58 wide, 30 high
Plate 10 part C	4637800	75 wide, 30 high
Plate 10 part D	4519095	75 wide, 30 high
Plate 11 part E	5326492	85 wide, 30 high
Plate 11 part F	5432929	85 wide, 30 high

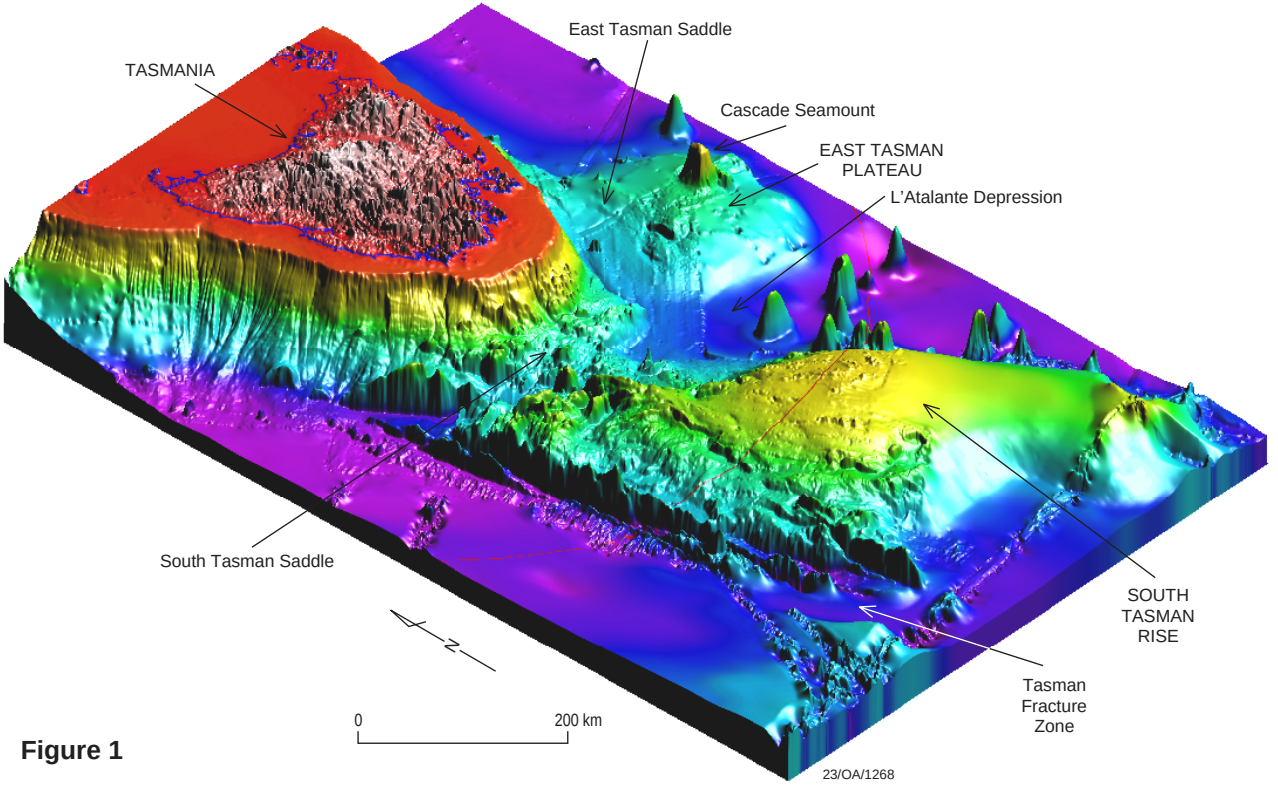

East Tasman Saddle
TASMANIA
Cascade Seamount
EAST TASMAN
PLATEAU
L'Atalante Depression
South Tasman Saddle
SOUTH
TASMAN
RISE
Tasman
Fracture
Zone
0
200 km
23/OA/1268

Figure 1

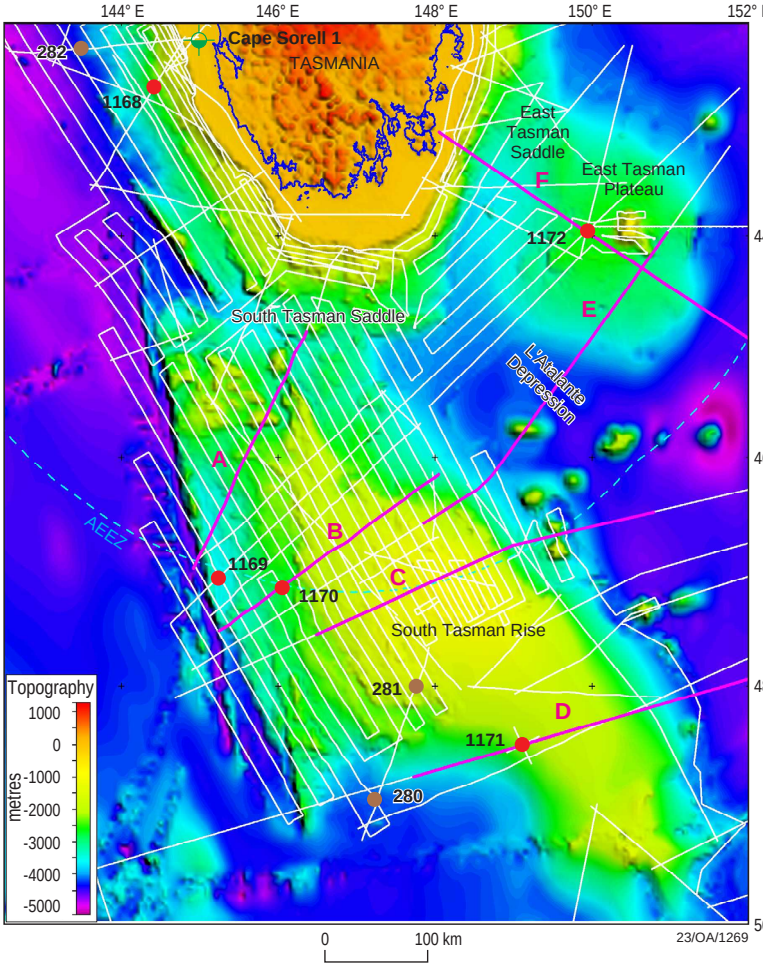

144° E
146° E
148° E
150° E
152° E
44° S
46° S
48° S
50° S
Cape Sorell 1
TASMANIA
282
1168
East Tasman Saddle
East Tasman Plateau
F
1172
E
South Tasman Saddle
L'Atalante Depression
A
AEEZ
B
1169
C
1170
South Tasman Rise
281
D
1171
280
Topography
1000
0
-1000
-2000
-3000
-4000
-5000
metres
0
100 km
23/OA/1269

Figure 2

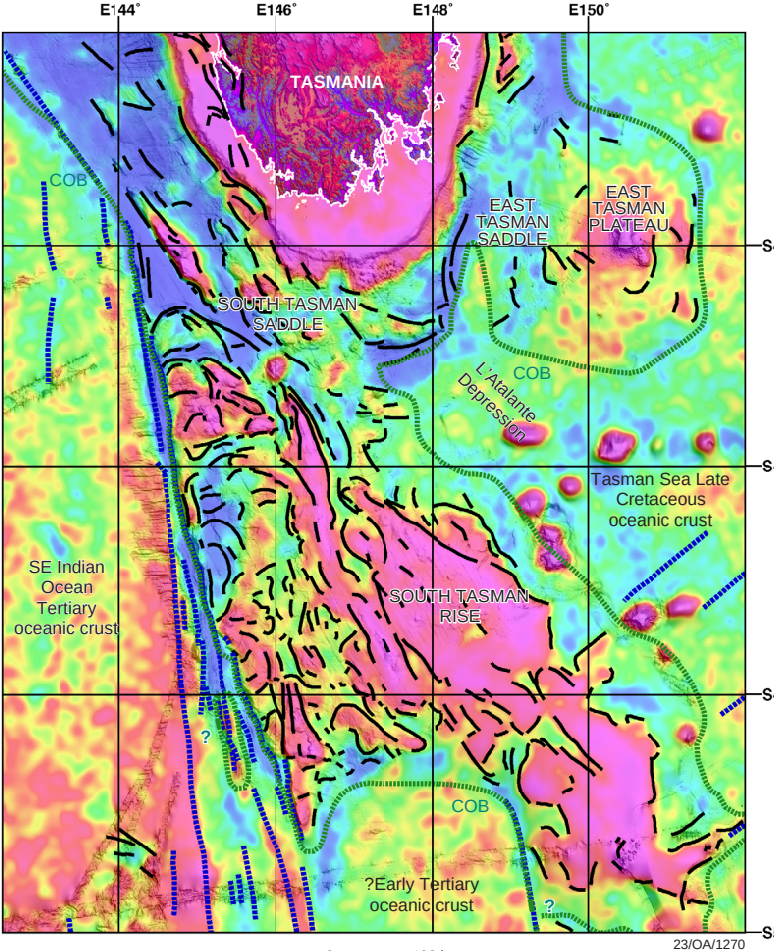

E144°
E146°
E148°
E150°
S44°
S46°
S48°
S50°
TASMANIA
COB
EAST TASMAN SADDLE
EAST TASMAN PLATEAU
SOUTH TASMAN SADDLE
COB
L'Atalante Depression
Tasman Sea Late Cretaceous oceanic crust
SE Indian Ocean Tertiary oceanic crust
SOUTH TASMAN RISE
?
COB
?Early Tertiary oceanic crust
?
23/OA/1270
0
100 km

Figure 3

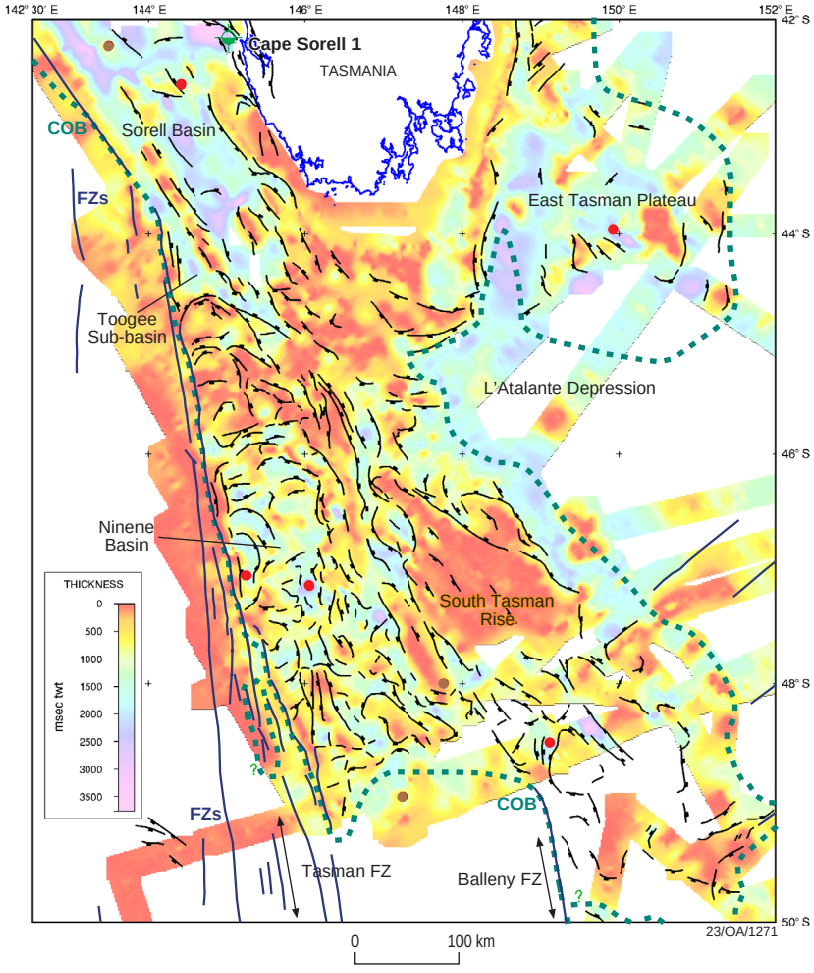

142° 30' E
144° E
146° E
148° E
150° E
152° E
42° S
44° S
46° S
48° S
50° S
Cape Sorell 1
TASMANIA
COB
Sorell Basin
FZs
East Tasman Plateau
Toogee
Sub-basin
L'Atalante Depression
Ninene
Basin
South Tasman
Rise
THICKNESS
0
500
1000
1500
2000
2500
3000
3500
msec twt
FZs
COB
Tasman FZ
Balleny FZ
23/OA/1271
0
100 km

