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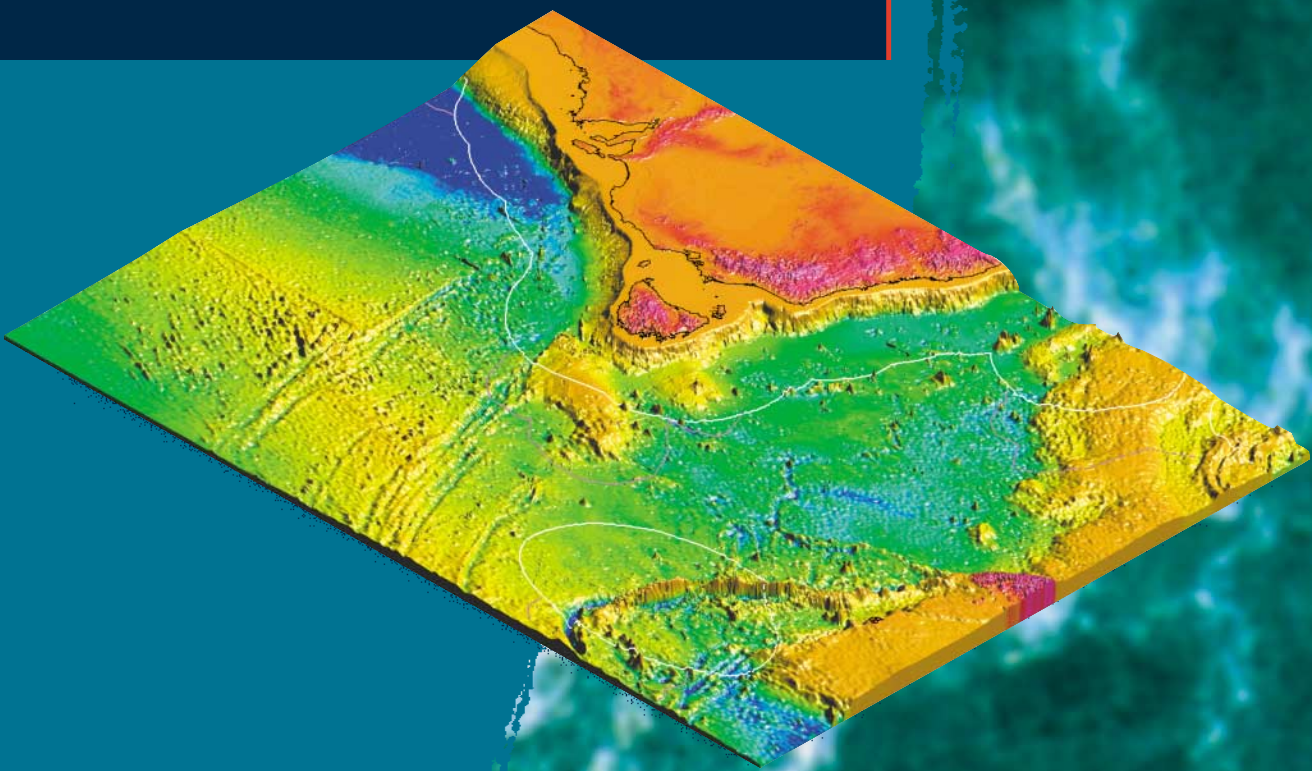
AUSTREA final report: southern Macquarie Ridge.

George Bernardel and Phil Symonds.



Geoscience Australia/National Oceans Office cooperative project

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Seafloor mapping of the South-east Region and adjacent waters - AUSTREA final report: southern Macquarie Ridge

by

George Bernardel and Philip Symonds

CANBERRA

A Geoscience Australia/
National Oceans Office cooperative project

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CONTENTS

LIST OF FIGURES

descriptive partitioning of the entire Macquarie Ridge Complex – Puysegur segment to the north not shown.

10. Hill-shaded view of terrain for the central and southern Macquarie Ridge region with earthquake epicentres (Appendix 4) marked as filled circles. Smallest to largest circles represent magnitudes less than 4, between 4 and 5, between 5 and 6 and greater than 6, respectively.

11. Hill-shaded view of terrain in the Hjort region study area. Black polygons represent subdivision of newly swath-mapped seafloor into physiographic provinces. Bathymetric contour (white) interval is 500 m and colour bar represents depth range in metres. The AEEZ (white) and the Macquarie Island Marine Park (white) are also shown on this and following maps.

12. 3D perspective view from the south of the newly swath-mapped seafloor in the Hjort region study area. The AEEZ (white) and the Macquarie Island Marine Park (white) are shown draped over the seafloor. Colour bar represents depth range in metres.

13. Seafloor backscatter for the Hjort region study area. Seafloor sample sites and Deep Sea Drilling Project site are also indicated (see Appendix 5). Bathymetric contour (blue) interval is 500 m.

14. 3D perspective view from the south of the newly-mapped seafloor backscatter in the Hjort region study area. The backscatter signal is draped over swath bathymetry. Also shows the AEEZ (yellow) and the Macquarie Island Marine Park (yellow) draped over the seafloor.

15. Terrain slope image of the newly-mapped seafloor in the Hjort region study area. Areas of interpreted sediment cover are shown as white hachured polygons. Slope ranges are: dark blue - 0-5^{o}; light blue - 5-10^{o}; green - 10-20^{o}; yellow - 20-30^{o}; orange - 30-40^{o}; and red - 40-60^{o}.

16. Terrain aspect image of the newly-mapped seafloor in the Hjort region study area. Areas of interpreted sediment cover are shown as white hachured polygons. Aspect azimuths are divided into 45^{o} sectors as indicated on the colour wheel.

17. Acoustic facies distribution in the Hjort region study area based on the classification of Whitmore and Belton (1997). See Figure 19 for the acoustic facies types along survey track and Figures 18a and 18b for echosounder signatures of the marked examples.

18. Examples of 3.5 kHz acoustic facies echo types based on Whitmore and Belton (1997). (a) Echo types IA on the top of a seamount; IB and IIA associated with contourites. (b) Echo types IIB associated with sediments at the base of a seamount; IIBa sediments distant from seamounts; and III (combines hyperbolae types IIIA, IIIC and IIID of Whitmore & Belton, 1997) on barren oceanic crust.

19. Acoustic facies correlated with seafloor backscatter signal to extrapolate sediment cover in the Hjort region study area. Acoustic facies types along track are (based on the classification of Whitmore & Belton, 1997): red – III (hyperbolae); white - IA; green - IB; dark blue - IIA; light blue - IIB; pink - IIBa; and absent - indeterminate.

20. Hill-shaded view of the seafloor in the Hjort region study area showing the distribution of volcanic features and current effects. Shown are volcanic features (hachured white polygons), contourites (purple lines), moat features (black lines) and evidence of current scour (pink dots).

21. Example of 3.5 kHz echosounder record of contourite mound. Location is along survey track at approximately 161^{o}22.3' E, 58^{o}7.25' S.

22. Hill-shaded view of the seafloor in the Hjort region study area showing modelled 'drainage' into sedimented areas derived from the bathymetric grid. Sediment cover is shown as hachured white polygons and the downslope flow network as black lines.

23. 3D perspective view from the south of the northern Hjort Trench terrain, centred at 157^{o}30' E, 56^{o}30' S, showing interpreted scouring effects related to an eastward flowing ocean-bottom current.

24. Hill-shaded view of the seafloor in the Hjort region study area showing modelled source regions for turbidites (white areas) and the distribution of a hypothetical benthic species X (see text) (black polygons).

25. Hill-shaded view of terrain and grayscale backscatter along the transit from the South Tasman Rise to the southern Macquarie Ridge survey area showing a detail (insets) of a mid-ocean seamount. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter and insets are offset for display purposes. Colour bar represents depth range in metres.

26. Hill-shaded view of terrain and grayscale backscatter along the transit from the Hjort region study area to the AEEZ boundary north of Macquarie Island showing a detail (insets) of the area east of Macquarie Island. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter and insets are offset for display purposes. Colour bar represents depth range in metres.

27. Hill-shaded view of terrain and grayscale backscatter along the transit from the eastern base of the northern Macquarie Ridge to New Zealand. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter is offset for display purposes. Colour bar represents depth range in metres.

28. Marine jurisdictional zones contained in the 1982 United Nations Convention on the Law of the Sea. Note that M refers to nautical mile. After Symonds et al. (1998).

TABLE CAPTIONS

ABSTRACT

The marine geophysical survey AUSTREA-2 was commissioned in early 2000 by the Australian Geological Survey Organisation (now Geoscience Australia), on behalf of the National Oceans Office and Environment Australia, to map and better understand the complex seafloor south of Macquarie Island. This collaborative effort aimed to address certain marine jurisdictional and management requirements of the Australian Government's *South-east Regional Marine Plan*.

The area mapped was over the southern extents of the Macquarie Ridge Complex, an elevated oceanic ridge extending for 1600 km south of New Zealand and defining the earthquake-prone plate boundary between the Australian and Pacific Plates. A total of 76 000 km^2 of multibeam swath bathymetry and reflectivity covered the area and was supplemented by continuously recorded echosounder sub-bottom profiling, high-resolution seismic, and both gravity and magnetic field sampling.

In terms of seafloor physiography, the area is dominated by an arcuate deep trench, which is paralleled to the east by a narrow elevated axial valley and, beyond, by a broad section of uplifted oceanic crust. A series of spectacular seamounts are developed to the southeast, with the largest rising more than 4 km above the surrounding seafloor. The entire ridge complex is abruptly terminated to the south where a system of large-scale right-lateral oceanic transforms accommodate the respective motions between the abutting Australian, Pacific and Antarctic Plates. Finer mapped detail reveals widespread relict seafloor spreading fabric and volcanic activity, the stress-strain effects of continued plate motion and extensive effects of bottom-current action.

In terms of seafloor character, the echosounder records and swath reflectivity afford a characterisation of the probable distribution of sediment type lying on the seafloor. Acoustic signatures indicate the widespread effects of current-shaping depositional styles, whilst correlation with morphology suggests a distribution largely controlled by current action and more localised deposition due to down-slope debris flows.

The swath spatial data sets of bathymetry and reflectivity, and those parameters which may be derived from them, is of sufficient quality and density to allow for the confident modelling of spatial distributions. For example, the spatial characterisation of seafloor depth, and therefore determinable seafloor slope, aspect and downslope flow, allow any phenomenon whose existence depends on quantifiable values for these parameters to have its probable distribution across the mapped area defined.

Analysis of the mapped region's morphology defines a preliminary area of extended Continental Shelf of up to 106 000 km^2 that could be added to Australia's marine jurisdiction under the provisions of the United Nations Convention on the Law of the Sea. This would give a total marine jurisdiction off Macquarie Island of about 580 000 km^2.

EXECUTIVE SUMMARY

The marine geophysical survey AUSTREA-2 was commissioned in early 2000 by the Australian Geological Survey Organisation (now Geoscience Australia) on behalf of the National Oceans Office and Environment Australia, to map several areas of ocean floor off southeast Australia. The primary focus was an area of seafloor to the south of Macquarie Island. The aim was to fulfil certain requirements of the Australian Government's recently instituted *South-east Regional Marine Plan*, and thereby better understand Australia's marine jurisdiction.

The region surveyed extended over the southern Macquarie Ridge, bounded approximately by the latitudes 55^{o} S to 61^{o} S and the longitudes 156^{o} E to 163^{o} E, and covered some 76 000 km^2. The seafloor was mapped using swath bathymetry, swath backscatter and acoustic sub-bottom profiling techniques.

The southern Macquarie Ridge region has steep and complex seafloor topography. To the west it is bounded by an arcuate-shaped deep oceanic trench, while paralleling it to the east is a narrow, long elevated ridge and valley system defining the present-day boundary between the Indo-Australian and Pacific Plates. The central province is characterised by a broad elevated zone of ocean floor, which retains a prominent fabric of relict seafloor spreading. Further east, a broad expanse of abyssal ocean floor is dominated by a northwest-trending chain of several large seamounts. The sparsely surveyed southern portion reveals the northern convergence of a zone of segmented oceanic crust offset by a major system of transform faults.

About one-third of the mapped seafloor is covered by a layer of sediments. Sub-bottom profiling delineates a broad distribution of both undisturbed and reworked deep-ocean sedimentation, which has been deposited as uniform layers, or shaped and eroded by bottom currents, primarily the Antarctic Circumpolar Current. The identification of debris flow deposits may indicate the effects of regional and local seismicity on steep-slope environments.

The large seamounts in the east and smaller volcanic edifices over the central elevated province indicate the importance of magmatism to the evolution of the region. The volcanic features may be related to mantle hot spot activity, or to current and/or former subduction of Indo-Australian Plate beneath an overriding Pacific Plate, probably along the eastern trench system.

The existence of primary and derived spatial data sets of seafloor parameters allows the region to be examined for both the spatial and statistical distribution of a particular phenomenon. For example, the query of terrain depth, slope, aspect and sediment cover regimes can provide information on the habitats of organism or sedimentary processes.

The new data sets have led to the preliminary definition of up to 106 000 km^2 of extended Continental Shelf (ECS) over the southern Macquarie Ridge region, giving a total marine jurisdiction off Macquarie Island of about 580 000 km^2.

INTRODUCTION

In January-February 2000 the AUSTREA-2 (AUSTRalia Environment Australia survey 2) marine geophysical survey was conducted by the Australian Geological Survey Organisation (AGSO; now Geoscience Australia) on behalf of Environment Australia (EA) and the newly formed National Oceans Office (NOO). It used the French marine science research vessel N/O *L'Atalante* to map the seafloor off southeast Tasmania and to the south of Macquarie Island, mostly in Australia's respective Exclusive Economic Zones (EEZs) and over adjoining areas of claimable extended Continental Shelf (ECS). The justification for this mapping effort was broadly two-fold: to increase the knowledge of, and aid in, the management of Australia's Marine Jurisdiction, and to acquire data to support Australia's claim to legal Continental Shelf.

As part of the Australian Government's recently endorsed *Australia's Oceans Policy* an initiative has been developed to increase the knowledge-base of, and better manage in a sustainable fashion, the large marine environment that is to fall under Australia's jurisdiction[1]. This initiative is developed in a detailed document, termed the *Marine Science and Technology Plan*, which lays down a framework for marine zone research and development over the next ten to fifteen years. This plan is further characterised into three programs, which address various aspects of the marine environment. Several of the objectives[2] within these programs directly and indirectly underpin the goals of the AUSTREA-2 survey in the waters south of Macquarie Island:

- to characterise and better understand the geological framework and evolution of Australia's continental margin and adjacent ocean basins;
- to define the boundaries of Australia's Marine Jurisdiction;
- to map the form and nature of the seabed of Australia's Marine Jurisdiction;
- to improve understanding of the principal physical and chemical oceanographic processes in Australia's coastal and open ocean waters;
- to define, research and explore regions in Australia's Marine Jurisdiction that are potentially important to the petroleum and minerals industries;
- to understand marine biodiversity and biological processes in Australia's oceans; and
- to understand the dynamics of Australia's marine habitat and ecosystems.