Figure 4

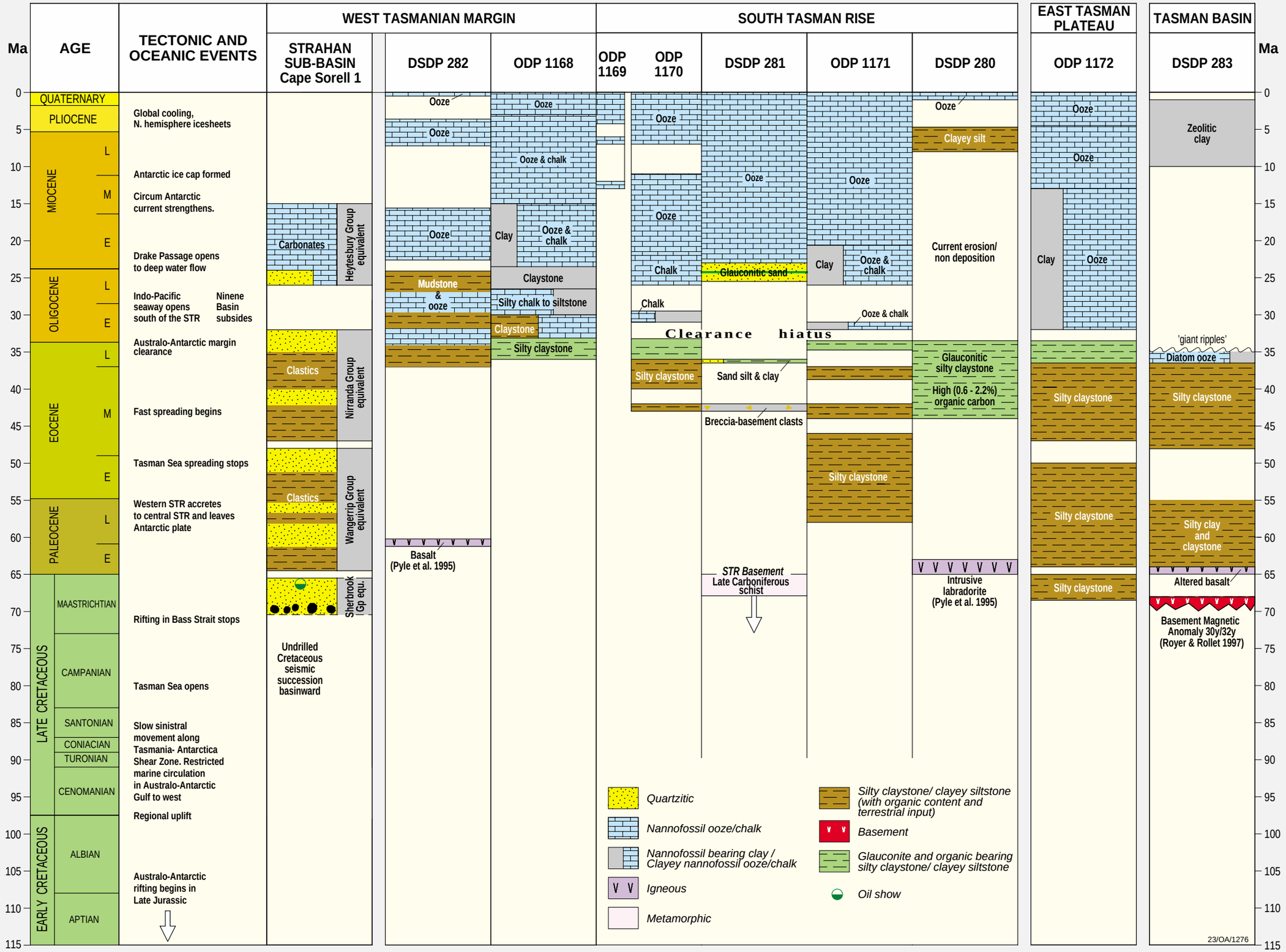
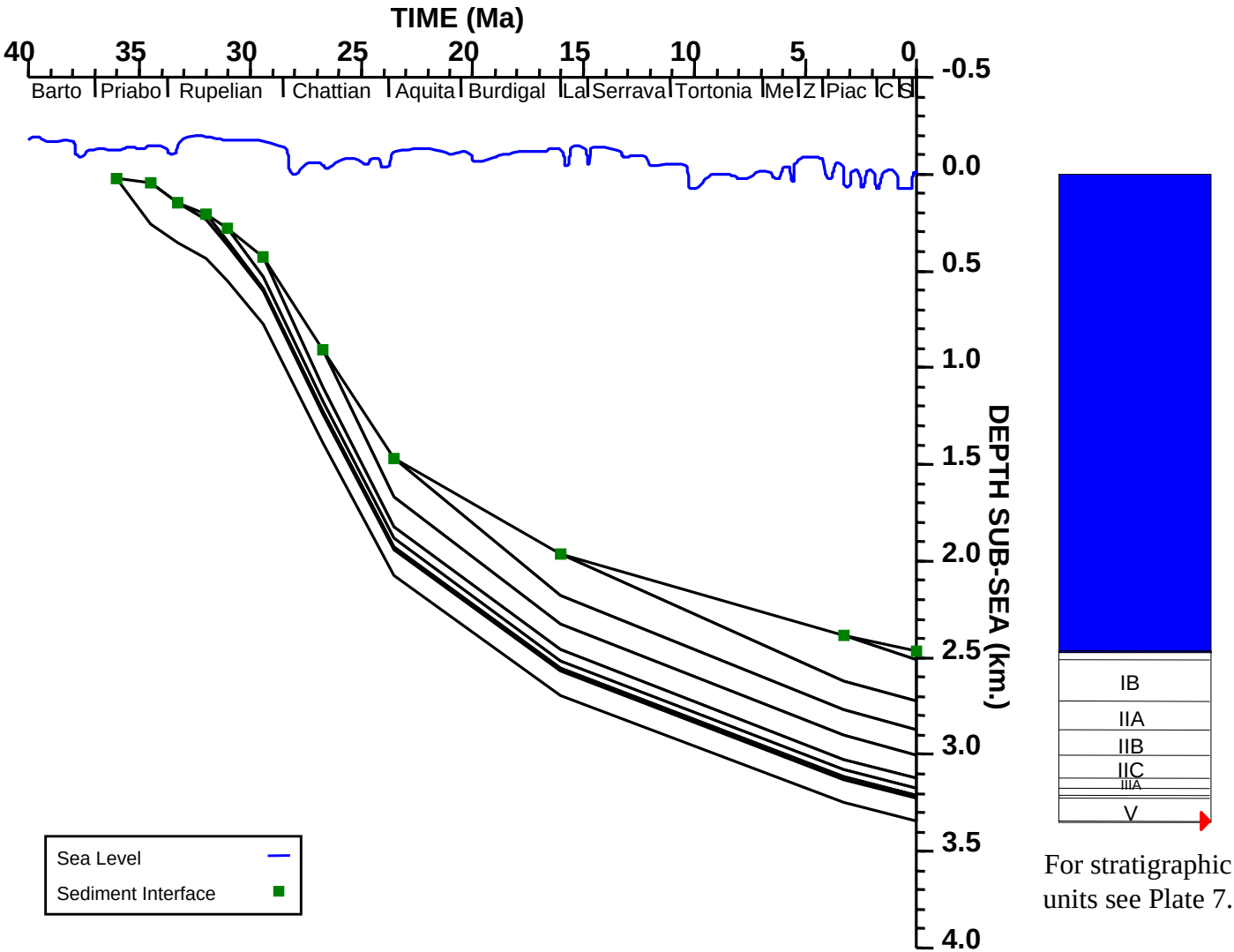
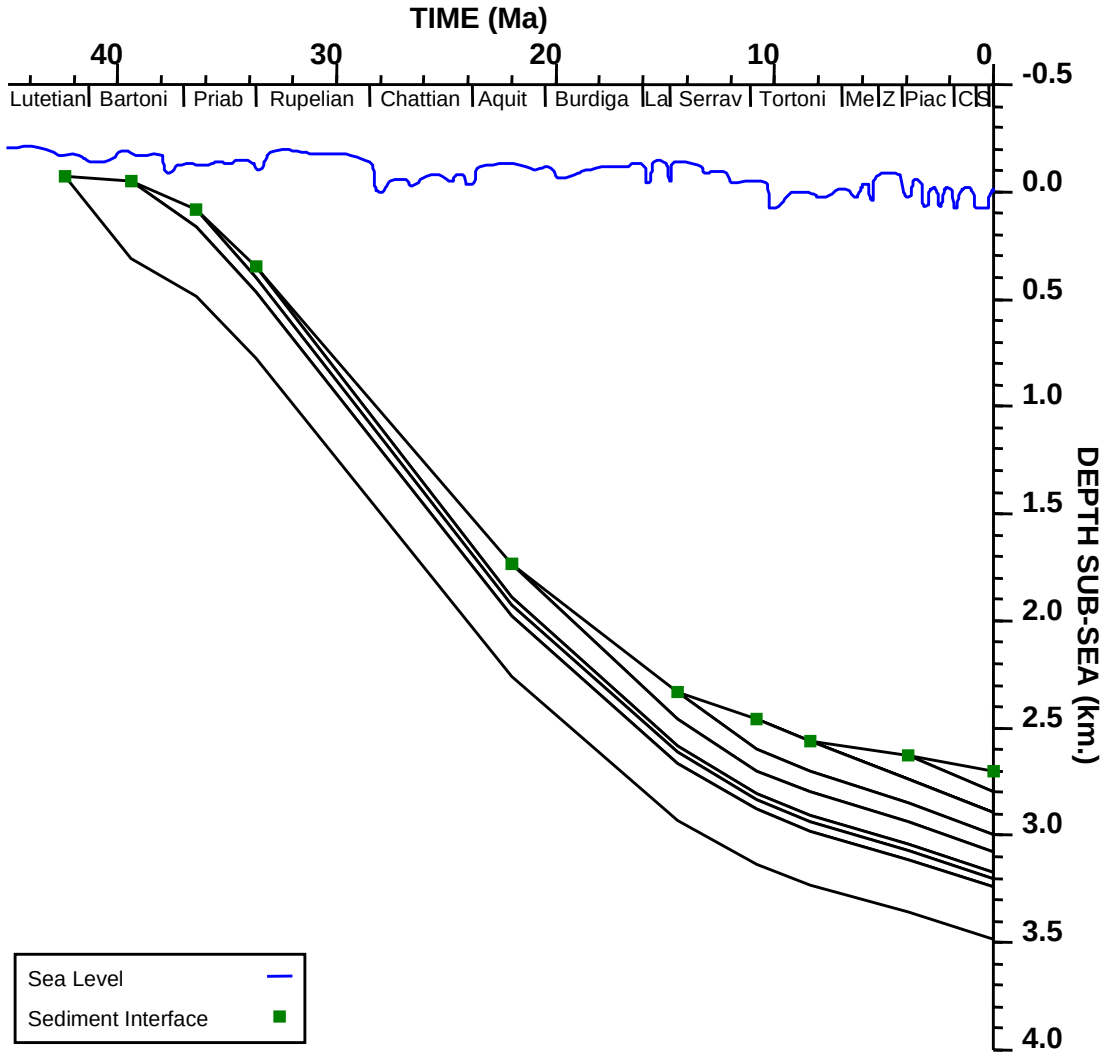

Ma
AGE
TECTONIC AND OCEANIC EVENTS
WEST TASMANIAN MARGIN
SOUTH TASMAN RISE
EAST TASMAN PLATEAU
TASMAN BASIN
STRAHAN SUB-BASIN Cape Sorell 1
DSDP 282
ODP 1168
ODP 1169
ODP 1170
DSDP 281
ODP 1171
DSDP 280
ODP 1172
DSDP 283
QUATERNARY
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
LATE CRETACEOUS
EARLY CRETACEOUS
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
Global cooling, N. hemisphere icesheets
Antarctic ice cap formed
Circum Antarctic current strengthens.
Drake Passage opens to deep water flow
Indo-Pacific seaway opens south of the STR
Ninene Basin subsides
Australo-Antarctic margin clearance
Fast spreading begins
Tasman Sea spreading stops
Western STR accretes to central STR and leaves Antarctic plate
Rifting in Bass Strait stops
Tasman Sea opens
Slow sinistral movement along Tasmania- Antarctica Shear Zone. Restricted marine circulation in Australo-Antarctic Gulf to west
Regional uplift
Australo-Antarctic rifting begins in Late Jurassic
Carbonates
Heytesbury Group equivalent
Clastics
Nirranda Group equivalent
Wangerrip Group equivalent
Sherbrook Gp equ.
Undrilled Cretaceous seismic succession basinward
Ooze
Ooze & chalk
Clay
Mudstone & ooze
Claystone
Silty chalk to siltstone
Silty claystone
Basalt (Pyle et al. 1995)
Chalk
Glauconitic sand
Clearance hiatus
Sand silt & clay
Breccia-basement clasts
STR Basement
Late Carboniferous schist
Clayey silt
Current erosion/ non deposition
Glauconitic silty claystone
High (0.6 - 2.2%) organic carbon
Intrusive labradorite (Pyle et al. 1995)
Zeolitic clay
'giant ripples'
Diatom ooze
Silty clay and claystone
Altered basalt
Basement Magnetic Anomaly 30y/32y (Royer & Rollet 1997)
Quartzitic
Nannofossil ooze/chalk
Nannofossil bearing clay / Clayey nannofossil ooze/chalk
Igneous
Metamorphic
Silty claystone/ clayey siltstone (with organic content and terrestrial input)
Basement
Glauconite and organic bearing silty claystone/ clayey siltstone
Oil show
23/OA/1276

Figure 5



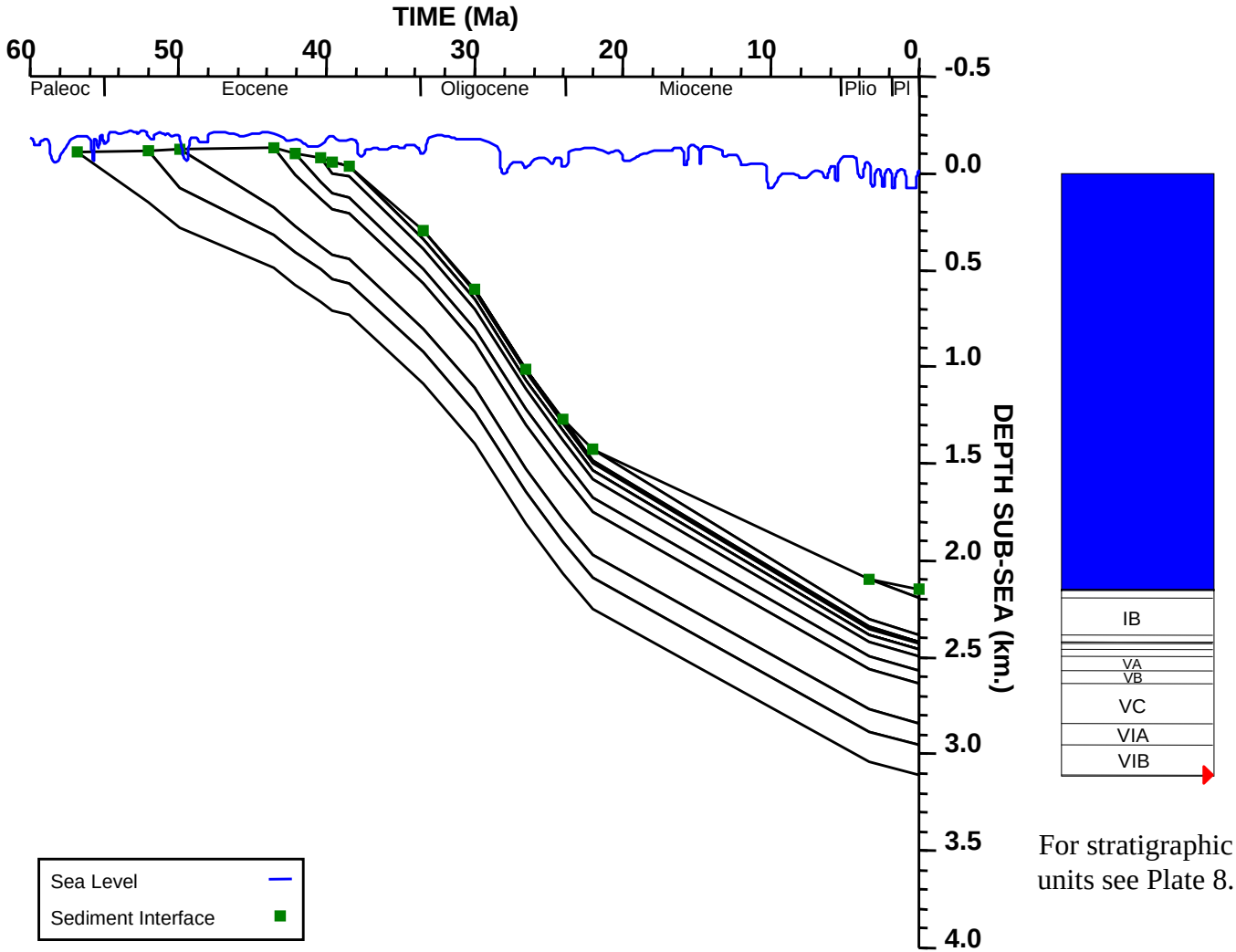
For stratigraphic units see Plate 7.

Figure 6 GEOHISTORY PLOT : ODP 1168



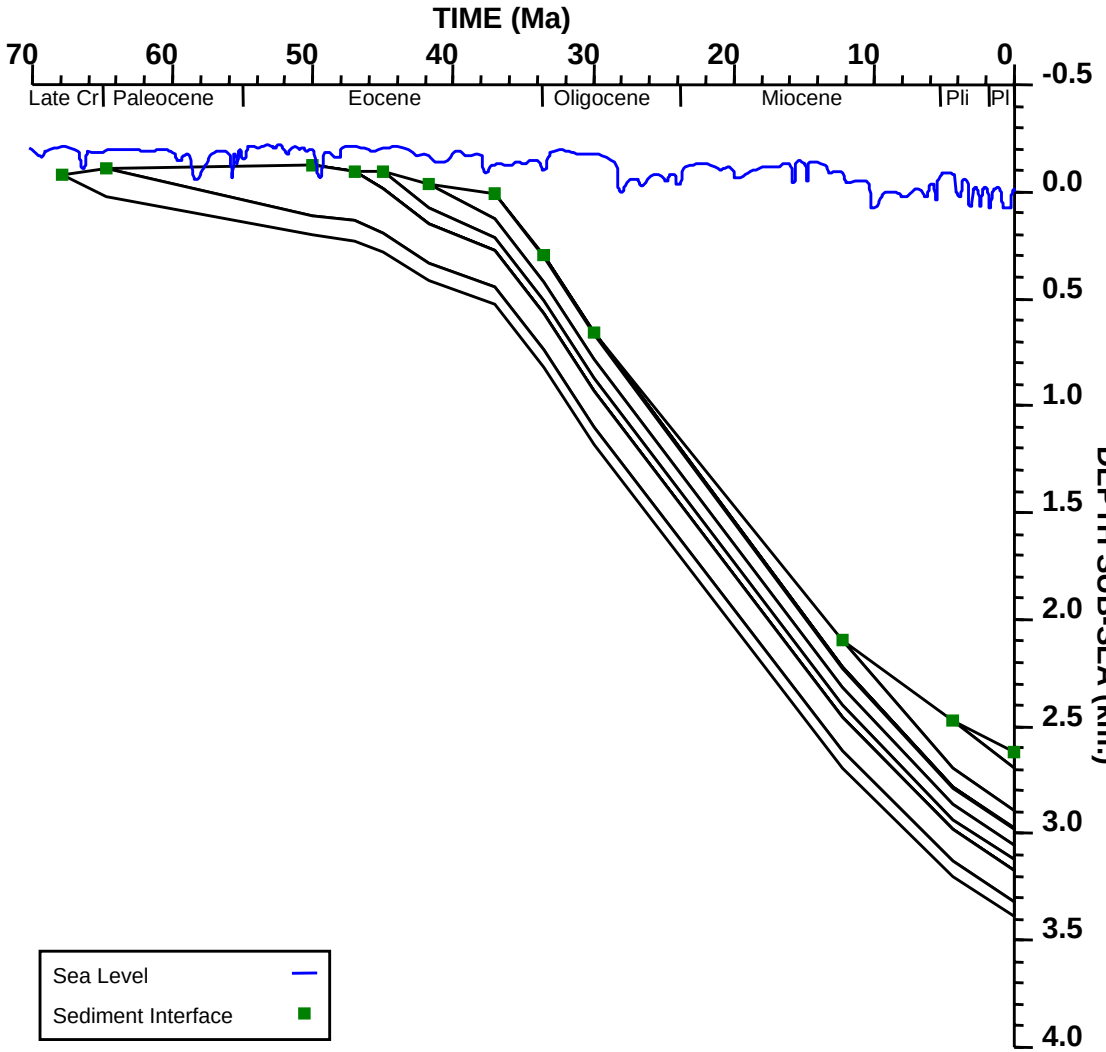
For stratigraphic units see Plate 7.