[1] Currently, Australia's marine jurisdiction over the water-column, seabed and subsoil beyond the territorial sea relates to its Exclusive Economic Zone (EEZ) out to 200 nautical miles beyond the baselines, whilst that over areas of seabed and subsoil beyond the EEZ awaits acceptance of the definition of the outer limit of the extended continental shelf by the United Nations.

[2] Taken from *Australia's Marine Science and Technology Plan: An Overview*.

The AUSTREA-2 survey was the second of two surveys to map parts of Australia's southeast marine region, and followed on directly from the AUSTREA-1 survey. AUSTREA-2 began in Hobart, Tasmania, on Saturday, 15 January 2000, and ended in Bluff, New Zealand, on Wednesday, 9 February 2000. The survey was essentially divided into seabed mapping efforts offshore of southeast Tasmania and to the south of Macquarie Island. The primary data set acquired was 10 200 km of multibeam bathymetry and backscatter and 8 000 km of high-resolution low-fold reflection seismic data. This was supported by the continuous acquisition of a suite of other geophysical and oceanographic data. The marine vessel used was the N/O *L'Atalante* of the French Institut Français de Recherche pour l'Exploitation de la MER (IFREMER), which is fully equipped for oceanographic research and geophysical data collection. A full description of survey parameters and preliminary survey findings is to be found in Bernardel et al. (2000).

The AUSTREA-2 survey effort to the south of Macquarie Island was concentrated mostly in the area bounded by longitudes 156° E and 163° E and latitudes 55° S and 61° S (Figs 1 & 11), and includes part of the recently created Macquarie Island Marine Park. This region of seafloor is known as the Hjort region of the southern Macquarie Ridge, and is characterised by depth ranges from about 390 m, over a large flat-topped seamount, to about 6700 m in the deepest zone of a trench. However, the vast majority of seafloor lies at typical abyssal depths of 3000 to 4500 m.

The Hjort region comprises the arcuate-shaped deep Hjort Trench and adjoining Hjort Ridge. Both features form the southern-most part of the Macquarie Ridge Complex, a 1600 km-long oceanic ridge that extends from the South Island of New Zealand, mostly as a series of linear ridge segments, to just north of a triple plate boundary at about 161° E and 61°30' S. For its entire length this ridge defines the tectonic boundary between the Pacific Plate to its east and the Indo-Australian Plate to its west. Furthermore, it is characterised by predominate right-lateral strike-slip motion between the respective plates and, as such, is the scene for some of Australia's largest earthquakes.

This report results from a contractual agreement made between AGSO and NOO in 1999. It represents the final report arising from this agreement and builds on all the digital and hardcopy products derived from the data acquired on the AUSTREA-2 survey. The primary aim of the report is to present a broad synthesis and analysis of seafloor physiography and character, as well as discuss the implications for resource potential and 'legal' Continental Shelf limits[3] in the Hjort region of the southern Macquarie Ridge.

Although this report represents a study of the AUSTREA-2 data over the southern Macquarie Ridge region, it does not contain a detailed analysis of the seismic data that was acquired to better resolve the tectonic framework of the region. As the seismic data is of excellent quality it is hoped that further tectonic studies of the region will follow.

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

Finally, the importance of the region should not be understated. The Macquarie Ridge is one of the world's great submarine ridges, and defines a major transform plate boundary. Moreover, its overall north-south trend means that it acts as a major physiographic barrier to the Antarctic Circumpolar Current, the Earth's largest and most important oceanic current, which flows eastward around the Antarctic landmass. The current's spatial variation, largely affected by seasonal dynamics, impacts on the balance of oceanic and atmospheric heat and chemical exchange, which, in turn, has an effect on the southern hemisphere's climate.

BACKGROUND

This report results from an agreement between the National Oceans Office (NOO) and the Australian Geological Survey Organisation (AGSO) under cooperative project OP2000-SE01. This project was designed to support the development of the *South-east Regional Marine Plan.* Regional marine plans form an important part of *Australia's Oceans Policy* framework.

In December 1998 the Australian Government instituted *Australia's Oceans Policy*, which was aimed at developing an integrated and ecosystem-based approach to planning and management for all ocean and seabed uses. This policy was supported by the release in 1999 of *Australia's Marine Science and Technology Plan*, which is concerned with developing a better understanding of the nature of Australia's vast marine jurisdiction. Specifically, this plan aims to:

- understand the form and structure of the seabed;
- understand the ocean's thermal characteristics, current patterns and chemistry, and its role in Australia's weather and climate;
- understand the marine species and ecosystems, and their behaviour over time;
- assist environmental conservation; and
- support the ecologically sustainable long term planning and management of our marine resources and environments.

These objectives will be achieved through the development of *Regional Marine Plans*, based on large-scale marine ecosystems covering the entire marine jurisdiction. These plans need to provide accessible and accurate information for planning and management on bathymetry, seabed structure and processes. The first of the plans to be prepared will be for the Exclusive Economic Zones and adjacent extended Continental Shelf for Australia's South-east Marine Region, which encompasses the ocean waters off Victoria, Tasmania, southern New South Wales, eastern South Australia and Macquarie Island.

In order to oversee implementation of *Australia's Oceans Policy* and, in particular, the Regional Marine Planning process, the National Oceans Office (NOO) was formed as an Executive Agency under the *Public Service Act 1999 (Cwth)*.

To implement some requirements of the *South-east Regional Marine Plan*, the development of which formally commenced in April 2000 and will continue for two to three years, NOO entered into an agreement with AGSO in mid-1999. As a result of this agreement a decision was made to charter France's premier oceanographic and geoscientific research vessel N/O *L'Atalante* to produce high-resolution bathymetry maps of the seafloor environment within parts of Australia's southeast marine jurisdiction. This vessel, owned by IFREMER, is equipped with excellent oceanographic and geophysical equipment, and has at its disposal the expertise for large-scale seabed mapping ventures.

The major focus of the NOO-AGSO agreement was to provide funding for a survey program, named AUSTREA (ie from AUSTRalia Environment Australia), to map, in particular, the seafloor along the eastern margin of Victoria and Tasmania, part of the western Tasmanian and Otway margins toward South Australia, the Great Australian Bight Marine Park, part of the Macquarie Island Marine Park and Hjort region of the southern Macquarie Ridge, south of Macquarie Island. Because of the amount and distribution of surveying effort involved, the acquisition program was divided into two legs, which were operated by AGSO: AUSTREA-1 and AUSTREA-2. AUSTREA-1 concentrated on the southeast region directly offshore of the Australian and Tasmanian landmasses, while the following AUSTREA-2 survey concentrated largely in the region further to the south and east of Tasmania and south of Macquarie Island. The work in the Macquarie Ridge region, in particular, also addressed issues related to the definition of the outer limit of Australia's legal Continental Shelf under the provisions of the United Nations Convention on the Law of the Sea (UNCLOS; Appendix 2).

As indicated, part of the mapping effort was to be directed over the Macquarie Island Marine Park. This region covers the southeastern quadrant of the 200 nautical mile (M) EEZ encircling Macquarie Island (Fig. 1), and with a size of some 160 000 km^2 is currently the world's largest marine park. The park was declared in October 1999 under the *National Parks and Wildlife Conservation Act 1975* (NPWC Act) to protect the unique and vulnerable marine ecosystems of the southeastern portion of the Macquarie Island Region. The NPWC Act was replaced by the *Environment Protection and Biodiversity Conservation Act 1999* in July 2000.

The preliminary survey findings, along with survey parameters, for the AUSTREA-1 and AUSTREA-2 cruises are summarised in Hill et al. (2000) and Bernardel et al. (2000), respectively. These two reports formed an initial output of the NOO-AGSO agreement.

This final report focuses on the seafloor morphology and sediment and rock characteristics of the Hjort region, along the southern extension of the Macquarie Ridge and including part of the Macquarie Island Marine Park. It presents a compilation, integration and preliminary analysis of a component of the AUSTREA-2 survey results.

GEOLOGICAL SETTING OF THE SOUTH-EAST MARINE REGION – AN OVERVIEW

In terms of regional marine planning, the South-east Marine Region includes all areas within Australia's marine jurisdiction that lie off Victoria, Tasmania, eastern South Australia, southern New South Wales and Macquarie Island (legally considered part of Tasmania). The region (Fig. 2) extends from the outer limit of the 200 nautical mile (M) Australian Exclusive Economic Zone (AEEZ) between Kangaroo Island off South Australia (35°30' S) in the west to approximately 36° S off New South Wales in the east, where the boundary is extrapolated from the northern limit of the Twofold Shelf meso-scale region (Interim Marine and Coastal Regionalisation for Australia, 1999). The South-east Marine Region also includes adjacent areas of seabed and subsoil that lie within the extended Continental Shelf beyond the AEEZ, as defined under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS; Appendix 2; UNCLOS, 1983).

The South-east Marine Region encompasses thirteen of the IMCRA (1997) meso-scale shelf regions (Fig. 3) – eastern part of Eyre (EYR), Coorong (COR), Otway (OTW), Franklin (FRA), Davey (DAV), Bruny (BRU), Freycinet (FRT), Boags (BGS), Central Bass Strait (CBS), Central Victoria (CVA), Victorian Embayments (VES), Flinders (FLI) and Twofold Shelf (TWO), as well as the Sub-Antarctic (incorporating the South Tasman Rise) and Macquarie Island marine domains of the EEZ. It includes parts of the Southern Ocean and the Tasman Sea, as well as Bass Strait. It is a physically complex region extending through 24 degrees of latitude (36^{o}-60° S) and 30 degrees of longitude (135^{o}-165° E), encompassing a variety of climatic zones, seafloor types and oceanographic conditions, and therefore a diverse range of marine habitats. The southeast part of Australia contains Australia's highest population density, and the coastline of the South-east Marine Region forms the residential and recreational area for a large percentage of the population.

The bathymetry, geology and tectonic evolution of the main physiographic elements of the South-east Marine Region (Fig. 4) are described in more detail in the AUSTREA-1 and AUSTREA-2 cruise reports (Hill et al., 2000 and Bernardel et al., 2000, respectively). To the west of Tasmania the continental margin varies from about 130-450 km in width where it faces the 5000 m deep oceanic South Australian Basin and Abyssal Plain. The narrower part of the margin from South West Cape in Tasmania, to Cape Jaffa in South Australia, consists of a 30-60 km wide shelf to about 200 m depth; a relatively steep, 100-150 km wide canyoned and gullied slope from 200 m to 3500 m depth; and, in places, a smoother 50 km wide lower slope that is commonly bound on its outer edge by northwest-trending ridges of continental bedrock (Hill et al., 1997). Further west, the broad margin of the central Great Australian Bight consists of a 200 km wide shelf, and, beyond the South-east Marine Region seaward extent, a broad slope province containing the 200 km wide, 300-2500 m deep Ceduna Terrace. South of Tasmania the margin can be more than 550 km wide. Here the 40 km wide shelf is separated from the triangular-shaped 1000-3000 m deep, current-swept, continental South Tasman Rise by the 3500 m deep South Tasman Saddle. Off southeast Tasmania the margin is also up to 400 km wide, due to the presence of the circular 2000-3000 m deep continental East Tasman Plateau. This plateau is surmounted by the Cascade Seamount, which rises to within 600 m of the sea surface. The East Tasman Plateau is separated from the upper slope by the 3500 m deep East Tasman Saddle, and from the South Tasman Rise by the partly oceanic 4000-4500 m deep L'Atalante Depression (Royer & Rollet, 1997; Exon et al., 1997).

Off northeast Tasmania, eastern Victoria and southern NSW the margin is only about 60-80 km wide, and consists of a narrow (20-40 km) shelf and a steep (3-10°), 40-50 km wide canyoned slope. The 80 km wide west-northwest-trending Bass Canyon complex dissects the slope from depths of 2000-4000 m to the east of the 250 km by 500 km broad shelfal depression that forms Bass Strait. In the South-east Marine Region, the eastern margin lies adjacent to the 4200-4600 m deep oceanic Tasman Basin and Abyssal Plain. The Tasman Basin separates the Australian margin from the 750-3000 m deep continental Lord Howe Rise and Challenger Plateau. Major volcanic seamounts and guyots on the western margin of Lord Howe Rise, within the Tasman Basin, and south of the East Tasman Plateau (Fig. 4) form part of the hot-spot related Lord Howe, Tasmantid and Balleny Seamount Chains, respectively.

Southeast of the Tasman Basin, Macquarie Island surmounts a system of narrow (generally less than 25 km), 500-2000 m deep ridges and adjacent 5000-6500 m deep troughs that form the Macquarie Ridge Complex – from north to south the Puysegur, McDougall, Macquarie and Hjort paired ridge and trench systems. This north-northeast-trending oceanic ridge complex extends north from the Australia-Pacific-Antarctic triple plate junction at about 160^{o} E, 61°30' S, to the Alpine Fault System of New Zealand's South Island, a distance of some 1600 km. In the north, the Macquarie Ridge Complex is separated from the large continental Campbell Plateau to the east by the Solander Trough, which joins to the south with the oceanic Emerald Basin.

East-west oriented ridge segments within the Australia-Antarctic Basin correspond to the Southeast Indian Ridge seafloor spreading system (Fig. 4), along which new oceanic crust is being created during the separation of Australia and Antarctica. Associated north-trending ridge-trough systems that run between Australia and Antarctica (Fig. 1) are oceanic fracture zones (eg George V, Tasman and Balleny Fracture Zones) - transform faults that mark the flow-lines along which Australia and Antarctica drifted apart. Other more subtle northwest- and northeast-trending lineaments in the Tasman Basin also correspond to the extinct spreading ridge and transform faults, respectively. The irregular northeast-trending ridge complex at the southern end of the Tasman Basin, that includes Resolution Ridge, corresponds to the boundary between the older oceanic crust of the Tasman spreading system, and younger oceanic crust of the Southeast Indian and Pacific-Antarctic spreading systems to the south.

The arrangement of physiographic provinces and features described above is largely the result of the progressive rifting and breakup of Gondwana since the Late Jurassic (~160 Ma), and separation of the various continental fragments during the creation of new ocean floor by seafloor spreading, possibly from about the Cenomanian (~95 Ma) in places, but certainly from the Campanian (~80 Ma), to the present. The most recent syntheses of basin and margin development off southern and eastern Australia are contained in Symonds et al. (1996) and Stagg et al. (1999). The sedimentary basins of the South-east Marine Region (Fig. 5) are largely the product of a protracted episode of Mesozoic extension within eastern Gondwana, which led to the development of the 'Southern Rift System' (Willcox & Stagg, 1990) and ultimately to the breakup of the supercontinent into the Australian and Antarctic Plates. The 'Southern Rift System', containing the Bremer, Great Australian Bight, Duntroon, Otway, and Sorell Basins, extends for more than 4000 km, from Broken Ridge in the far west, to the South Tasman Rise in the southeast, with a major splay passing through the Bass and Gippsland Basins of the Bass Strait region. There is no direct evidence for rift basins of this age in New Zealand or beneath Lord Howe Rise, and, in fact, New Zealand and New Caledonia were active convergent margins at this time (Bradshaw, 1989) driven by the oblique subduction of the Phoenix Plate. The 'Southern Rift System' began to form at about the same time as Callovian-Oxfordian (~160 Ma) breakup off northwest Australia, on a trend that was roughly perpendicular to the convergent plate boundary of the proto-Pacific further to the east.

The central southern Australian margin to the west of Kangaroo Island is underpinned by the Proterozoic Fraser-Albany and Gawler cratonic blocks and overlying Proterozoic (eg the Polda Trough; Fig. 5) and Palaeozoic (eg the Kanmantoo Trough) intracratonic basins. Old cratonic blocks do not exist further east, and during most of the Palaeozoic to early Mesozoic eastern Australia was a convergent margin associated with periods of oblique subduction represented by northwest-trending, parallel belts of volcanic arc, forearc basin and subduction complex successions (Korsch & Totterdell, 1996) of the Tasman Fold Belt. Thus, in the east, 'basement' underlying the present-day continental margin and its conjugates is likely to comprise an amalgamation of these convergent terranes. A short-lived Middle Jurassic tholeiitic magmatic event (175±18 Ma; Hergt et al., 1989) formed the Tasmanian dolerite province as part of a long, linear flood basaltic belt within Gondwana that stretched from southern Africa (Karoo province) through Antarctica (Ferrar province) to Australia (Tasman province) (Elliot, 1992). This magmatism probably represents the initial stages of Gondwana breakup along eastern Australia.

The extension history of the 'Southern Rift System' is complex and poorly understood, with the azimuth of the earliest Late Jurassic-Early Cretaceous phase of extension (> 160 Ma) thought to be northwest-southeast in the central Great Australian Bight (Etheridge et al., 1989) with possible associated strike-slip and oblique extensional basin systems developing in the newly-formed Otway, Bass and Gippsland Basins. A younger Tithonian (> 145 Ma) north-northeast-south-southwest extension azimuth has been suggested for the Otway Basin (Hill et al., 1995), and Moore et al. (2000) suggest that this phase produced a new east-west basin system that overprinted the earlier phase and linked the Gippsland Basin, the onshore-nearshore Otway Basin and perhaps the Duntroon Sub-basin (Fig. 5). From the Barremian-Cenomanian (120-95 Ma) the southeast Australian basin system (Otway, Bass and Gippsland) was flooded with volcanogenic sediments, which are thought to have an eastern provenance (Hill et al., 1995). These sediments may indicate the existence of a Barremian-Cenomanian extensional/transtensional magmatic province off eastern Australia along the line of incipient Tasman Sea breakup (Bryan et al., 1996; Symonds et al., 1996). This province may now lie largely on the Lord Howe Rise. A final phase of Cenomanian-Santonian (~95-85 Ma) rifting created northwest-southeast and north-south extensional and transtensional rift trends in the deep-water Otway-Sorell Basins, offshore Gippsland Basin, Bass Basin, and both on and adjacent to the South Tasman Rise, East Tasman Plateau (Fig. 5; Moore et al., 2000), and margins of Lord Howe Rise. This phase of extension, which preceded seafloor spreading to the south and east of Australia, is also represented by significant lower crust/upper mantle thinning that produced the continent-ocean transition zone in the central Great Australian Bight (Sayers et al., in press) and by tectonism/magmatism on the South Island of New Zealand (Laird, 1994).

Breakup, and the start of seafloor spreading with the creation of new ocean crust in the South-east Marine Region, were initially thought to have commenced in the central Great Australian Bight during a period of very slow spreading (<1-2 cm/yr, full rate; Cande & Mutter, 1982; Veevers, 1986) from the Cenomanian - Middle Eocene (magnetic anomaly 34y-21y; ~95-47 Ma; Fig. 6). Recently, on the basis of an interpretation of new deep-seismic and magnetic data, Sayers et al. (in press) suggested that new ocean crust only began to form around 83 Ma (early Campanian), about the same time as in the Tasman Basin to the east (see Tasman Sea in Fig. 7), although spreading was considerably faster here. Spreading accelerated (4-5 cm/yr) south of Australia in the Middle Eocene (anomaly 18, ~40 Ma) and continued at approximately this rate to the present. No anomalies older than Middle Eocene have been identified off the Otway Basin and west Tasmania margins (Fig. 7) indicating that seafloor spreading propagated eastwards from the Great Australian Bight. During seafloor spreading the western sector of the South Tasman Rise (Fig. 5) initially slid past western Tasmania as part of the Antarctic Plate. However, during the Late Palaeocene to Early Eocene it rifted away from Antarctica and became welded to the central sector of the STR. The Antarctic Plate began to move rapidly southward relative to the Australian Plate in the Middle Eocene forming the extensive Tasman Fracture Zone (Fig. 4) along the western margin of the STR. The Antarctic Plate cleared the South Tasman Rise in the early Oligocene (~33 Ma; Fig. 8b), significantly affecting ocean circulation both regionally and globally.

Seafloor spreading between eastern Australia, the East Tasman Plateau, the South Tasman Rise and the Lord Howe Rise/Challenger Plateau (Fig. 7) began in the Campanian (anomaly 33, ~83 Ma; Hayes & Ringis, 1973; Gaina et al., 1998), propagated north along the eastern Australian margin and ended abruptly in the Early Eocene (anomaly 24, ~55 Ma). The complex ocean floor between the STR, Macquarie Ridge and Antarctica has recently been re-examined by Cande et al. (2000). They recognise Australia-West Antarctic spreading from the Middle Eocene - Late Oligocene (anomalies 20 to 8, ~46-26 Ma) off the South Tasman Rise (Fig. 6b) and the Ross Sea that indicates extension between East and West Antarctica. At the same time, Australia-Pacific spreading, orthogonal to that in the Tasman Basin, occurred in the south Tasman Basin south of Resolution Ridge and in the Emerald Basin (Wood et al., 1996; Cande et al., 2000), both of which now abut against, and are offset by, the Macquarie Ridge. The Macquarie Ridge Complex marks the seismically active Australia-Pacific plate boundary that links north to the Alpine Fault of New Zealand, and south with the Southeast Indian and Pacific-Antarctic spreading ridges at the Macquarie Triple Junction (Figs 6b & 7). Massell et al. (2000) suggest that the present-day, right-lateral strike-slip boundary along the Macquarie Ridge coincides with the relict spreading centre responsible for creating the south Tasman/Emerald Basin oceanic crust. Pure strike-slip motion, transpression and possibly underthrusting (incipient subduction) have probably occurred along various segments of the Macquarie Ridge Complex during at least the last 10 Ma (Massell et al., 2000).

An important aspect of the plate kinematic evolution of the South-east Marine Region is the opening of the Tasmanian Gateway and the development of the modern oceanic circulation system as Antarctica cleared the South Tasman Rise in the early Oligocene (~33 Ma; Fig. 8). This development of the Antarctic Circumpolar Current (ACC) is critical both to global climate evolution and to the modern marine ecosystems of the region. With the Tasmanian Gateway closed during the Middle Eocene (43.7 Ma; Fig. 8a) weak gyral circulation is inferred in the highly restricted Australo-Antarctic Gulf south of Australia, while the Antarctic margin further east is influenced by the warm East Australian Current (Shipboard Scientific Party, 2000). During the earliest Oligocene (33 Ma; Fig. 8b) the Tasmanian Gateway opened to deep-water circum-Antarctic circulation, and this began to weaken the influence of the East Australian Current on the Antarctic margin. During the Late Oligocene (26 Ma; Fig. 8c) the Gateway was fully open expanding the ACC and rapidly increasing the decoupling of the East Australian Current from the Antarctic margin (Shipboard Scientific Party, 2000). This produced cooling of Antarctica and some ice sheet formation, contributing significantly to global cooling. With the opening of the Drake Passage off South America in the Neogene (approximately 24-1.5 Ma) and strengthening of the ACC through the widening Tasmanian Gateway, global cooling and thermohaline circulation intensified leading to the arrival of the current “Icehouse” world by about 15 Ma. This is the environment in which the South-east Marine Region’s diverse ecosystems have developed.

GEOLOGICAL SETTING OF THE MACQUARIE RIDGE REGION

Regional Morphology

The entire Macquarie Ridge bathymetric feature is an elevated, narrow oceanic ridge, which extends for some 1600 km from the southern tip of the South Island of New Zealand to a position at about 159°30’ E, 59°30’ S (Figs 1 & 9). It can be considered to comprise four discrete elements, which from north to south are: the mostly linear Puysegur segment from the South Island to about 50°30’ S, the McDougall segment thereon to about 53°30’ S (Fig. 9), the Macquarie segment thereon to about 56° S (Fig. 9) and the broader and more arcuate-shaped Hjort segment thereon to about 59°30’ S (Fig. 9; Hayes & Talwani, 1972; Frohlich et al., 1997; Massell et al., 2000). All four ridge segments are generally separated by a bathymetric deep and/or a change in general strike direction. All ridge segments are paired with an adjoining trench. Although a large part of the ridge and adjoining terrain is covered by detailed swath bathymetry the main axis of the ridge is poorly surveyed and remains an obstacle to maritime traffic in the areas directly to the north and south of Macquarie Island along the entire Macquarie segment.

The northern-most Puysegur segment of the Macquarie Ridge Complex (MRC) is approximately 330 km long and is paired with a trench reaching depths of 6000 m on its western side. From north to south the ridge narrows and shallows along its apex from an average of 1500-2000 m to possibly shallower than 100 m depth. Collot et al. (1995) examine swath data to present a good overview of the morphology in the southern half of the segment.

The McDougall segment (Fig. 9) lies directly to the south of the Puysegur segment and trends more towards the northeast. It is the most linear and longest of all segments, at about 400 km, and although the ridge segment is mostly continuous from the Puysegur region it is discriminated both on the basis of a change in strike and by having the adjoining trench on its eastern side. This trench is termed the Solander Trough and reaches depths of about 6000 m.

The Macquarie segment (Fig. 9) strikes more to the north than the McDougall segment and, like it, has its trench on the eastern side. These two segments are separated by a deep bathymetric passage of about 4000 m depth, termed the "53°30' S passage". The Macquarie segment contains the only subaerial exposure of the entire ridge system at Macquarie Island and its neighbouring islands. Recently acquired AGSO swath bathymetry data (HMR1[4] swath system) reveals that half of the segment's length lies shallower than 100 m and that the ridge is bisected into parallel eastern and western ridges at its crest (Massell et al., 2000). The Macquarie Trough defines the trench along the segment's eastern flank and averages 5500 m depth in its deepest parts.

The Hjort segment (Figs 9 & 11) is the southern-most segment of the MRC. It is arcuate in shape, being convex towards the west. The ridge is separated by a short north-south trough, which offsets the broader and deeper Hjort Ridge to the east from the more linear and shallower Macquarie Ridge to the west. The Hjort Trench is located on the western side and is the best-developed trough of the entire Macquarie Ridge system, reaching depths of nearly 6700 m in its deeper southern half. As this report presents the results of the new swath mapping data over this Hjort region of the MRC a more detailed morphological description will follow in a later section.

The overall form of the MRC changes markedly in the Hjort region, where it changes from a series of mostly narrow, north-northeast striking linear ridge-trench pairings to a more arcuate shape and broadened form, bending around gradually to the southeast so as to strike more to the northwest. This, in turn, ceases abruptly at about 59°36' S where a major oceanic fracture zone extends down to the Macquarie Triple Junction at about 161° E, 61°30' S. This transition effectively marks the southern limit of the Macquarie Ridge system.

Geological Evolution and Tectonic Framework

The Macquarie Ridge Complex (MRC) is a term used to designate the entire suite of ridge-trench segments and adjoining ocean floor that comprise the boundary between the Pacific Plate and Indo-Australian Plate from the South Island of New Zealand to just north of the Macquarie Triple Junction. It is of geological interest for several reasons: defining a geological plate boundary, high seismicity, subaerial exposure of an ophiolite, southward continuation of the well-studied Alpine Fault zone of New Zealand and unusual topography in an intra-oceanic setting. The entire complex is

[4] Hawaii Institute for Geophysics Acoustic Wide Angle Imaging Instrument Mapping Researcher 1.

believed to be of oceanic crust composition as there is no evidence both for continental-type rocks or a past setting in a continental domain. Notwithstanding its remote location it has been, and remains, of particular scientific interest, chiefly in the field of neotectonics, but also in terms of its effect on southern ocean circulation patterns and, in turn, the total climatic budget.

The MRC and surrounding regions have been the subject of several scientific papers. The region's morphology, oceanography and tectonic setting are considered in several papers of volumes 15 and 19 of the Antarctic Research Series (Reid [ed.], 1971 and Hayes [ed.], 1972, respectively), where the results of several cruises by the USNS *Eltanin* and RV *Conrad* were examined. Seafloor sedimentary processes and current interaction are presented in Schuur et al. (1998). Direct geologic studies of rocks and spatial outcrop on Macquarie Island are made in Griffen and Varne (1980), Duncan and Varne (1988) and Goscombe and Everard (1999). Plate kinematic settings have also been the focus of several works, including the ridge's genesis (Kamp, 1986; Lamarche et al., 1997; Massell et al., 2000), the nature of the boundary in the Puysegur segment (Collot et al., 1995) and evidence for subduction (Williamson et al., 1989; Ruff et al., 1989; Collot et al., 1995; Massell et al., 2000). The Macquarie Triple Junction was examined in Falconer (1972) and, in terms of the surrounding segmented oceanic crust, in Lodolo and Coren (1994, 1997) and Lodolo et al. (1996). Furthermore, the region's high seismicity and associated mechanics of plate motion are discussed in Jones and McCue (1988), Ruff et al. (1989) and Frohlich et al. (1997) and, with regard to the large 1989 earthquake, in Anderson (1990) and Das (1992, 1993). Finally, the ridge's geophysical characteristics are considered in terms of the local gravitational field in Ruff and Cazenave (1985).

The Hjort region at the southern end of the MRC, which is the focus of this report, has been sparsely covered by the literature, because of the paucity of geophysical data. Nevertheless, it has been considered in several papers: Williamson et al. (1989) and Lodolo and Coren (1994); in terms of evidence indicating subduction; Frohlich et al. (1997), in terms of earthquake thrust mechanisms; and Massell et al. (2000), where its northern extent was mapped by both swath and seismic data. We expect that the survey data acquired, and the preliminary findings addressed in this report, will present significant opportunities to examine the region in greater detail, and provide some ideas on the nature of plate motion, both in particular regard to the region and in general regard to the mechanics of strain partitioning along an active plate boundary.