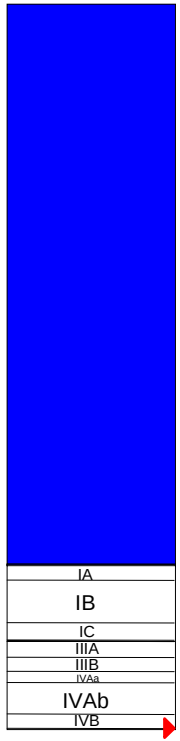
Figure 7 GEOHISTORY PLOT : ODP 1170



For stratigraphic units see Plate 8.

Figure 8 GEOHISTORY PLOT : ODP 1171





For stratigraphic units see Plate 8.

Figure 9 GEOHISTORY PLOT : ODP 1172

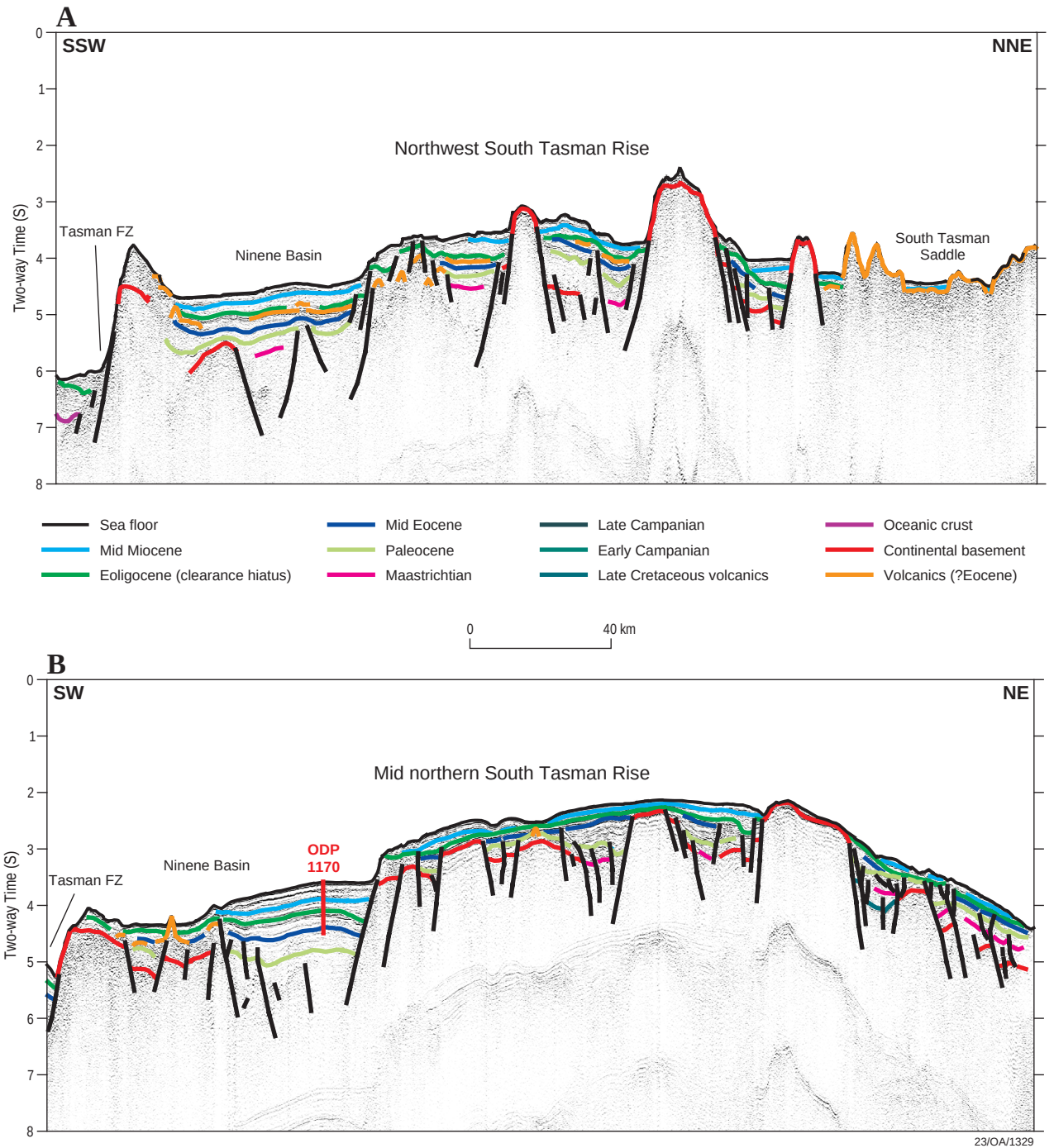

A
SSW
NNE
Northwest South Tasman Rise
Two-way Time (S)
Tasman FZ
Ninene Basin
South Tasman Saddle
0
1
2
3
4
5
6
7
8
Sea floor
Mid Miocene
Eoligocene (clearance hiatus)
Mid Eocene
Paleocene
Maastrichtian
Late Campanian
Early Campanian
Late Cretaceous volcanics
Oceanic crust
Continental basement
Volcanics (?Eocene)
0
40 km
B
SW
NE
Mid northern South Tasman Rise
Two-way Time (S)
Tasman FZ
Ninene Basin
ODP
1170
0
1
2
3
4
5
6
7
8
23/OA/1329

Figure 10

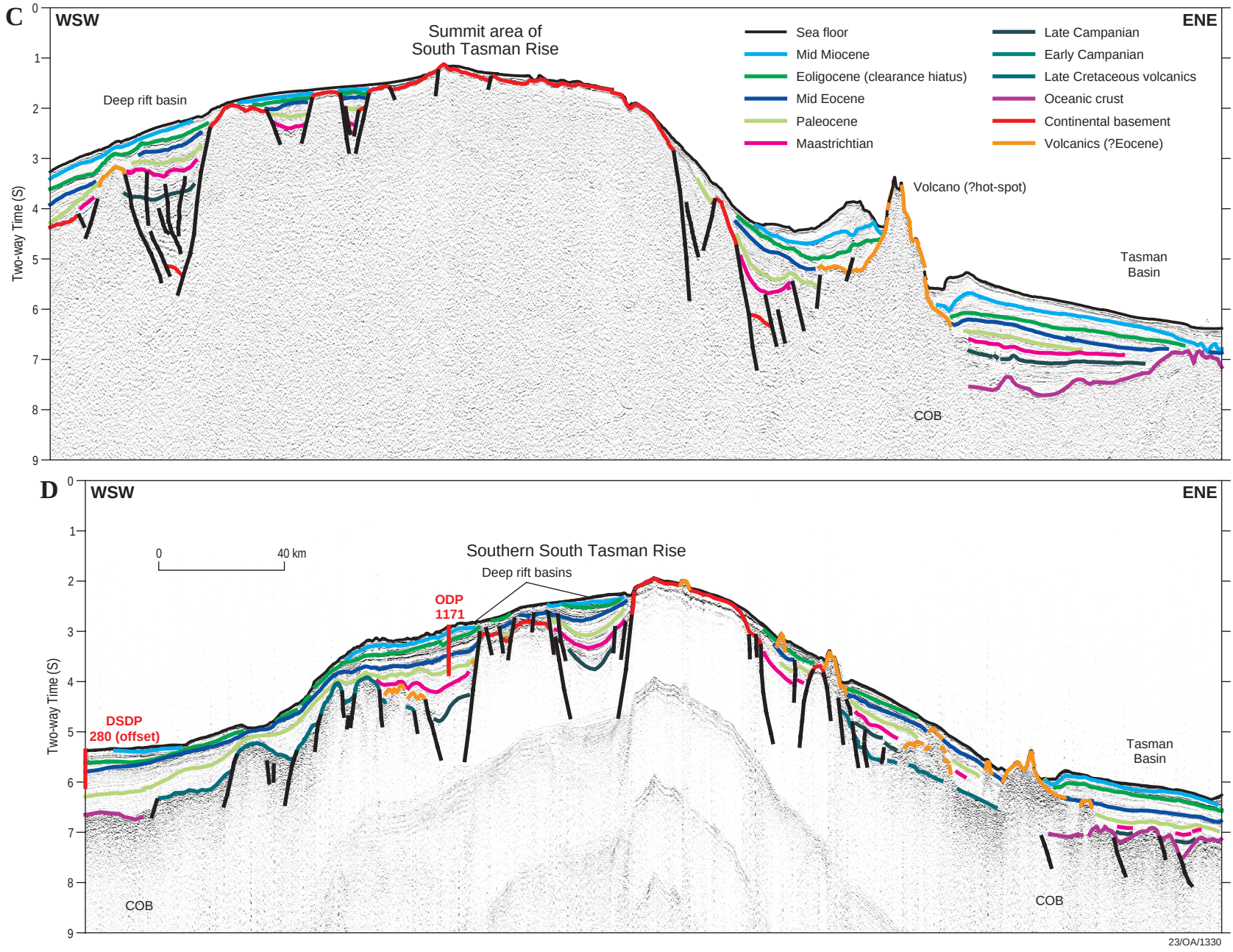

C
WSW
ENE
Summit area of
South Tasman Rise
Deep rift basin
Sea floor
Mid Miocene
Eoligocene (clearance hiatus)
Mid Eocene
Paleocene
Maastrichtian
Late Campanian
Early Campanian
Late Cretaceous volcanics
Oceanic crust
Continental basement
Volcanics (?Eocene)
Volcano (?hot-spot)
Tasman
Basin
COB
Two-way Time (S)
0
1
2
3
4
5
6
7
8
9
D
WSW
ENE
0
40 km
Southern South Tasman Rise
Deep rift basins
ODP
1171
DSDP
280 (offset)
Tasman
Basin
COB
COB
Two-way Time (S)
23/OA/1330

Figure 11

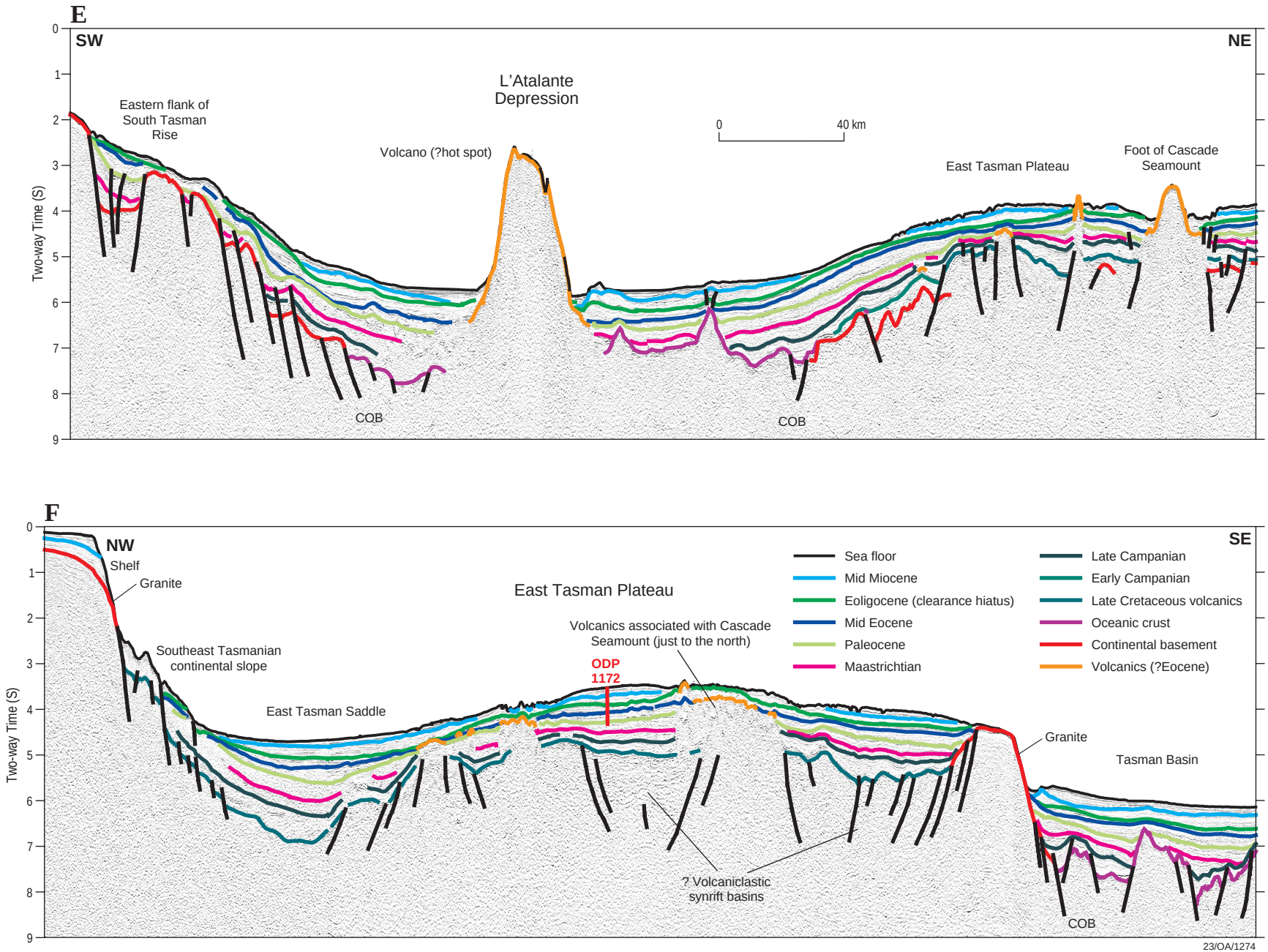

E
SW
NE
Eastern flank of South Tasman Rise
L'Atalante Depression
Volcano (?hot spot)
0
40 km
East Tasman Plateau
Foot of Cascade Seamount
Two-way Time (S)
COB
COB
F
NW
SE
Shelf
Granite
Southeast Tasmanian continental slope
East Tasman Plateau
Volcanics associated with Cascade Seamount (just to the north)
ODP 1172
East Tasman Saddle
Granite
Tasman Basin
? Volcaniclastic synrift basins
COB
Two-way Time (S)
Sea floor
Mid Miocene
Eoligocene (clearance hiatus)
Mid Eocene
Paleocene
Maastrichtian
Late Campanian
Early Campanian
Late Cretaceous volcanics
Oceanic crust
Continental basement
Volcanics (?Eocene)
23/OA/1274

Figure 12

SEABED TOPOGRAPHY

E143° E144° E145° E146° E147° E148° E149° E150° E151° E152° E153°

S43° S44° S45° S46° S47° S48° S49° S50° S51°

Tasmania

1168

Toogee Ridge

East Tasman Saddle

East Tasman Plateau

1172

Cascade Seamount

South Tasman Saddle

Lowreenne Massif

Tasman Escarpment

L'Atalante Depression

Tasman Basin

AEEZ

Needwonne Ridge

1169

1170

South Tasman Rise

1171

0
-499
-999
-1499
-1999
-2499
-2999
-3499
-3999
-4499
-4999
-5499
Metres

Southeast Indian Basin

Tasman FZ

Balleny FZ

Plate 1.

STR - ETP Region

TASMANIA

AEEZ

Cape Sorell

Tasman FZ

Balleny FZ

Oceanic suture

GEOLOGICAL SAMPLING SITES

Sampling Method

- Dredge
- Gravity core
- Piston core
- Box core
- Vibro core
- Grab
- Free fall grab
- Drill site
- Unknown

Main Facies

- Rock
- Gravel
- Sand
- Silt
- Mud/clay
- Not available

Tectonic elements

- Fault
- COB
- Transform / FZ

200 m contour interval

GEOLOGICAL SAMPLING SITES AND LITHOLOGICAL SUMMARY

Plate 2.

SATELLITE GRAVITY / SEABED RELIEF / STRUCTURE

Plate 3.

E143° E144° E145° E146° E147° E148° E149° E150° E151° E152° E153°

S43° S44° S45° S46° S47° S48° S49° S50° S51°

Sorell Basin

Tasmania

AEEZ

1168

East Tasman Plateau

1172

Tooggee Sub-basin

L'Atalante Depression

Ninene Basin

1169

Ninene Basin

1170

South Tasman Rise

1171

Oceanic suture

Tasman FZ

Balleny FZ

1300 1200 1100 1000 900 800 700 600 500 400 300 200 100 0 -99 -199 -299 -399 -499 -599 -699 -799 -899 -999

mGal/10

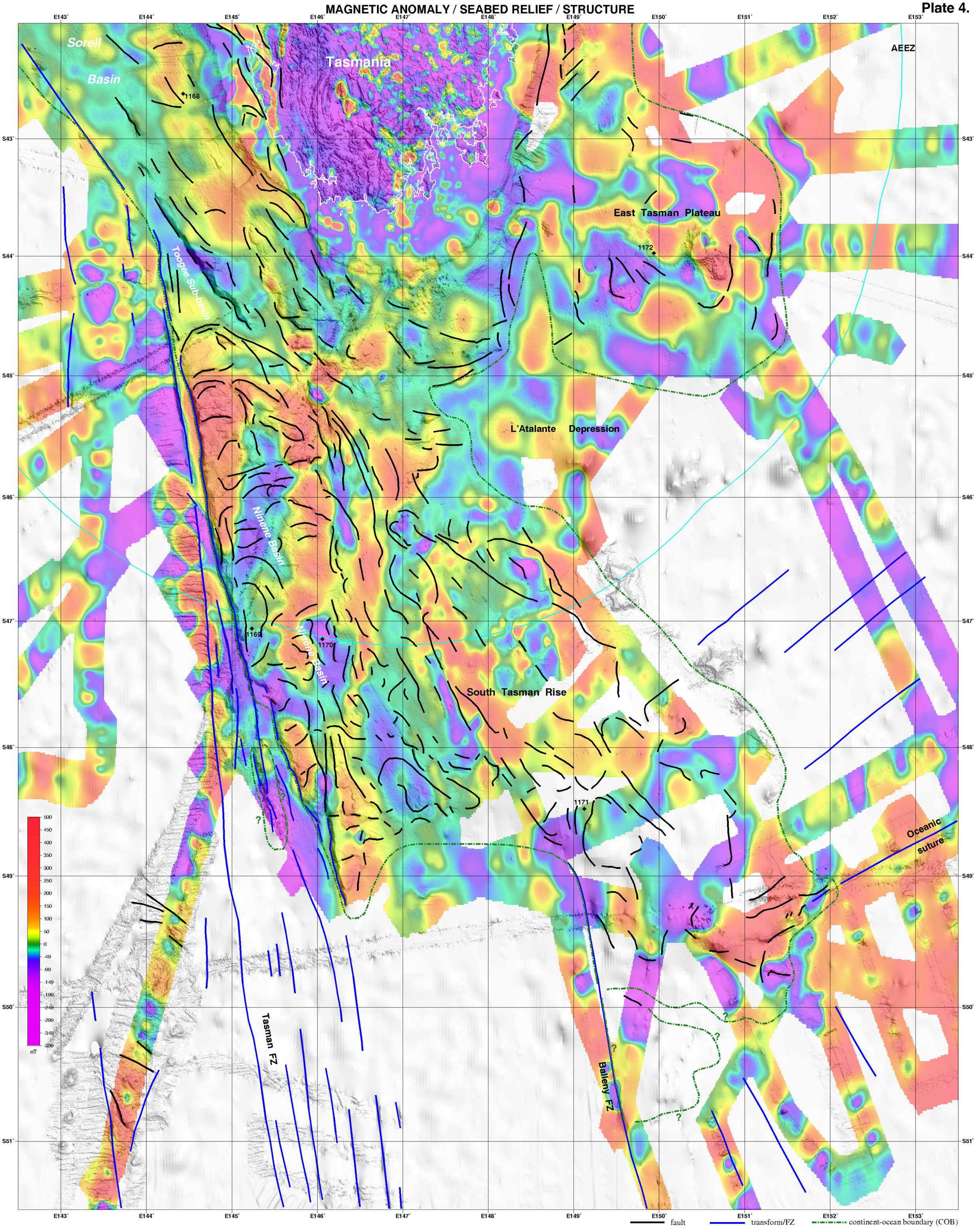
fault

transform/FZ

continent-ocean boundary (COB)

MAGNETIC ANOMALY / SEABED RELIEF / STRUCTURE

Plate 4.



TASMANIA

AEEZ

Oceanic suture

Tasman FZ

Balleny FZ

GEOLOGICAL SAMPLING SITES

Sampling Method

- Dredge
- Gravity core
- Piston core
- Box core
- Vibro core
- Grab
- Free fall grab
- Drill site
- Unknown

Main Facies

- Rock
- Gravel
- Sand
- Silt
- Mud/clay
- Not available

Sediment thickness (msec twt): -0, 500, 1000, 1500, 2000, 2500, 3000, 3500, 3765

Tectonic elements

- Fault
- COB
- Transform / FZ

200 m contour interval

Sediment thickness, basin structure and tectonic elements map

Plate 5.