Present tectonic motion along the MRC plate boundary is predominantly right-lateral strike-slip (Hayes & Talwani, 1972). This is confirmed by teleseismically determined focal mechanisms, which support relative right-lateral motion along a very narrow zone for most of the plate boundary (Frohlich et al., 1997). This, however, does not preclude the occurrence of main or aftershock earthquake foci on adjoining lines of weakness (see spread of earthquake foci on Fig. 10), such as the large cluster of aftershocks spread along a flanking oceanic fracture to the major 1989 plate boundary event located at approximately 160°38' E, 52°22' S (Das, 1993). Little teleseismic evidence is provided for ongoing subduction, incipient subduction or transpression except for the northern MRC near Fiordland, in New Zealand, and a thrust-mechanism aftershock in the southern Hjort Trench (Frohlich et al., 1997). However, Massell et al. (2000) argue for possible underthrusting of the Pacific Plate in the

Macquarie segment of the MRC as a result of interpreted swath-mapped seafloor lineaments and Macquarie Island geology, which indicates recent transpression. Respective plate motion (DeMets et al., 1990) and slip motion vectors (Frohlich et al., 1997) position an instantaneous Australian-Pacific pole, describing average relative motion, in the region about 180^{o} E and within latitudes 57^{o}-61^{o} S. This motion indicates anti-clockwise rotation of the Pacific Plate, about this pole, relative to the Australian Plate.

Because of its intra-oceanic setting the entire MRC crust is believed to be oceanic in origin. This is generally confirmed by the sampling of 9.7-11.5 Ma mafic-ultramafic volcanic and deep-seated igneous rocks on Macquarie Island (Duncan & Varne, 1988), as well as seafloor dredge samples (Appendix 5) across the region and core samples from DSDP 278 and DSDP 279 to the east of the MRC. The rocks indicate geochemical compositions in accordance with a mid-ocean ridge setting or ocean island basalts. Macquarie Island's northern geology is composed mainly of serpentinised peridotites, gabbros and metamorphosed dolerite dyke swarms, whereas the southern part is dominated by fresh or slightly metamorphosed extrusive rocks, both suites possibly having been formed in a submarine spreading zone (Varne & Rubenach, 1972). Furthermore, Massell et al. (2000) support the oceanic spreading centre origin and provide a simplified kinematic model describing its transformation into a strike-slip boundary.

The morphostructure of the MRC has led some authors to suggest that the presence of a transpressive/compressive regime is evidence for subduction (Williamson et al., 1989). Although right-lateral strike-slip motion is proven to be the primary mechanism for respective plate motions along the MRC boundary (Frohlich et al., 1997), subduction is certainly present in the Fiordland region of the South Island of New Zealand, and has been strongly inferred for the Puysegur segment (Collot et al., 1995), as well as argued for in the Macquarie segment (Massell et al., 2000) and suggested for in the southern Hjort segment (Massell et al., 2000). Collot et al. (1995) examine in detail swath-mapped seafloor for the southern Puysegur segment, where they interpreted reverse faults along the ridge's eastern flank and infer compressive propagation of an incipient underthrusted Indo-Australian Plate along its western trench. This contrasts with their interpretation for a more advanced stage of subduction of the Indo-Australian Plate in the north. Massell et al. (2000) provide a detailed study of swath-mapped seafloor along the MRC and suggest that features indicating transpression provide some evidence for westward subduction of the Pacific Plate underneath the Indo-Australian Plate in the Macquarie segment. They use evidence for uplift of Macquarie Island to support the argument for a convergent regime in the recent past. In addition, limited data over the northern Hjort Trench reveals some reverse faulting, which coupled with plate motion vector solutions of DeMets et al. (1990), lead the authors to infer a situation similar to the Puysegur segment, that is, eastward subduction of the Indo-Australian Plate beneath the Pacific Plate.

The MRC is argued to be a relic oceanic seafloor spreading centre that was subsequently uplifted and transformed into a strike-slip boundary due to the change in respective motion of the Indo-Australian and Pacific Plates (Massell et al., 2000). Its geological evolution can be summarised as:

- At some time in the early to mid-Eocene (45-50 Ma) a period of rifting gave way to breakup between the Campbell Plateau and Resolution Ridge (Fig. 4).

- From the mid-Eocene to the Late Miocene (~10 Ma) oceanic crust was being formed along the MRC spreading centre and flooring the South Tasman Basin to its west and the Emerald Basin to its east. Decreasing distances between the fracture zones, which bend asymptotically into the MRC, infer a gradual reduction in the production of oceanic crust with time (Massell et al., 2000).

- At some stage effective spreading ceased and the spreading centre became a zone of both convergent and transcurrent motion. This was probably due to the pole of rotation between the Pacific and Indo-Australian Plates, which is east of the MRC, migrating southward (Sutherland, 1995; Lamarche et al., 1997), so that extension gave way to shear motion. Kamp (1986) examines New Zealand's geology and models the commencement of transcurrent motion in the MRC at 23 Ma, with a specific 500 km right-lateral motion component along the Alpine Fault since about 12 Ma (Hunt, 1978). This is in contrast to regional plate reconstructions (Stock & Molnar, 1987; Cande & Kent, 1995), which suggest that strike-slip motion began in the New Zealand sector closer to 35 Ma, with most of the right-lateral motion occurring before 19.9 Ma.

- According to the model of Massell et al. (2000) as shearing motion began to dominate the movement between the respective plates the orthogonal transform faults began to bend in an arcuate fashion, producing shorter spreading segments. This transition is expected to have been ductile as a result of the younger and hotter nature of the crust in the immediate vicinity of the spreading centre. The dating of a 9.7 Ma basalt on Macquarie Island suggest that oceanic crust was still being created at least as late as the Late Miocene.

- The variation in the Pacific-Indo-Australian pole-of-rotation during the southward propagation of transcurrent motion from New Zealand may be responsible for the differentiation of the MRC boundary into four distinct regional segments (see description above). Their present-day geometry and current plate motion vectors (DeMets et al., 1990) indicate localised zones of probable transpression and transtension.

SEAFLOOR MORPHOLOGY

The morphology of the seafloor mapped in the southern MRC is visualised in Figures 11 and 12, where the general arcuate nature of the Hjort region is clearly evident. To aid in its interpretation the region is subdivided into the following smaller tectonically related provinces (Fig.11): the Hjort Trench; the flanking Hjort Ridge; the intervening narrow Macquarie Ridge; the adjoining Hjort Ridge seamounts; and the region of segmented oceanic crust to the south. The descriptions address general planimetric extent and shape, general depth ranges and both slope and aspect characterisation.

Hjort Trench province

The Hjort Trench province is a crescent-shaped deep oceanic trench, which is flanked to the west by abyssal plain terrain and to the east by an elevated narrow axial valley (Macquarie Ridge province) that parallels it for its entire length. It is largely restricted to an area between latitudes 56^o S and 60^o S and longitudes 157^o E and 159^{o}30’ E. In its northern third (north of 57^{o}30’ S) it maintains a more linear form, striking north-northeast, while it is convex to the southwest in shape for its southern two-thirds, where the strike varies continuously from north to approximately northwest as it bends eastwards. Its deepest parts lie in the south.

Considering the province’s western side, bathymetry along the Hjort Trench’s western wall ranges from about 3000-4000 m on abyssal plain to an average trench floor depth of 5000-5500 m in the north and 6000-6500 m in the south. The descent to the trench floor is steepest in the south, being evident from the density of contours and higher slope angles (Figs 11 & 12). These slopes are generally consistent except for an area between 57^{o}30’ S and 58^o S, where the western flank broadens and forms a minor platform between 4500 m and 5000 m depth. North of this terrace, from about 56^o S to 57^{o}30’ S, the depth contours are slightly more irregular in shape as they descend to the sediment-covered trench floor. This reflects the rough form of un-sedimented oceanic crust, where the west-southwest to east-northeast seafloor ridging correlates with the strike of basaltic crust production at the Indo-Australian-Antarctic spreading centre to the south. This contrasts with the trench wall to the south of the terrace feature, where the general continuous and parallel form to the contours indicates a consistently sedimented seafloor. However, this smooth descent is partly broken from about 58^{o}15’ S to 59^o S, where a series of minor ridges and troughs, sub-parallel to the trench strike, embed the slope.

The province’s eastern side is characterised by a general moderate- to high-angle slope, which extends up to the western-most ridge of the axial valley that separates the Hjort Trench and Hjort Ridge (ie the Macquarie Ridge province). From about 56^o S to 57^{o}30’ S the slope is relatively uniform and steep, rising from a trench floor at 5500 m to a broken ridge top lying at about 4000 m depth. At about 57^{o}30’ S the trench wall has a marked spur that protrudes into the trench proper from a ridge segment with peaks shallower than 3000 m. From this spur to the southern extent of the trench the eastern wall is uniformly steep from a trench floor averaging 6000 m depth to a narrow ridge line averaging 3000 m depth. A further smaller spur is found at about 59^{o}20’ S, while parts of the wall are punctuated by canyons extending down to the trench floor.

The trench floor region separates the western and eastern sidewalls. From the constriction at 57^{o}30’ S (5 km width) the floor broadens to the north (about 15-20 km) and averages 5500-6000 m depth, while it is narrower to the south (about 10 km) and averages 6000-6500 m depth. In the north it narrows and shallows considerably to its northern tip and supports a series of wide sinuous-like minor ridge developments accompanied by a depression along its western edge with the trench wall. In the south the floor maintains a more uniform width throughout and supports a narrow sinuous ridge along most of its length that is, on average, 500 m higher than the surrounding trench floor. The deepest part of the entire trench exists as an elongate depression centred at about 158°40’ E, 59°20’ S, which reaches a maximum depth of approximately 6700 m. Furthermore, a minor ridge exists along the southern flank of the eastern trench wall spur, at the indicated constriction, and seismic data suggests that it may have formed due to a major slump event off this spur.

Hjort Ridge province

The Hjort Ridge region is a broad, slightly arcuate-shaped area of seafloor directly to the east of the Macquarie Ridge province (see below), and is located within longitudes 158° E and 159°30’ E and latitudes 56° S and 58°30’ S. It is slightly convex towards the west, with both its northern and southern extents bending towards the east. Being of a ridge-like form it is generally shallower than the surrounding seafloor, with the greatest relief found at its northern extremity. Seafloor of abyssal plain character is found directly to its north, east and south, while an elongate region of seamounts lies to its southeast (Hjort Ridge seamount province, see below) and a complex zone of inter-laced narrow ridges and trenches is situated along its western flank (Macquarie Ridge province, see below).

The northern nose of the Hjort Ridge province is its shallowest part, averaging 1500 m depth and, although not completely surveyed, shallower than 900 m in parts. Its western flank has a high gradient of predominantly 10°-30° (Figs 11 & 12) and descends down to depths of about 3000-4000 m into a north-northeast to south-southwest-trending trough, which acts to separate this part of the Hjort Ridge from the elevated Macquarie Ridge proper directly to the west. Furthermore, depth contour inflections indicate some canyon development down to the trough with slopes greater than 30°. The slopes on the northern and eastern sides, however, are less steep in their descent to abyssal depths, while those to the south descend more gradually over some 1000 m to the deeper, broader zone of the central Hjort Ridge.

The most striking feature of the central and southern portion of the Hjort Ridge province is the presence of a strong superimposed fabric of parallel, narrow ridge-like features trending mostly northeast to southwest across its top and down its sides. They are generally associated with steep sides and are less pronounced in the southwest (Fig. 11). This strongly suggests that the origin of the crust defining the ridge is oceanic in nature and, therefore, was formed at and moved away from an oceanic spreading centre to its south. These ridges average 100-200 m in amplitude and 20-40 km in their along-strike extent. Slight curving trends are observed, which probably indicate differing stress-strain regimes across the whole province.

The main body of the Hjort Ridge province can be defined by an encircling 3500 m depth contour, with about half of it lying shallower than 3000 m and one quarter shallower than 2500 m. Several sub-circular mounds rise above the surrounding terrain and are likely to represent volcanic edifices (see below). These are best developed in the southeast, where the two largest are centred at 159°15’ E, 57°50’ S and 159°30’ E, 58°05’ S, with peaks at 1300 m and 1700 m depth, respectively, although their overall form is largely affected by the superimposed ridging fabric discussed. A more perfectly rounded example of a volcanic cone is found at 158°46' E, 57°58' S, where it rises some 800 m above the surrounding terrain and is encircled by a consistent slope of 10-20° (Figs 11 & 15).

Except for the northern elevated nose of the Hjort Ridge province slopes average a modest 0°-5° around most of its margins (Fig. 15). However, this increases to 5°-20° in the southeast as a result of the presence of the higher-relief seamounts. Furthermore, whereas most of the ridge's margins are characterised by spreading fabric descending to the surrounding deeper seafloor, the southwest quadrant is distinct in having a fairly characterless low-degree slope lying at the base of a prominent northwest- to southeast-trending escarpment.

Macquarie Ridge province

The Macquarie Ridge province is a narrow arcuate-shaped zone of complex seafloor morphology wedged in between the Hjort Trench province, extending along its entire western side, and the Hjort Ridge province along much of its eastern side. It is restricted to longitudes 157°30' E and 159°30' E and latitudes 55° S and 59°30' S and, like the adjoining provinces, is convex to the west. Its southern and northern ends bend gradually around to the east producing a curvilinear northwest to southeast trend and more linear north-northeast to south-southwest trend, respectively. Although its southern extremity is morphologically defined, its northern extremity is chosen simply as the limit to fill-in mapping performed by the AUSTREA-2 survey (Fig. 11), as the Macquarie Ridge proper extends to the 53°30' S passage, well to the north.

The province can be described as an axial valley, that is, a ridge bifurcated by a valley down its axis. Massell et al. (2000) mapped this form as characterising much of the entire ridge system of the MRC. The province gradually narrows southward and averages 15-20 km width throughout. Furthermore, it can be subdivided into three morphologically distinct zones: a clearly defined northern segment of a large, mostly linear, bifurcated ridge; a central segment of more sinuous shape flanked by less pronounced and less continuous ridges; and a southern segment continuing with an internal sinuous shape, but flanked by more continuous and elevated ridges. These flanking ridges represent the boundary with the Hjort Trench to the west and both the Hjort Ridge and abyssal seafloor to the east.

The northern zone of the province represents the gradually deepening southern extent of the Macquarie Ridge segment (Massell et al., 2000). Here, the elevated bifurcated ridge segment is clearly evident with a steep western slope descending to abyssal plain and the northern embayment of the Hjort Trench, while the eastern slope descends with moderate gradient to the trough separating it from the northern nose of the Hjort Ridge province. The western ridge segment is continuous in form and gradually descends southward from depths around 1000 m to about 3500 m at 56°20' S. However, the parallel eastern ridge descends similarly, but is narrower and less continuous in form. The intervening valley lies about 1000-1500 m below the flanking ridge segments, but conforms in depth to their continued southward deepening.