STR - ETP Region

TASMANIA

AEEZ

Cape Sorell 1

DSDP 282

DSDP 281

DSDP 280

1168

1169

1170

1171

1172

Tasman FZ

Balleny FZ

Oceanic suture

GEOLOGICAL SAMPLING SITES

Sampling Method

- Dredge
- Gravity core
- Piston core
- Box core
- Vibro core
- Grab
- Free fall grab
- Drill site
- Unknown

Main Facies

- Rock
- Gravel
- Sand
- Silt
- Mud/clay
- Not available

Sediment thickness (msec twt): 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000

Tectonic elements

- Fault
- COB
- Transform / FZ

200 m contour interval

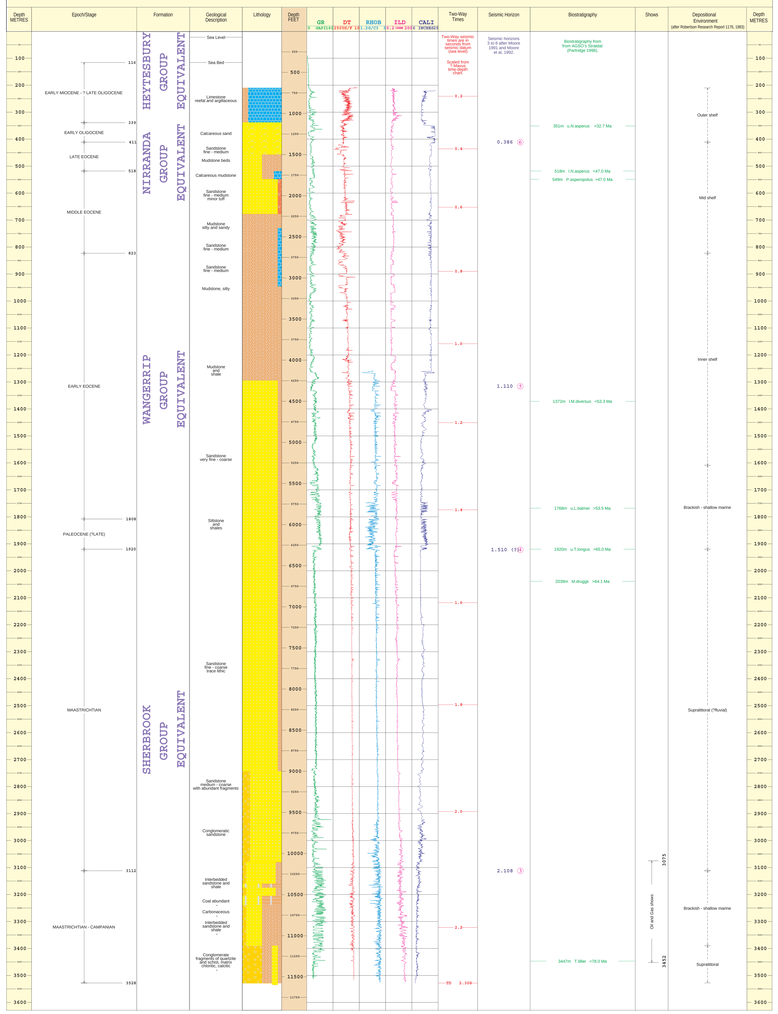
Plate 6.

Isopach (twt) map of post 'clearance hiatus' succession, Oligocene-Quaternary

Well Composite Data - West Tasmanian Margin and Western South Tasman Rise

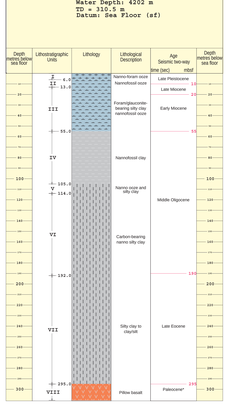
Cape Sorell 1

Latitude: 42 08 09.6468
Longitude: 145 01 45.848
Water Depth: 94 m
TD: 3528 m
Datum: KB



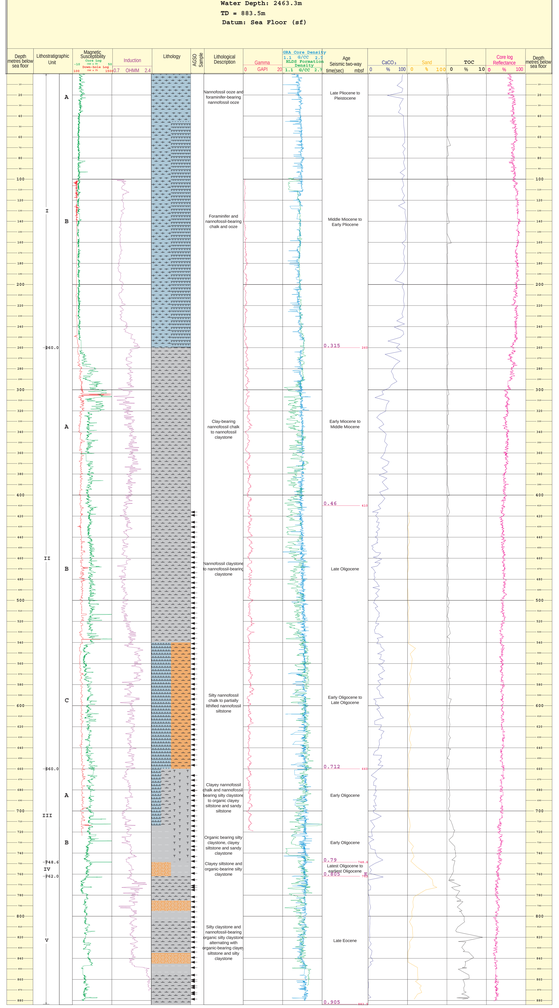
DSDP 282

Latitude: 42 14.76S
Longitude: 143 29.18E
Water Depth: 4202 m
TD = 312.5 m
Datum: Sea Floor (sf)



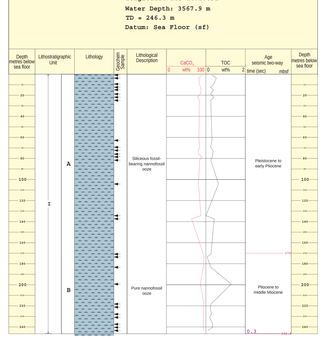
ODP 1168A,B,C

Latitude: 42 36.5809S
Longitude: 144 26.7620E
Water Depth: 2463.3m
TD = 883.5m
Datum: Sea Floor (sf)



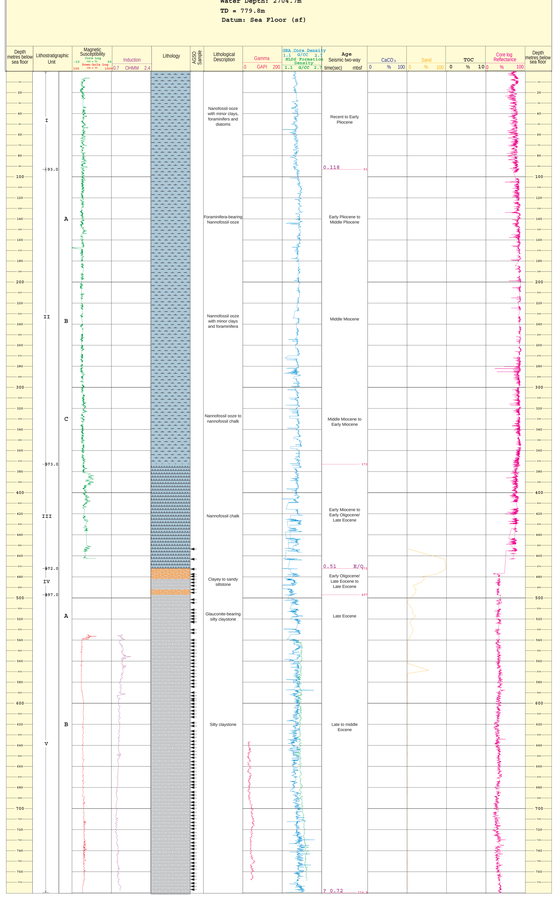
ODP 1169

Latitude: 47 03.9159S
Longitude: 145 14.2089E
Water Depth: 3567.9 m
TD = 246.3 m
Datum: Sea Floor (sf)



ODP 1170A,B,C,D

Latitude: 47 09.0435S
Longitude: 146 02.9881E
Water Depth: 2704.7m
TD = 779.8m
Datum: Sea Floor (sf)



LITHOLOGY LEGEND

- fnooze - Nanno-Foram or Foram-Nanno Ooze
- nooze - Nannofossil Ooze
- cy - Claystone
- slcly - Silty Clay / Clayey Silt
- vr - Volcanic rock
- no2 - No sample
- fchalk - Foraminiferal Chalk
- nchalk - Nannofossil Chalk
- ncl - Nannofossil bearing claystone
- nst - Nannofossil siltstone
- scl - Sandy claystone
- cl - Clay
- st - Siltstone
- stl - Siltstone
- cyl - Clay
- cys - Glauconite bearing silty claystone

LITHOLOGY LEGEND

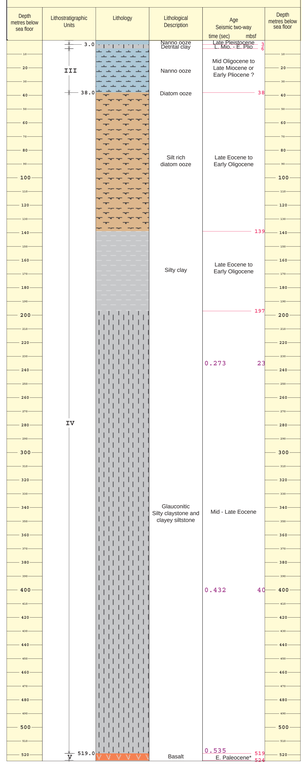
- ss - Sandstone
- st - Siltstone
- ls - Limestone
- ss3 - Sandstone, calcareous
- vr - Volcanic rock
- ss1 - Sandstone, medium to coarse grained
- cg - Conglomerate
- no2 - No sample
- blnk - blank
- ssl2 - Sandstone, coaly
- stc - Siltstone, coaly

Plate 7

Well Composite Data - Southern South Tasman Rise and East Tasman Plateau

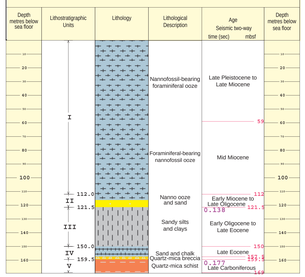
DSDP 280

Latitude: 48 57.44S
Longitude: 147 14.08E
Water Depth: 4176 m
TD = 524 m
Datum: Sea Floor (sf)



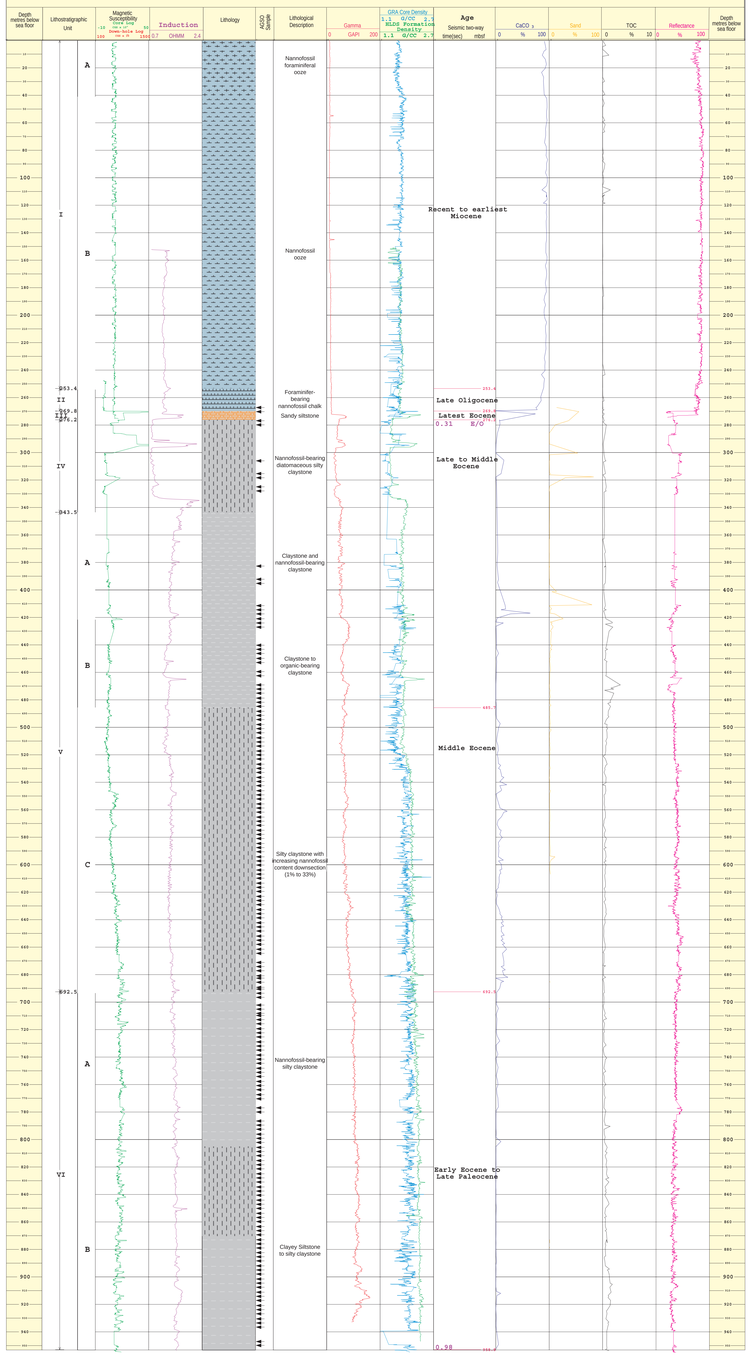
DSDP 281

Latitude: 47 59.84S
Longitude: 147 45.85E
Water Depth: 1591 m
TD = 169 m
Datum: Sea Floor (sf)



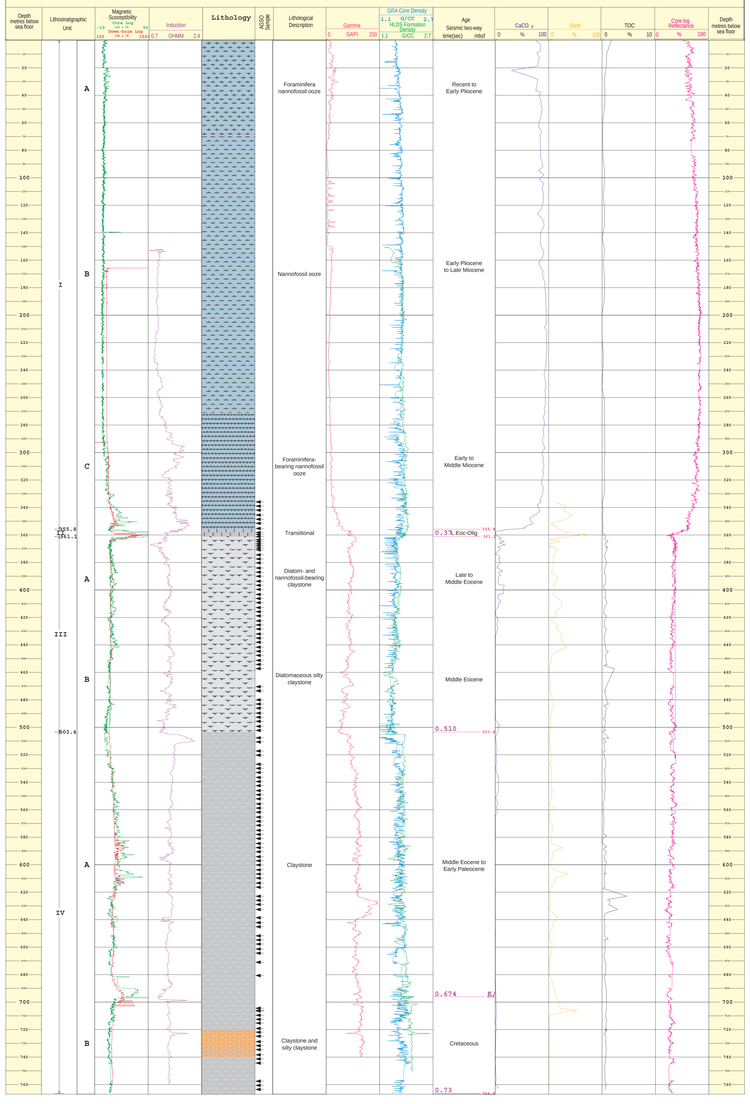
ODP 1171A,B,C,D

Latitude: 48 29.9960S
Longitude: 149 06.6901E
Water Depth: 2148.2m
TD = 958.8m
Datum: Sea Floor (sf)



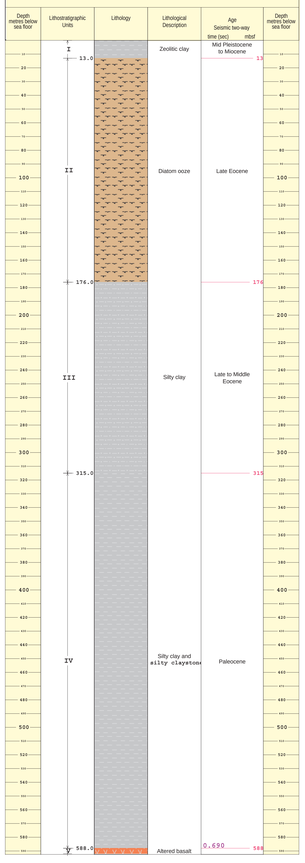
ODP 1172A,B,C,D

Latitude: 43 57.5854S
Longitude: 149 55.6961E
Water Depth: 2621.9m
TD = 766.5m
Datum: Sea Floor (sf)



DSDP 283

Latitude: 43 54.60S
Longitude: 154 16.96E
Water Depth: 4729 m
TD = 592 m
Datum: Sea Floor (sf)



LITHOLOGY LEGEND

- noozе - Nannofossil Ooze
- dooze - Diatom Ooze
- vr - Volcanic rock
- f - Sand
- br - Breccia
- no2 - No sample
- st - Siltstone
- dclay - Diatom Clay
- sicly - Silty Clay / Clayey Silt
- cy - Claystone
- fnooze - Nanno-Foram or Foram-Nanno Ooze
- fnchalk - Nanno-Foram or Foram-Nanno Chalk
- sc - Schist
- nchalk - Nannofossil Chalk
- cl - Clay
- scly - Sandy Mud / Sandy Mudstone

Plate 8

A

PLATE 9

Line–Tie SP | 125_08 | 125_09 | 125_10 | 125_11 | 125_12 | 125_13 | 125_16 | so36-125028 | 125_29 | 125_30 | 125_31 | 125_32 | 125_33 | 125_34 | 125_35 | Line–Tie SP

–22 | 272.9 | 567.8 | 862.7 | 1157.6 | 1452.5 | 1747.4 | 2042.3 | 2337.2 | 2632.1 | 2927 | 3221.9 | 3516.8 | 3811.7 | 4106.6 | 4401.5 | 4696.4 | 5100.41

SSW

SO36-62

NNE

NORTHERN SOUTH TASMAN RISE

Tasman FZ

Ninene Basin

South Tasman Saddle

Volcanics

TWT (Seconds)

0 1 2 3 4 5 6 7 8 9

40 km

23/OA/1314

B

PLATE 9

Line–Tie SP 5177.98 | 125_08 4881.58 | 125_09 4585.18 | 125_10 4288.78 | 125_15 3992.38 | 125_14 3695.98 | 125_13 3399.58 | 125_16 3103.18 | 125_28 2806.78 | 125_29 2510.38 | so36-050 2213.98 | 125_31 1917.58 | 125_32 1621.18 | 125_33 1324.78 | 125_34 1028.38 | 125_35 731.98 | 125_36 435.58 | 125_37 139.18 | 125_38 -9.02 | so36-057 Line–Tie SP

SW

SO36-58

CENTRAL SOUTH TASMAN RISE

NE

NE Margin

Tasman FZ

Ninene Basin

ODP 1170

TWT (Seconds)