The central zone of the province extends between latitudes 56°30' S and 58° S. Although being the southward extension to the Macquarie Ridge proper, it is more subdued in relief, which appears to have resulted from a tectonic collapse of this ridge segment. The western flanking ridge maintains an average depth of 3500-4500 m with the shallowest area above 3000 m on the spur feature that constricts the Hjort Trench to the west at about 57°30' S (see above). The eastern flanking ridge is less continuous and completely non-existent at about 56°50' S, where a 4500 m depression indicates that the trough separating the Macquarie Ridge and the northern node of the Hjort Ridge coalesces with the province's axial valley. This axial valley lies mostly between 4000 m and 4500 m, and is a complex intertwining of two sub-sinuous trenches separated by a discontinuous ridge, which, in parts, is characterised by an en echelon series of highs. This morphology represents the classic stress-strain signature of a strike-slip fracture zone.

The southern zone of the province extends from about 58° S, where both western and eastern flanking ridges begin to develop higher relief and increased continuity, to the province's southern extremity at about 59°30' S. Both ridges are well defined, with the eastern being the higher, and appear to join at the southern end as a large linear seamount reaching a height of some 1500 m depth at two summits on opposing sides, and offset dextrally, of an elevated axial trough. The central axial valley continues to the south as an en echelon series of low relief ridge and trough segments. Its sinuous nature is less pronounced than in the central segment. Furthermore, the entire ridge sags slightly at about 158°25' E, 58°45' S where the axial valley deepens to over 4500 m, and then rises sharply to the south to form a more linear elevated trough, at about 2000 m depth, between the indicated shallowest parts of the bifurcated ridge.

At the southern extremity of the province there exists over 5000 m of relief between the eastern ridge summit (about 1500 m depth) and the deepest part of the flanking Hjort Trench floor (about 6700 m depth), where slopes are in the range of 20°-40° (Figs 11, 12 & 15).

Hjort Ridge seamounts province

The Hjort Ridge seamounts province covers the northwest- to southeast-trending group of seamounts lying to the east and southeast of the Hjort Ridge province (Fig. 11). This province is essentially limited to bounding longitudes 159°40' E and 162° E and bounding latitudes 57°45' S and 59° S. It is dominated by two groupings of three and two large seamounts to the northeast and southeast, respectively, which are aligned in a general northwest to southeast direction. The more northern grouping is encircled by three smaller seamounts. All the seamounts rise above surrounding seafloor that lies at abyssal depths of 4000-4500 m.

At the southeast extremity of the province lie two adjoining seamounts centred at 161°10' E, 58°35' S and 161°30' E, 58°40' S with summits averaging 1400 m and 400 m depth, respectively, and are separated by a saddle at 2300 m depth. They are aligned in a more east-west direction and have an abyssal seafloor base depth of 4000 m along the northern flank and 4500 m along the southern flank. Slopes average 5°-30° (Figs 11, 12 & 15), tending to be steeper along the combined northern flank and the western flank of the smaller western seamount. The eastern-most seamount is the largest and shallowest in the Hjort region and has a flat summit (guyot) consistently around 400 m depth indicating either subaerial exposure and consequent erosion, or wave-base erosion in the recent geological past. It is slightly elongated in an east-west direction and has a sharp spur protruding from its eastern side. The western-most deeper seamount is more circular in shape and is characterised by a more uniform slope gradient. Both have slopes dotted with fields of small volcanic cones.

The northern half of the province is dominated by a slightly arcuate lineament of three large seamounts. This lineament generally trends northwest to southeast and is convex to the northeast. The three seamounts are centred at approximately 160°03' E, 57°53' S, 160°28' E, 58° S and 160°44' E, 58°10' S with minimum depths at 1650 m, 800 m and 950 m, respectively, and have consistent slopes of 5°-30°. The seafloor about the seamounts lies at abyssal depths of 3500-4000 m. The westernmost seamount is elongate in an east-west sense and averages between 2000 m and 1500 m depth at its summit. Its slope gradients are mostly consistent, with several small spurs off its northeastern flank. The seamount to its east lies beyond a 3000-2500 m saddle with a summit elevation averaging 1500-1000 m depth and a more circular shape in planimetric view. Its slope gradients are less continuous, particularly along the southeast flank, where there is a greater development of minor volcanic cones and ridges. The third and easternmost seamount is generally oval in shape and has a slightly domed summit lying between 1500 m and 1000 m depth, which is crowned by a singular peak, and probably represents the final stage or continuation of volcanism. The encircling slope gradient is relatively uniform, being less so down to the joining saddle region with the central seamount, where minor cones and ridges are embedded.

Three smaller seamounts encircle the larger mounts, centred at 159°40' E, 57°47' S, 160°09' E, 58°22' S and 160°49' E, 57°49' S with peaks at approximate depths of 2750 m, 2200 m and 2700 m, respectively. The two largest, in the east and south, are oriented somewhat northeast to southwest, while that to the west is predominantly circular in shape. All encircling slopes average 5°-30° with some reaching 30°-40°, particularly on the southernmost highest mount.

As mentioned above, the deeper seafloor in the province lies at moderate abyssal depths of between 4000 m and 4500 m. The abyssal plain's form is strongly marked by the developments of several moats about the bases of the seamounts – the most impressive being that circumscribing the southern basal slope of the northern group of three seamounts. Furthermore, to the east of these seamounts lies an anomalous depression on the seafloor, which appears to represent the dextral offset of a northeast- to southwest-trending shallow trench. Seafloor spreading fabric is revealed by a single swath track immediately beyond the province's southern boundary.

Segmented transform province

The segmented transform province refers to the triangular zone enclosed by a single swath track to the south of the Hjort Trench province. In extent it stretches from longitudes 159°20' E to 162°20' E and latitudes 59°30' S to 61° S. Tectonically, it covers the northern zone of a section of oceanic crust to the east of the Macquarie Triple Junction formed by the segmenting of newly formed basaltic oceanic crust by a series of large-scale parallel fractures. This area of segmentation trends northwest to southeast. Morphologically, the province can be described by reference to the three swath tracks defining the respective sides of the triangle formed.

The western track follows the westernmost transform bounding the region of segmented oceanic crust. As such, it highlights a strongly linear trench trending north-northwest to south-southeast, which at its northern tip defines the southern end of the Hjort Trench and adjoining Macquarie Fault Zone (ie Macquarie Ridge province). The trench averages 500-1000 m depth below the surrounding seafloor with an abutting short ridge segment to the north providing some 1500 m of relief. The trench is asymmetric in both profile and planimetric view with the eastern flank forming a scarp and the western flank presenting a gentler slope descending down to the trench axis. The alternating series of small-scale linear highs and lows of seafloor spreading fabric is evident on both sides of the trench, but is more pronounced and asymptotic to the main trench axis on the western side. This indicates the stress field induced by strike-slip motion of a right-lateral sense.

The southern track trends east-northeast to west-southwest and traverses the entire segmented zone in the north, connecting the bounding westernmost and easternmost oceanic transforms. The seafloor lies mostly between 2500 m and 3000 m and is dominated by a strongly linear west-northwest- to east-southeast-trending trench of no more than 500 m relief, crossing the swath track at approximately 161^{o}40' E, 60^{o}40' S. This trench probably represents another of the series of oceanic transforms in the region as it is flanked on its western side by elevated crust with spreading fabric bending asymptotically towards it, and is aligned with a major trough evident in the predicted bathymetry data (Figs 1 & 9). Directly to the east of the trench lies a section of seafloor of complex form, comprising a series of east-west trending linear to slightly sinuous shallow ridges and troughs.

The eastern track trends northwest to southeast and follows the easternmost transform bounding the region of segmented oceanic crust, which ends to the northeast against the more linear westernmost bounding transform. The overall morphology is described as a strongly sinuous trench with a moderately steep eastern side partnered by a steeper western side. The trench floor is partitioned into two elongate, lobate-like depressions of 4000-4500 m depth. The structural form and inter-relationship of these two depressions strongly suggest that they are pull-apart styled basins being formed along a strike-slip fracture zone of right-lateral movement.

Physiographic depth analysis

The fundamental parameter acquired by the swath mapping technique is bathymetry, or the depth of the seafloor below sea level. Water-bottom currents, seafloor-dependant fauna and sedimentary characteristics are largely influenced by depth, so that spatially defining depth variability is a means to inferring their respective characteristics.

The spatial view of seafloor depth represents terrain and is presented in Figures 11 and 12 as colour-coded images, while Table 1 presents a statistical overview of the depth regime for the seafloor covered by the AUSTREA-2 swath data in the study area. The numbers tabulated are calculated off the representative grid with a cell size of 0.001°.

Minimum:	-386 m
Maximum:	-6658 m
Mean:	-3750 m
- standard deviation:	1025 m

Depth range (m)	% of total	Comments*
386 – 500	0.04	summit of large southeast seamount
500 – 1000	0.2	summits of large southeast seamounts
1000 – 1500	1.1	northern Hjort Ridge nose
1500 – 2000	2.9	southern end Macquarie Fault Zone
2000 – 2500	6.2	central Hjort Ridge summit
2500 – 3000	11.2	lower slopes encircling Hjort Ridge
3000 – 3500	16.7	southern Macquarie Fault Zone flanks
3500 – 4000	26.5	abyssal floor south and southeast of Hjort Ridge
4000 – 4500	16.5	upper slopes of Hjort Trench flanks
4500 – 5000	7.3	upper slopes of Hjort Trench flanks
5000 – 5500	3.7	mid-region of Hjort Trench flanks
5500 – 6000	4.6	most of northern Hjort Trench floor
6000 – 6658	3.0	most of southern Hjort Trench floor

* refers to first major appearances of morphology into respective depth ranges

Table 1. Statistical analysis of terrain depth over the Hjort region study area covered only by the AUSTREA-2 survey swath data (ie Fig. 12 extents).

Much can be gleaned from the listed figures, along with an examination of the spatial distribution of depths (Figs 11 & 12). For example, the calcite compensation depth defines the ocean depths below which dissolved carbonate is unable to accumulate within seafloor sediments (eg calcareous oozes). Ignoring bottom-current effects this generally lies at about 4500 m, which indicates that nearly 20% of the mapped seafloor is free of carbonate deposits. This occurs mostly on the Hjort Trench floor and is confirmed by the only seafloor sample taken from it (see Appendix 5 and Fig. 13).

Physiographic slope analysis

Slope is a primary attribute of terrain and is readily calculated from a regularised cell representation of bathymetry. It details the gradient across the terrain, or the maximum rate of change in depth, and can be used to highlight those areas of seafloor, for example, of high slope (ie greater than 30°) which are susceptible to instability and, so, provenances for slump deposits. This is of particular interest in the region as earthquakes are likely to provide the impetus for such mass wastage.

Figure 15 depicts a colour-coded image of slope across the study area, while Table 2 presents a statistical overview of the slope regime for the seafloor covered by the AUSTREA-2 swath data in the study area. The numbers tabulated are calculated off the representative slope grid with a cell size of 0.001°.

Minimum:	0.001°
Maximum:	58.74°
Mean:	5.86°
- standard deviation:	4.78°

Slope range (°)	**% of total**	**Comments***
0 – 1	7.0	abyssal depths about southeast seamounts
1 – 5	47.5	abyssal depths about southeast seamounts, northern Hjort Trench and southwest flank of Hjort Ridge
5 – 10	28.5	eastern flank of northern Hjort Trench and mid Hjort Trench region flanks
10 – 20	15.0	southern and northern Macquarie Fault Zone and upper flanks of southeast seamounts
20 – 30	1.5	upper slopes of bounding ridges to southern Macquarie Fault Zone
30 – 40	0.06	upper slopes of bounding ridges to southern Macquarie Fault Zone
40 – 60	0.002	uppermost slope of western bounding ridge to southern Macquarie Fault Zone

* refers to areas of seafloor where slope range is dominant

Table 2. Statistical analysis of terrain slope over the Hjort region study area covered only by the AUSTREA-2 survey swath data (ie Fig. 12 extents).

As expected the low slope regimes of 0°-5° are concentrated to the south of the Hjort Ridge and about the southeast seamounts. These are regions distant from the major tectonic events expected to be concentrated at or near the plate boundary along the Macquarie Fault Zone. In contrast, the higher slopes of 20°-60° are concentrated along this zone, and reflect the continuing active plate boundary forces that act to produce high-relief seafloor.

Physiographic aspect analysis

Aspect is a primary attribute of terrain and is readily calculated from a regularised cell representation of bathymetry. It details the direction of maximum rate of change in depth across the terrain, and can be used to highlight those areas of seafloor, for example, facing west and, so, more susceptible to the scouring action of the eastward flowing ACC.

Figure 16 depicts a colour-coded image of aspect across the study area, while Table 3 presents a statistical overview of the aspect of seafloor terrain covered by the AUSTREA-2 swath data in the study area. The numbers tabulated are calculated off the representative aspect grid with a cell size of 0.001°.

Minimum:	0°
Maximum:	360°
Mean:	171.1°
- standard deviation:	105.8°

Aspect range (°)	**% of total**	**Comments***
000 – 045	17.2	western flank of southern Hjort Trench and both transforms of segmented transform province
045 – 090	10.9	western flank of Hjort Trench and eastern half of Hjort Ridge
090 – 135	10.1	western flank of northern Hjort Ridge and eastern flanks of northern Macquarie Fault Zone
135 – 180	14.6	well distributed throughout
180 – 225	15.5	western half of Hjort Ridge and southeast side to large southeast seamounts
225 – 270	10.0	mid-region eastern flank of Hjort Trench
270 – 315	9.1	eastern flank of northern Hjort Trench and western flank of northern Hjort Ridge
315 – 360	12.6	well-distributed throughout, but largely absent from southern Hjort Trench and southern Macquarie Fault Zone

* refers to areas of seafloor where aspect range is dominant

Table 3. Statistical analysis of terrain aspect over the Hjort region study area covered only by the AUSTREA-2 survey swath data (ie Fig. 12 extents).

The data shows a general even distribution, based on a 45° azimuthal partitioning, of seafloor aspect across the region. The bias towards more northerly (ie 315°-045°) and more southerly (ie 135°-225°) aspects is probably representative of the superimposed east-northeast to west-southwest-trending seafloor spreading fabric largely situated on the Hjort Ridge, but also along the barren western flank of the northern Hjort Trench region. This is manifested on the figure by the rib-like alternations of colour. Furthermore, the bias is reinforced by the more extensive north and south flanks of the southeast seamounts, which are elongate in an east-west direction.

SEAFLOOR CHARACTER

Seafloor character, herein used, is taken to include the acoustic character of the sub-bottom. The acoustic property of the seafloor is a geophysical parameter, and, although not discriminating the seafloor for actual sedimentological composition, it is able to provide some evidence for the probability of sediment distribution and type.

In this section an interpretation of both the *L'Atalante's* multibeam backscatter and 3.5 kHz echosounder data is made for the Hjort region study area of the southern Macquarie Ridge region. The interpretation draws on both seafloor morphology and direct seafloor sampling where appropriate.

Data Inventory

Multibeam acoustic backscatter

Multibeam acoustic backscatter (also known as multibeam reflectivity or imagery) refers to the reflected signal strength recorded by each beam's receiving transducer during the along-track process of ensonifying the subsurface to determine depth. The processes affecting the signal's travel path and interaction with the seafloor are complex, and the reader is referred to Augustin et al. (1996) for a detailed discussion. Generally, a degradation of bottom-reflected signal strength results of which part is due to the nature of the sub-bottom with which the beam interacts. Lower levels of intensity are likely to indicate increased attenuation of the signal at the subsurface boundary and, therefore, the presence of sediment.

It is important to note that the acoustic backscatter data set used for interpretation in this report is uncompensated for many of the processes affecting the signal travel path. Although many sophisticated algorithms are available, and are currently being developed, for extracting that part of signal loss due solely to the subsurface interaction none were employed on the data presented. The acoustic backscatter presented (Figs 13 & 14) is a contrast enhanced grey-level stretch of values from 0 to 255 applied to the spread of recorded pixel intensity values. Therefore, the interpretation of sediment distribution can only be considered as preliminary and simplified in its scope.

Echosounder sub-bottom profiling

The *L'Atalante* employs a 3.5 kHz echosounder as a sub-bottom profiler. The transmitted signal is able to penetrate the near-surface layers of the seafloor and provide a profile of sonar reflection signature for the topmost subsurface, which details the form of the sediment facies. This form, in turn, can provide evidence of sediment type, sedimentation processes, mass wasting and current effects and can be used, given adequate track spacing, to characterise the deep seafloor form over large areas (Damuth, 1980). Penetration is dependent on signal strength and sediment characteristics, and has reached up to 200 m depth in seafloor about the southeast seamounts.

The interpretation of the 3.5 kHz echo presented is largely based on the classification structure worked out by Whitmore and Belton (1997; see their Figure 4). They used a good spread of gravity cores to establish a general correlation of echo character with direct knowledge of seafloor sediment type. The Hjort region study area has a paucity of such samples and, as such, no independent classification was attempted, although it is expected that sediment types do not vary markedly with those of the South Tasman Rise region.

Seafloor sampling

The remoteness of the southern Macquarie Ridge region means that the study area is poorly covered by seafloor sampling (Fig. 13). Appendix 5 lists the database for the wider region and indicates the presence of only two samples within the mapped confines of the new swath data. Nevertheless, the wide distribution of samples provides a probabilistic framework for the sediments likely to be encountered.

Mapping Results

Using the data acquired several characteristics of the seafloor have been mapped in a first-pass analysis. These include the distributions of acoustic sediment facies, volcanic edifices, slumps, contourites and turbidites.

Acoustic facies distribution

Figure 17 presents a map of acoustic facies over the Hjort region study area of the southern Macquarie Ridge. Its construction was based on the following methodology:

- all along-track 3.5 kHz analog records were examined and classified according to the echo type (ie acoustic facies) of Whitmore and Belton (1997), of which examples are shown in Figures 18a and 18b;

- this interpretation was posted on a map of AUSTREA-2 survey multibeam backscatter (Fig. 19) similar to that presented in Figure 13;

- with the understanding that light-shaded areas of intensity generally represent sediment cover the along-track spread of echo type was extended spatially by discrimination of intensity levels on the backscatter image; and

- the mapped extents of echo type were then digitised.

It is to be noted that several of the mapped zones represent the dominant echo type resolved on the 3.5 kHz records and, therefore, can only be taken as a generalisation of the facies type encountered. Furthermore, various light-coloured areas not crossed by 3.5 kHz records were delineated and highlighted as potential sedimented areas, and are marked as ‘unknown’ acoustic facies type. Therefore, Figure 17 basically depicts the probable extent of seafloor sediments across the area, although a thin veneer of pelagic sediment is expected to cover most of the seafloor, but in thicknesses beyond the resolving power of the 3.5 kHz and multibeam signals.

The correlation between echo type and sedimentology used by Whitmore and Belton (1997) is based on a ground-truthing study of acoustic facies using 74 core and dredge samples in the South Tasman Rise region off southern Tasmania. The following analyses are based on their study.

Acoustic facies type IA is seen as a sharp, continuous single echo lacking sub-bottom reflectors (Fig. 18a). It may be diagnostic of terrain covered by pelagic deposition with little current reworking or hardgrounds such as manganese nodule fields. It has been mapped on the summits of the two guyots in the Hjort Ridge seamounts province (Fig. 11), where they represent hard volcanic rock.

Acoustic facies type IB represents a sharp continuous bottom echo with multiple continuous, parallel sub-bottom reflectors (Fig. 18a). It is found on typically flat to undulating seafloor terrain, and is likely to represent undisturbed pelagic clays, silts and oozes with possible mud turbidites. This facies is the most common in the region. It is dominant in the Hjort Trench region where the trench's sunken relief is likely to afford some protection from current reworking by the strong easterly-flowing ACC.
Acoustic facies type IIA comprises a series of sharp discontinuous, parallel sub-bottom reflectors (Fig. 18a). These are interpreted as current-reworked pelagic sedimentation or distal turbidite deposits. Further work needs to be done to identify those areas likely to be prone to turbiditic input, which is expected to rely on a morphological analysis.

Acoustic facies type IIB is seen as a somewhat 'fuzzy' zone devoid of sub-bottom reflections (Fig. 18b). It is often associated with sand or silt turbidites or current reworked pelagics and current winnowed sands.

Both acoustic facies types IIA and IIB are distributed across the region (Fig. 17), being well spread on the summit of the Hjort Ridge and on the abyssal plain about the seamounts in the Hjort Ridge seamounts province (Fig. 11). These areas are expected to be exposed to the direct effects of current action by the ACC flow, and spawned eddies, over and through the Macquarie Fault Zone elevated axial valley.

Acoustic facies type IIBa is characterised by an irregular sharp echo overlying a IIB-type echo, which is separated by an acoustically transparent zone (Fig. 18b). This is interpreted as a debris, slump or mass flow deposit. It has been unequivocally mapped for the region to the northeast of a large seamount in the Hjort Ridge seamounts province and, therefore, may likely represent mass wasting of this seamount's northeastern flank. Close examination of the morphological character of this flank reveals a slight concavity, which also suggests that the current form of the slope was formed by a slide.

The mapped acoustic facies type III is an amalgamation of echo types IIIA, IIIC and, to a lesser extent, IIID of Whitmore and Belton (1997) (Fig. 18b). No discrimination was attempted because of the time involved and the subjective nature of the classification given the geometric configuration of ship track direction with the echosounder wave path and the general roughness of the underlying topography in areas. Nevertheless, this facies indicates areas of rough topography due to scarps, slope canyons, seamounts, abyssal ridging of seafloor spreading fabric, volcanic edifices and the probable effects of heavy current scouring. It is to be noted that the large spatial extent of the diffracted 3.5 kHz echos will often render unresolvable small pockets of sediment perched on a steep slope, such as turbidite flows.

The mapped "unknown" acoustic facies type extends across the area and defines those zones on the backscatter image that are a lighter shade of grey (Figs 17 & 19). That is, they are of similar intensity to those zones indicated by the 3.5 kHz signal to correlate with sediment-styled acoustic facies. Without a traversing 3.5 kHz signal it is not possible to assign an acoustic facies type.

Again, the uncompensated nature of the multibeam backscatter data for slope variability used in the interpretation given is drawn to the reader's attention. The extrapolation of acoustic facies beyond the echosounder data along track is based on visual discernment of lighter intensity levels, which are taken to indicate higher levels of signal attenuation due to the presence of seafloor sediments. Generally, there was excellent correlation between sediment-type 3.5 kHz signatures and the presence of these lighter intensity levels in the underlying backscatter data, thereby lending some support to the association of these areas with the presence of seafloor sediments. However, an undetermined proportion of grey-level in these areas will be due to the effects of terrain slope and not solely to the composition of the water-bottom interface.

Once compensated for anomalous intensity levels due to slope variability various algorithms may be employed to attempt a more rigorous form of seabed sediment type classification. These would require the establishment of training zones within the backscatter data centred about seafloor samples (Müller et al., 1997), which could then be used in an automatic traversal over the entire dataset to construct a seabed classification database. Before this could be performed more sample sites would be needed within the area of seafloor covered by the backscatter signal than currently exists (Fig. 13).

Seamounts and volcanic pinnacles distribution

Figure 20 highlights the distribution of seamounts and probable volcanic edifices across the study area. The seamounts were readily identified as large conical to semi-conical features rising up from the surrounding seafloor. The smaller pinnacle-like features were identified by close examination of the seafloor bathymetry and associated backscatter. That is, small circular to semi-circular protrusions with associated high backscatter levels (ie darker shades of grey) were discriminated.

The large seamounts cluster in the region to the east and southeast of the Hjort Ridge. They are characterised predominantly by high backscatter levels with some pockets of lighter shades that have been interpreted as small perched basins of sediment. Their flanks are often characterised by numerous conic-like features and several spur-like protrusions, which likely represent subsidiary cones and vents, respectively, to the main volcanic phase of their development. It is unknown whether any remain volcanically active. The two largest seamounts have planated tops characterised by acoustic facies type IA. Given their exposed nature to the easterly flowing ACC these summits are likely to be devoid of significant sediment accumulations. Their genesis is either related to the formation of a hotspot trail, which sources volcanic material from the deep mantle or as the generated melt of subducted Indo-Australian crust under Pacific crust along the Hjort Trench, which is discussed below.

The smaller interpreted volcanic edifices are concentrated over the Hjort Ridge, where they superimpose the relict seafloor spreading fabric, and on the seafloor about the large seamounts in the east. In the latter case they are expected to represent subsidiary venting to the main volcanic feeders to the seamounts, whereas in the former case their genesis is more problematic. As with the larger seamounts they may have formed via the melt of subducted Indo-Australian crust along the Hjort Trench, of which there is some evidence (see below).

The cause of volcanism in the region can only be considered speculative without direct evidence of rock type. As stated previously the area is sparsely sampled with no evidence of volcanic material (Fig. 13 and Appendix 5).

Contourite distribution

The distribution of contourites or, strictly speaking, sediment waves is found in Figure 20. Contourites are large-scale sediment ridges formed on the seafloor as a result of the shaping action of deep-water bottom currents, which are also termed contour currents. Their wavelengths range from several hundred metres to tens of kilometres, with amplitudes as low as a few tens of metres and lengths hundreds of kilometres long. Many different geometries are possible (Faugères et al., 1999) and they may be a misinterpretation of deposits resulting from down-slope turbidity currents (eg turbidite fans). Their interpretation rested on a two-fold approach: the identification of laminar-like deposition, often eroded at the seafloor, from the reflection patterns on the 3.5 kHz records and a correlation with a spatially extensive mound-like feature on the seafloor (Fig. 21). It is most probable that many more such features are prevalent in areas distant from the echosounder data along track, and would require a more detailed examination of the seafloor morphology.

Except for a strong north-south lineament in the northern Hjort Trench the majority of interpreted sediment drifts align in a predominant east-west sense. This is expected to correlate with the prevailing direction of the ACC and any deviations are more likely due to subsidiary eddy action as a result of the deflecting forces provided by large-scale bottom topography. The contourite-like deposit in the northern Hjort Trench may result, however, from a north-to-south component flow to the ACC due to a southwards deflection provided by the blocking action of the shallow Macquarie Ridge, just to the deposit's east and north. This bottom flow may extend some way southwards into the trench as the submerged topography acts to protect it from the more dominant easterly-flowing ACC.

Turbidite distribution

Turbidite deposits are the result of sediment deposition from turbidity currents. These currents are generally localised in extent and driven by down-slope gravity forces, and are mostly found on continental slopes where they act to supply the abyssal regions with terrigenous sediment. They are predominantly caused by the input from sediment-charged rivers, slide-producing earthquakes or by the over-steepening of a depositional slope through sediment buildup. As the study area is not a continental slope setting, but a seismically active plate boundary the only trigger for turbidity currents is expected to be the destabilisation of slope material via earthquake activity. However, the effect of slope destabilisation by continual strong current action should also be considered.

Figure 22 depicts the pseudo-drainage network for the seafloor terrain in the study area. It was calculated in Arc/INFO™ using a series of tools to determine an inferred stream network across terrain where there exists a down-slope focusing of at least 100 grid cells (ie where the cell size used was approximately 100 m). Although used widely to model down-slope water run-off and stream delineation for land topography, this technique also has application for subsea topography, where the network is expected to define down-slope channelling and, therefore, possible paths for turbidity current flow. The interpretation suggests that those areas of sediment cover in the vicinity of base of slopes with a major convergence of channels are possible concentrations of turbidite deposits. This is particularly likely where the 3.5 kHz records indicate the presence of acoustic facies type IIA and IIB (Fig. 17). In terms of sedimentological composition, these are a probable melange of down-slope transported pelagics and loosened volcanic rock.

Slumps distribution

Slumps, or debris flows, refer to the chaotic, rapid downslope movement of material, and can occur in areas of low gradient. Figures 17 and 19 depict those facies (ie acoustic facies type IIBa) that have been interpreted as probable slump deposits, although all the areas identified as possible turbidite deposits are also potential accumulations of slump facies. Figure 19 depicts only three along-track locations with the appropriate 3.5 kHz signature.

The interpreted slump at about 158°36’ E, 58°36’ S is not associated with encircling terrain of great relief, but is associated with the convergence of several modelled channels. Therefore, this deposit probably results from the accumulation of turbidite deposits rather than slumping.

The large region of interpreted slump-type facies in the east of the study area lies at the foot of a large seamount centred at about 160°45’ E, 58°10’ S. Close examination of the seamount’s morphology indicates a more subdued topography along its eastern to northeastern flank. The slope has a more gradual fall-line than the more expansive southern slope and is largely devoid of the many small cone-like features that dominate the northern and western flanks. Furthermore, the generated contours are slightly concave in shape along this east-facing slope. This analysis strongly suggests that the large region of acoustic debris-flow type facies (ie type IIBa) resulted from the catastrophic release of volcanic material and sediment down the seamount’s eastern flank. The ensuing mixture of debris and water appears to have had enough turbulent impetus to extend out to at least 20 km, that is, to the mapped limit of the seafloor backscatter signal. In addition, the dark northeast-trending backscatter zone correlates well with a slight bathymetric depression on the abyssal floor centred at approximately 161°15’ E, 58° S, thereby providing a large repository for the down-slope debris flow.