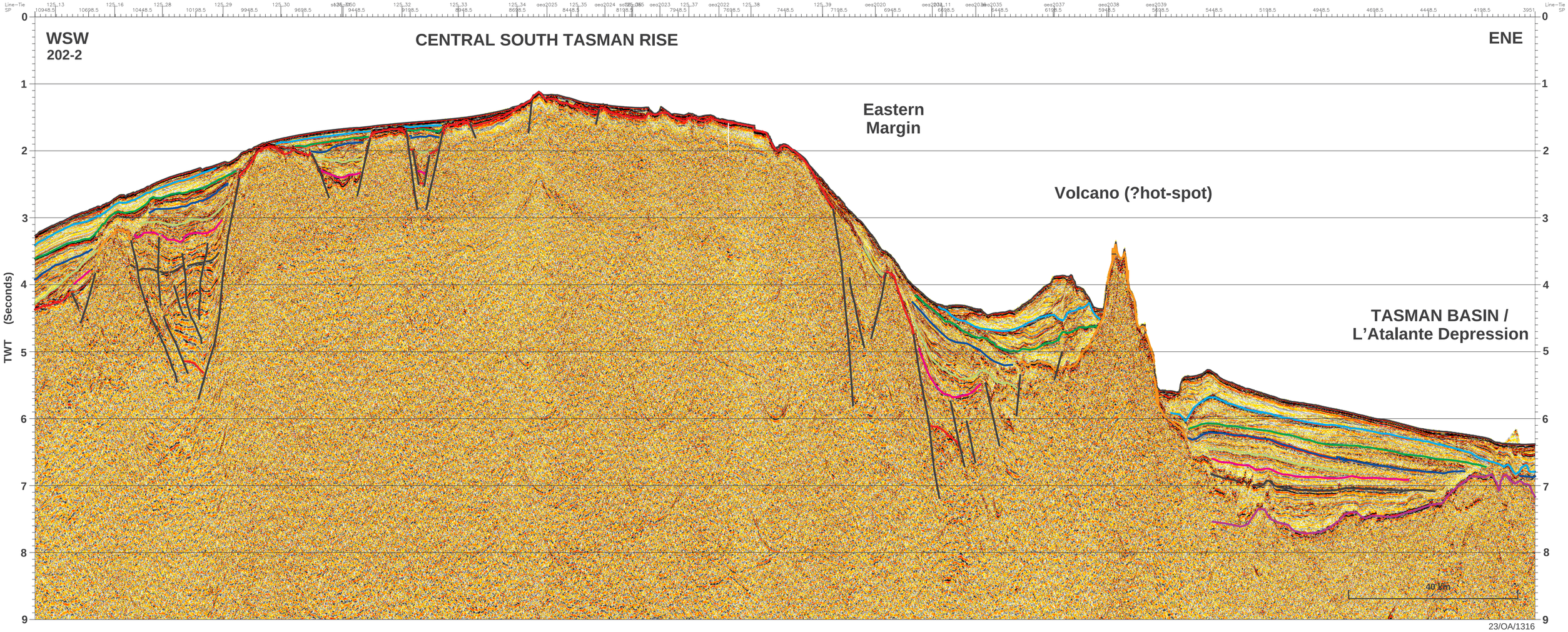
0 1 2 3 4 5 6 7 8 9

40 km

23/OA/1315

C

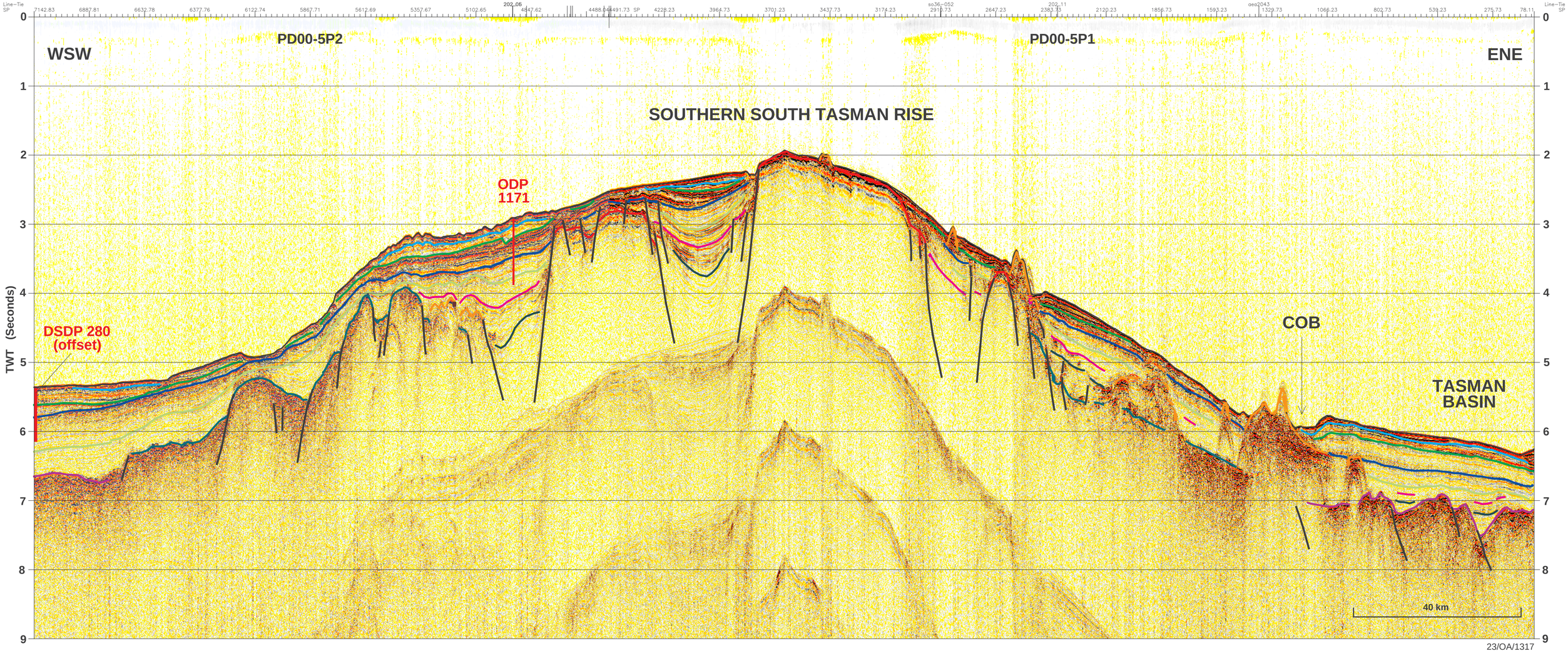
PLATE 10



23/OA/1316

D

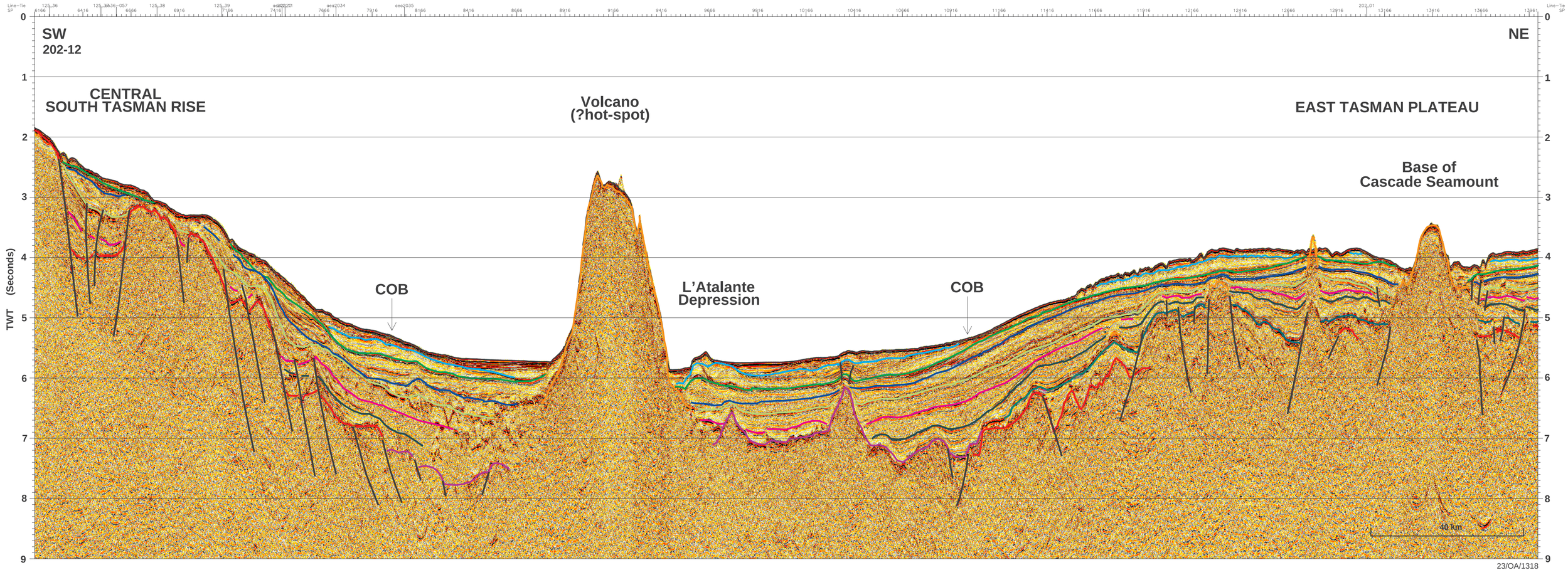
PLATE 10



23/OA/1317

E

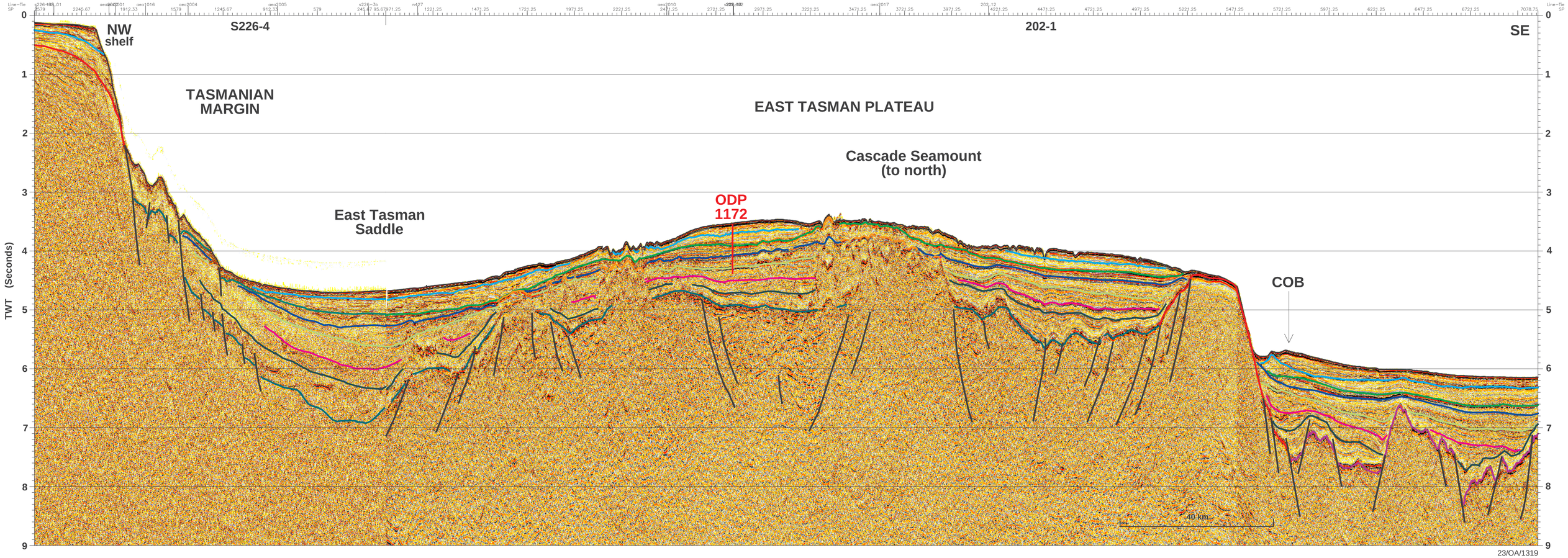
PLATE 11



23/OA/1318

F

PLATE 11



23/OA/1319

Instructions for the CD-ROM

Geological framework of the South Tasman Rise and East Tasman Plateau

This CD-ROM contains the above-titled document as
Geoscience AustraliaRecord2001_40.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 **GeoscienceAustraliaRecord2001_40.pdf** to launch the document.

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

DIRECTORIES ON THIS CD

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

RECORD directory:
GeoscienceAustraliaRecord2001_40.pdf

PLOTFILE directory:
This directory contains the PLATES diagrams in postscript format. The postscript (.ps) files are compressed (zipped). Each .ps file has an attached executable file that will automatically uncompress and download the .ps to your local drive.
Access the PLOTFILE directory through a file manager. Double click on the file required. The file will automatically unzip. You will be prompted for a directory path into which to place the unzipped file.

Plotfile Table for PLATES

Plotfile Name (.ps)	Total Size (bytes)	Dimensions (cm)
Plate 1	86591667	86 wide, 108 high
Plate 2	138818254	88 wide, 112 high
Plate 3	87002888	86 wide, 108 high
Plate 4	87002888	86 wide, 108 high
Plate 5	144219101	88 wide, 112 high
Plate 6	144158145	88 wide, 112 high
Plate 7	4321672	197 wide, 87 high
Plate 8	3007625	146 wide, 89 high
Plate 9 part A	2533212	58 wide, 30 high
Plate 9 part B	2600507	58 wide, 30 high
Plate 10 part C	4637800	75 wide, 30 high
Plate 10 part D	4519095	75 wide, 30 high
Plate 11 part E	5326492	85 wide, 30 high
Plate 11 part F	5432929	85 wide, 30 high