The cause behind the large debris flow is possibly due either to a large-scale regional earthquake or to volcanic activity. A large earthquake along the distant plate boundary to the west is unlikely to have produced the slide as similar debris evidence would be expected at the base of other seafloor features of high relief. Therefore, this may suggest more localised seismic activity. In contrast, the small volcanic cone existing at the seamount's planated summit provides strong evidence for volcanic activity being the cause of the slide. It may indicate the reactivation of volcanism after a quiescent stage during which the seamount was being eroded at the sea surface. This activity may have been accompanied by violent eruptions, which, in turn, may have acted to destabilise the volcanic material along a steep eastern flank.

Sedimentary Environment Analysis

The correlative distribution of acoustic facies types IB, IIA and IIB with low backscatter intensity levels (Fig. 19) indicates the presence of substantial thicknesses of seafloor sediment. The analysis shows that sediment cover across the study area is concentrated in four areas:

- the entire floor of the Hjort Trench along with its western flank south of latitude 57°30' S;
- the east-southeast to west-southwest linear zones on the summit of and along the southwestern flank of the Hjort Ridge;
- several areas of the seafloor about the large seamounts to the east and southeast of the Hjort Ridge; and
- as more elongate deposits in the deeper parts of seafloor lying at the base of and along the slopes of the transform trenches in the segmented transform province in the south.

The overall distribution can be further characterised in terms of its relationship to actual seafloor samples and both physiographic slope and aspect.

Sedimentation characteristics

The seafloor sample database (Appendix 5) shows that the wider survey region is covered by 35 samples, two of which are within the bounds of the recently ensonified seafloor, as well as Deep Sea Drilling Project site 278. The predominant sediments are the abyssal deposits of biogenic calcareous oozes and siliceous oozes and non-biogenic muds/clays. Calcareous oozes form in moderate depth ranges of approximately 2000-4000 m, and consist chiefly of the calcareous skeletons of small ocean animals known as foraminifera. Siliceous oozes generally occur in the deeper regions between 3900 m and 5000 m depth, where silica becomes less soluble in seawater and precipitates out. The main constituents are radiolaria and diatoms, which are unicellular animals and plants, respectively, living in the water column. Several core samples obtained within these sediments in the Emerald Basin (Geomar, 1999) show intensive burrowing, which indicates the presence of a benthos community at considerable depth. The non-biogenic muds, although present everywhere, tend to dominate the seafloor deposits in the greatest depths beyond about 5000 m. These consist largely of ultra-fine particles such as wind-blown volcanic ash and meteoritic material. Furthermore, those samples with terrigenous components are likely to represent the most distal reaches of fine particle transport south from New Zealand over the Solander Trough lying between the Macquarie Ridge and Campbell Plateau, where a large fan complex has been mapped (Schuur et al., 1998).

Sediment-slope characteristics

The mapped sediment distribution lies predominantly on seafloor with a low slope regime of 0^o-5^o (Fig. 15), while that in the southern Hjort Trench floor and along the northern Hjort Trench eastern flank lies within the range 5^o-10^o. Steeper sedimented slopes of 10^o-20^o are found along the southern Hjort Trench western flank with very little sediment cover interpreted for slopes greater then 20^o.

Excepting for the western flank of the southern Hjort Trench the absence of sediment on moderate to steep slopes (ie greater than 20^o) suggests an environment of instability unfavourable for the quiet accumulation of precipitated biogenic and transported terrigenous material. This is probably due to two factors: slope destabilisation and current activity. The steeper slopes are more prone to wastage caused predominantly by earthquakes, resulting in the continuous removal downslope of both rock base and overlying accumulated sediment. However, current activity acts by continually sweeping more exposed higher relief terrain, thereby providing an environment unsuitable for the gradual accumulation of sediment. The effects of vortices being shed off more rough topography are also likely to produce localised scouring action.

Sediment cover down the moderately steep (ie 10^o-20^o) western flank of the southern Hjort Trench may result from the deposition of sediment in an environment largely unaffected by deep current activity (see discussion below). However, movement along the immediate plate boundary is expected to have provided favourable conditions for instability. This inconsistency suggests that steepening of this flank, via plate tectonic forces, may have occurred after a period of deposition and sediment consolidation on more subdued seafloor. Therefore, the greater degree of sedimentary diagenesis has been more resistant to the dislodging forces of earthquakes.

Sediment-aspect characteristics

A northerly aspect (ie azimuths 315^o-045^o) to seafloor sediment accumulations is largely localised in the southern Hjort Trench region and in an embayment centred at 160^o24’ E, 57^o48’ S (Fig. 16). The latter abuts the foot of the northward sloping side of a large seamount, whereas the former is distributed over many small areas, although a slight northeast to southwest alignment may be a response to differential sediment compaction over the spreading ridge fabric of oceanic crust.

A southerly aspect (ie azimuths 135^o-225^o) to seafloor sediment accumulations is largely concentrated in the northern Hjort Trench, about the east and southeast seamounts and on the Hjort Ridge summit. The northern Hjort Trench southerly aspect may be due to the effects of a southward flowing deflected component to the ACC, which is also accompanied by a general southward deepening of the trench. However, the distribution found about the seamounts is a combination of sediment deposited at the foot of the southward sloping sides of several seamounts and the gentle southern slope of a major east-west trending contourite mapped north of the seamount zone (see discussion above). Finally, the Hjort Ridge summit's zones of southerly aspect have a slight northeast to southwest trend and, as such, probably reflect differential compaction effects over spreading ridge fabric on the Hjort Ridge summit.

An easterly aspect (ie azimuths 045^{o}-135^{o}) to seafloor sediment accumulations dominates the southern Hjort Trench region, particularly the western flank. It is also found along the eastern edge of the northern Hjort Trench, where it represents the east-facing side of a prominent north-south ridge formed on the trench floor.

A westerly aspect (ie azimuths 225^{o}-315^{o}) to seafloor sediment accumulations dominates along the eastern flank of the northern Hjort Trench, and is distributed across several zones within the northern Hjort Trench, along the western flank of the Hjort Ridge and in small zones about the seamounts east of the Hjort Ridge. In the northern Hjort Trench this aspect dominates the western slope of the sedimented trench floor where a shallow moat has formed along the boundary with the more rugged exposed oceanic crust defining the western flank.

Ocean Current Effects

Figure 20 depicts those areas both along the survey track, where there is pronounced scouring of sedimentary facies along the bottom, and those areas where moat-like depressions have developed, particularly about volcanic edifices. These features all indicate the impact that current activity has on the seafloor.

General large-scale current activity

The water mass overlying the southern Macquarie Ridge region has a dominant west-to-east motion and is termed the Antarctic Circumpolar Current (ACC), which is under the influence of the prevailing west wind. This is the earth's largest, most continuous oceanic current, completely encircling the Antarctic continent, with a velocity usually less than 0.5 knots, and extends to the bottom with little attenuation (Gordon, 1971). On its eastward course its axis undergoes several large north-south deflections related to bottom topography. The major impact of the Macquarie Ridge, therefore, is to generally deflect the ACC southwards, where the more subdued topography of the Hjort Ridge gives it passage on its eastward course, and where it immediately joins up with and reinforces the Deep Western Boundary Current as it encircles the Campbell Plateau.

Of less impact in the region than the ACC is the northward flow of deep, cold Antarctic waters, sourced from beneath the Ross Ice Shelf, termed Antarctic Bottom Water. Its pathway lies along the west flank of the MRC at approximately 155^{o} E and at water depths greater than 4000 m (Schuur et al., 1998).

Reid (1986), Nowlin and Klinck (1986) and Orsi et al. (1995) provide a general analysis into the ACC's spatial extent and flow properties. Several earlier studies into the particular interaction between the ACC and the Macquarie Ridge are found in Gordon (1972) and Boyer and Guala (1972). The latter work provides experimental modelling to show the strong effects of eddies derived from flow over the ridge's crest and through ridge gaps such as the 53°30' S and 56° S passages (Fig. 9). Carter et al. (1996) examine the supply and distribution of sediment into the Emerald Basin and around the Campbell Plateau resulting from flow of the Deep Western Boundary Current and reinforcement by the ACC from the Macquarie Ridge. Schuur et al. (1998) discuss the distribution of sediments and the interaction of morphology with water motion for the recent swath mapping data over the central regions of the MRC. Although detailed knowledge of both current motion vectors and velocities are lacking for the southern Macquarie Ridge region some evidence is provided by Carter and McCave (1994) for the Campbell Plateau further to the east.

Local small-scale current activity

Local current activity on the seafloor within the study area is expected to be due largely to the main eastwards front of the ACC and the effects of local eddies being shed off topography. The effects are largely evident as scouring of seafloor sediments and the presence of moats about high-relief structures. Several interesting observations can be made which may reveal certain characteristics of bottom-current activity. More detailed study of the sediment features on the seafloor coupled with some dynamic modelling of fluid flow around the region's gross topography could provide a detailed framework of the ACC, subsidiary eddies and interactions with the Antarctic Bottom Water.

As indicated above, except for the long north-south lineament in the northern Hjort Trench the majority of the mapped contourite, or sediment drift, lineaments are generally directed east-west (Fig. 20). Contourites are aligned parallel to the currents that shaped them. This suggests a predominant eastwards movement of deep bottom-water over the region and, in turn, that the more subdued relief of the Hjort Ridge may not provide as strong a barrier to the ACC as the Macquarie Ridge to the north. However, the contourites mapped within the eastern-most arm of the segmented transform province are aligned more to the southeast, that is, in the direction of the transform in which they are deposited. This suggests that long, narrow and deep seafloor valleys may act to funnel bottom-current flow along their strike provided the azimuth is in a general easterly direction.

The western flank of the Hjort Trench is largely devoid of sediment cover north of 57°30' S, while well-covered to the south (see backscatter character and 3.5 kHz acoustic facies signature in Figure 19). Morphologically, the northern sector is characterised by strong east-northeast ridging representative of seafloor spreading fabric defining barren oceanic crust, whereas this crust is covered by expansive sediment lobes in the south. The marked contrast is most likely due to the continuous scouring action of bottom currents acting in the north, which although present in the south, as evidenced by the presence of moat lineaments and contourites at about 58° S, are probably stronger in the north. This may suggest a stronger component of flow to the ACC lying north of 57°30' S in the region to the west of the MRC, which coincides with the transition from the elevated Macquarie Ridge segment in the north to the more subdued relief of the broader Hjort Ridge. Therefore, as the accelerated ACC streams over the Hjort Ridge little opportunity is provided for precipitated pelagic and transported fine terrigenous sediment to accumulate on abyssal seafloor to its west, but rather to be swept into the deeper and more protected environment within the Hjort Trench. Furthermore, the conjunction of the eastwards flow of the ACC and the easterly strike of the seafloor ridging may act to reinforce the sweeping motion of the sub-bottom currents by focusing the flow down intervening valleys. This is suggested by the apparent gouging evident on the western flank of the interpreted contourite in the northern Hjort Trench (Fig. 23). Here, the prominent ridging descending into the trench floor probably funnels bottom flow jets into the mound's western flank, which becomes heavily scoured.

Interpreted moat lineations (Fig. 20) highlight the localised effects of current activity. They result from the deflection and focusing of currents about the base of current-resistant features, which have higher relief than the surrounding seafloor. These features are typically seamounts, knolls, ridges and escarpments. This action scours the sediments on the encircling seafloor leaving a linear depression. The prevalence of moats along the northern and southern bases of seamounts and other irregular features indicates the actions of a dominant west-to-east directed flow. Furthermore, the existence of sediment lobes at their eastern bases indicates that this side lies in the lee of the feature, thereby confirming the eastward flow of the ACC in the region.

The seafloor atop the Hjort Ridge is dominated by a series of narrow east-northeast to west-southwest ridges and valleys superimposed by several small sub-circular volcanic edifices. This rough topography is expected to extract and focus components of ACC flow in a more northeasterly direction and provide localised eddy currents about the volcanic features. In addition, there is a paucity of expansive sediment cover over the northern Hjort Ridge (Fig. 19), between the elevated northern protrusion paralleling the southern Macquarie Ridge segment and a prominent east-west directed trench at about 57^{o}10' S. This coincides latitudinally with the barren expanse of seafloor to the west of the northern Hjort Trench and, therefore, supports the notion that a major axis of the ACC sweeps across the region centred along the 57^{o} S parallel. A northeasterly trend to the contourites mapped on the deeper seafloor to the east may also support the conclusion that the ridging atop the Hjort Ridge redirects seafloor components of the ACC more to the northeast into the Emerald Basin.

TRANSIT OVERVIEW

As stated previously, apart from the southern Macquarie Ridge region, the AUSTREA-2 survey swath-mapped a large portion of seafloor to the southeast and south of Tasmania, as well as a single swath track on the transit to the study area, and from the study area to the survey's end in New Zealand. Figure 1, again, can be used to outline the overall mapping effort. The Tasmanian section is presented in Hill et al. (2000), while the discussion below will briefly present the seafloor morphology and character along the transits.

South Tasman Rise to southern Macquarie Ridge

The transit from the southern tip of the South Tasman Rise to the study area runs mostly south-southeast between latitudes 50^{o} S and 56^{o}12' S (Fig. 25). The salient features are:

- From 50^{o} S to 52^{o} S average depth is 4200 m with morphology characterised mostly by a west-southwest to east-northeast minor ridging fabric associated with seafloor spreading. The echosounder record indicates the presence of some sediment at about 50^{o}30' S.

- Centred at 52^{o}20' S is a very large seamount rising from abyssal depths of 4200 m to a planated summit at about 800 m depth. This planation indicates that the seamount may have been at, or close to, sea level in the past.

- From the seamount to about 55^{o} S the mean depth again lies at about 4200 m, but the spreading fabric is more subdued in relief till approximately 54^{o}42' S. At about 54^{o}20' S a pocket of low intensity backscatter correlates with a 3.5 kHz acoustic facies type IIB (see above for description), which indicates the accumulation of current-winnowed sands and/or pelagics.

- From 55^{o} S to the northwestern corner of the study area both bathymetry and backscatter show well-pronounced spreading fabric lying at a slightly more elevated depth of 4000 m. Low backscatter intensity at about 56^{o} S may indicate some thin sediment cover.

Along central Macquarie Ridge

The transit from the northern part of the study area to the EEZ boundary in the north runs mostly north-northeast along the eastern flank of the Macquarie Ridge between latitudes 55^{o}40' S and 51^{o}50' S (Fig. 26). The salient features are:

- From approximately 55^{o}40' S to 55^{o}20' S the single swath track traverses, in a southwest to northeast trend, the deep bifurcated ridge of the southern Macquarie Ridge segment. Depths vary from 500 m along the ridge crests down to 3200 m in the central axial valley. The morphology and echosounder records indicate steep rough topography throughout, with the backscatter suggesting a small pocket of sediment at the western base of the western ridge lineament.

- From 55^{o}20' S to the northern border of Australia's EEZ at about 51^{o}50' S the transit swath passes over the eastern flank of the Macquarie Ridge in the Macquarie and McDougall segments. Depths traversed vary from several hundred meters, near the ridge's axis, down to about 5800 m on the abyssal floor along its eastern base. A deeper north-northeast-trending zone is located at about 53^{o}30' S, which represents a ridge gap and offset between the Macquarie and McDougall segments. Backscatter levels and echosounder signals typically imply rough steep slopes with lighter shades along the transit's eastern edge suggesting abyssal sediments.

Along Campbell Plateau margin

The transit to and along the Campbell Plateau commences at about 49^o S, just to the east of the Puysegur segment of the Macquarie Ridge, and continues generally northward until about 46^{o}50' S (Fig. 27). The salient features are:

- From 49^o S to 48^{o}10' S the transit swath crosses the Solander Trough to the foot of the Campbell Plateau slope, averaging 3000 m depth. Low backscatter intensity indicates widespread sediment cover, while minor sinuous north-south escarpment-like formations indicate channel formation in the large Solander fan complex (Schuur et al., 1998).

- From 48^{o}10' S to 47^{o}20' S the swath tracks the eastern slope region of the Campbell Plateau, with depths ranging between 2500 m along the western base and 500 m along the eastern upper edge. There are large-scale canyons evident so that the variability in the backscatter signal is probably due to the complexity in slope geometry.

- From 47^{o}20' S to about 46^{o}50' S the track traverses the shallowing top of the Campbell Plateau, from about 1250 m to several hundred metres.

PRELIMINARY TECTONIC ANALYSIS

The new bathymetric and geophysical data acquired over the Hjort region of the southern MRC provides a means to study the mechanics of active plate boundary motion and its effects on the seafloor. Such a detailed study draws primarily on the integrated interpretation of seismic, bathymetry, gravity and magnetic data sets. It does not form part of this report, however, a brief preliminary analysis is provided.

Basin Distribution

The Hjort Trench depression is the only feature in the mapped area that contains substantial amounts of sedimentary strata, particularly to the north of the constriction at about latitude 57^{o}30' S. The thickest section traversed by seismic contains some 2 km of sedimentary strata, at about 157^{o}30' E, 56^{o}40' S, and probably represents the main depositional axis trending parallel to the plate boundary.

Although moderately faulted and folded, a preliminary analysis of the seismic indicates the absence of defining sequence stratigraphic boundaries. This suggests a continuous mostly uninterrupted depositional regime since the trench depression formed and sediments began to accumulate. Minor variations in seismic facies thickness are probably due to differential compaction effects and structuring. Furthermore, variations in seismic reflector amplitude record probable cyclic changes in sediment composition. Schuur et al. (1998) examined seismic across the northern part of the trench and reported the absence of past current-related erosional and depositional features (eg mounds and scours).

The Hjort Trench sedimentary basin appears to be the simple sedimentary infill of a deep depression formed by the gross strike-slip motion along a transform margin. It may also represent the infill of a forearc-associated trench in a current or former subduction complex (ie of the Indo-Australian Plate beneath the Pacific Plate). Further analysis may reveal the presence of accretionary features within the sediment fill, thereby providing some supporting evidence.

Structural Framework

Gross seafloor morphology is a manifestation of local and regional tectonism. The gross tectonic elements in the study area correlate well with the physiographic provinces presented previously, as the seafloor morphology has largely been shaped by mechanical forces acting along the plate boundary.

The entire Hjort Trench region represents the sedimentary infill of a large oceanic depression that has formed along a plate boundary. It is floored by oceanic crust of the Indo-Australian Plate formed along the spreading ridge trending northeast to southwest, located at about 62^{o} S (Figs 1 & 9), which in its progress northward may partly subduct beneath the Pacific Plate along the trench. Although there is, as yet, no clear evidence of this subduction, evidence of strike-slip styled faulting in the northern Hjort Trench sedimentary pile, as well as the bathymetric expression of a major central ridge in the southern Hjort Trench, indicates that there is a large component of strike-slip motion between the respective plates. However, it is not clear how these respective plate motions have been partitioned between the Hjort Trench and the Macquarie Fault Zone just to its east, which is believed to form the distinct transform boundary between the rocks of the two respective plates (Massell et al., 2000).

The Macquarie Ridge province (Fig. 11) is a narrow elongate zone "sandwiched" between the Hjort Trench to its west and both the Hjort Ridge and deeper abyssal seafloor to its east (Figs 11 & 12). It is the southward extension of the shallow bifurcated ridge of the Macquarie segment of the MRC, although more subdued and variable in profile (Fig. 12), and represents the continuation of the Macquarie Fault Zone (Massell et al., 2000). The en echelon expression of abutting seafloor mounds and depressions indicates that, in comparison to its more linear form to the north, it is a complex anastomosing system of faults, which define the characteristic elongate development of restraining and releasing bends along a major strike-slip boundary. More detailed analyses of the seafloor morphology may also directly confirm the right-lateral motion solutions to recent earthquake activity (Frohlich et al., 1997). It is unclear, however, how this motion has produced two prominent bounding ridges, particularly south of 58^{o} S, and how the motion is transmitted to the segmented transform province to the south. Furthermore, confirmation of subduction along the Hjort Trench will highlight this region as one of the foremost examples in the world of strain-partitioning along a plate boundary, similar, for example, to the plate boundary character developed along the Sumatra Fault and adjoining Java Trench in Indonesia.

The Hjort Ridge is a broad elevated section of Pacific oceanic crust to the east of the southern extension of the Macquarie Ridge. The prevalence of east-northeast ridging fabric, similar to that evident on other swathed parts of the seafloor, clearly confirms its oceanic origin. The uplifted nature of the crust may be due to localised crustal shortening of the Pacific Plate as a result of regional anticlockwise rotation of the plate relative to the Indo-Australian Plate. This compresses and forces up Pacific crust in the confined space along the concave front of the Hjort region plate boundary. In addition, the presence of small-sized seamounts and minor volcanic pinnacles may be the volcanic forearc expression of subducted Indo-Australian crustal melt. Direct sampling of these features may provide further evidence.

The reason for the distribution of large seamounts to the east and southeast of the Hjort Ridge is unknown. The five major seamounts are somewhat aligned in a northwest to southeast direction, which is parallel to the directional strike of seafloor spreading fabric. However, examination of the regional seafloor (Figs 1 & 9), as provided by the predicted bathymetry data set (Smith & Sandwell, 1997), does not indicate that it forms part of an extensive seamount lineament, which would suggest genesis resulting from the trail of a mantle hot spot. This cause could be confirmed, though, by direct sampling of all seamounts, whereby chronological alignment would add weight to the argument. In contrast, the seamounts may represent the formation of a volcanic arc complex as part of an intra-oceanic arc-trench system, coupled with subduction of Indo-Australian crust into the Hjort Trench.

The segmented ridge transform system lies in the south of the study area and although only partly swathed is best viewed in its entirety in the predicted bathymetry data set (Fig. 1). It is an expansive section of oceanic crust made up of multiple northwest- to southeast-trending transform faults, which offset the accretion of new oceanic crust along the spreading centre plate boundary between the Antarctic and both the Pacific and Indo-Australian Plates to its north. The clear asymptotic bending of Indo-Australian spreading fabric into the swath-mapped western-most transform, as well as a second transform to the east at about longitude 161^{o}40’ E, indicates right-lateral motion for the entire complex. As stated previously, the mechanism by which respective Pacific Plate and Indo-Australian Plate right-lateral motion is transferred from the Macquarie Fault Zone to this transform region is problematic. It is unclear whether motion in the arcuate Hjort region to the north is terminated by the western-most transform, and thus whether the deeper eastern-most fracture (transform) is the relic southern continuation of the Hjort Trench.

Aspects of this preliminary tectonic analysis were contained in a poster presented at the 15th Australian Geological Convention and copied here as Figure 32.

SEAFLOOR CHARACTER QUERY CAPABILITY

The occurrence of multiple primary and derived spatial data sets detailing various characteristics of the seafloor affords the opportunity to query those data sets for areas meeting certain criteria. These criteria are taken from some point sample knowledge-base so that an attempt is made to extrapolate beyond it for a spatial correlation. For example, the knowledge-base may be a list of known characteristics for the habitat of a particular benthic organism.

In this section various aspects of seafloor character in the study area are queried. These aspects can often be visualised simultaneously to better enhance the areas of interest – see Figures 33 and 34 for a snapshot of an interactive three-dimensional perspective view of various characteristics of the seafloor in the study area. To illustrate approaches in modelling a query two examples, one fictitious, are presented. They indicate the capabilities of the technique, and methodologies that can be used in constructing an iterative sequence of conditions to address questions of spatial distribution.

Habitat of a fictitious benthic species

Butler et al. (2000) provide the first detailed study of benthic habitats for the Macquarie Ridge environs about Macquarie Island. They present a database detailing several seafloor and environmental characteristics associated with particular organisms with the aim of defining their preferred habitat. Unfortunately, extrapolation of their findings further south into the study area is not particularly instructive, as the majority of the organisms examined live shallower than 1000 m. In any case, the fictitious example of benthic species "X" presented here suffices to model the distribution of a real organism.

Benthic species: X

- region: Macquarie
- feeder type: filter
- substratum preferred: very stable strata for attachment
- depth regime: 2000-3000 m

Therefore, for the detailed swath bathymetry and backscatter data sets in the Hjort region a cumulative series of questions can be built:

Query structure: define favourable spatial habitats for X

where -3000 m < [seafloor bathymetry grid] < -2000 m
- known depth regime for X's habitat

and

where [seafloor character] = hyperbolae facies
- these areas are probably bare volcanic rock and not loose sediment

and

where 1^{o} <[seafloor slope grid] < 20^{o}
- assume slopes > 20^{o} are historically unstable and those >1^{o} provide adequate exposure to water-suspended nutrient flow

and

where 180^{o} < [seafloor aspect grid] < 360^{o}
- assume filter feeders like energetic waters carrying nutrients

so query on westerly aspect into ACC easterly flow

The cumulative response to this query is presented in Figure 24. The highlighted zones identify those areas of the seafloor that are likely to host hypothetical benthic species X.

Source of turbidites

The query logic applicable to a benthic organism is also able to answer spatial questions on seafloor rock and sediment distribution. The example presented here is the identification of those areas of seafloor in the study area that are probable sources for turbidite deposition. As discussed previously turbidites result from the down-slope flow of a sediment-water mixture. A query structure can be built up and then used to interrogate the various spatial data sets over the seafloor.

Query structure: define probable source regions for turbidites

where [seafloor character] = sediment-type facies
- sediments are unconsolidated and able to freely mix with water

and

where 10^{o} < [seafloor slope grid]
- greater instability likely for moderate to steep slopes

and

where [seafloor] < 2 km distant from down-slope 'drainage network'
- the drainage network is a delineation of accumulated down-slope flow and may identify potential turbidite paths; 2 km chosen arbitrarily

The cumulative response to this query is presented in Figure 24. The highlighted zones identify those areas of the seafloor that are likely to supply loose sediment for turbidites.

Using sample data

The two examples presented above are hypothetical in that they are not based on any real data in the study area - they outline the usefulness in using spatial continuous data to extrapolate a sampled phenomenon of various characteristics. However, a suite of actual sampled phenomenon from the water-column and/or seabed may have characteristics relatable to the parameters stored in a continuous grid. Once determined by an analysis the conditions favourable for the sample's existence and development can be categorised and used to question the relevant spatial data sets. Within some quantifiable margin-of-error a distribution of existence should be determinable. The following sequence of steps may be useful:

1. Obtain the sample - that is, search historical data or devise a sampling survey with relevant objectives;

2. Analyse the sample - what are the characteristics of the environment in which the sample exists;

3. Determine usefulness of spatial data sets covering the sampled area - for example, analysis of multiple distributed samples indicating a preferred depth regime for a phenomenon suggests use of a bathymetric grid to examine the area of interest. Furthermore, consider how a combination of spatially continuous and discrete data may be used to address the phenomenon, for example, bathymetry and aspect grids with current information indicate areas likely to be scoured by current activity; and then

4. Present the modelled distribution in a meaningful way.

This is best done with a large suite of samples collected over the area of interest. As shown in Figure 13, however, there is a paucity of such seafloor data over the Hjort region of the southern Macquarie Ridge.

RESOURCE POTENTIAL

The marine environment is a great source of both current and potential economic resource. These include, amongst others, fishing stocks in the water column, benthic organisms and minerals at the seabed and hydrocarbons in the thick underlying sedimentary sequences. The great diversity in seafloor morphology and character of the southern Macquarie Ridge region suggests the potential to host a variety of resources.

Fishing resources

Apart from historical whaling and sealing, fishing did not start in Macquarie waters until 1994-95, and then only in an exploratory fashion. The fishing stock of primary importance is the Patagonian toothfish. These fish are found on the shelf and upper-slope areas in depth ranges of 300 m to more than 2000 m. Catch and habitat information is currently restricted, nevertheless the depth regimes of the study area indicate that it is likely to play host to this fish, although the effects of the ACC and bounding Antarctic Polar Front to its south need to be considered.

Benthic resources

Butler et al. (2000) provide the best current knowledge of the benthic environment in the Macquarie region. They collected 102 species from seafloor sled sample sites located directly east of Macquarie Island and to the north and south along the Macquarie Ridge. The biological community noted on video transects and benthic sled catches of the seabed were:

- mixed small macrobenthos (encrusters) including sponges;
- mixed large macrobenthos (erect) including seawhips;

- soft sediment communities including holothurians; and
- seapens, urchins and others.

The economic value of these organisms is currently unknown.

Mineral resources

The primary mineral deposit of interest lying on the seabed is manganese, mostly in the form of circular to semi-circular manganese nodules, but also as crusts on rock. These form by the accretionary process at the seafloor of manganese and other minerals, which are precipitated out of the water column. They are often found strewn across vast tracts of the seafloor, known as manganese nodule pavements. Their economic attractiveness is due to their high concentrations of manganese, copper, nickel and cobalt.

Manganese nodules were dredged in the western-most arm of the segmented transform province in the south (see sample Eltanin 34-4 in Appendix 5 and Fig. 13). The former sample lies to the east of the axis of the northward flowing Antarctic Bottom Water. Furthermore, more extensive surficial sediment mapping shows a correlation between this current and areas of manganese nodule pavements (Schuur et al., 1998), thereby suggesting that seafloor to the west of the Hjort Trench may play host to large deposits.

Other potential mineral deposits are those related to current or former submarine volcanic activity, which plays host to sulphide mineralisation. Although direct evidence is lacking the mapped seamounts and smaller volcanic edifices (Fig. 20) are potential locations for such hydrothermal deposits.

Hydrocarbon resources

Hydrocarbon resources refers to entrapped accumulations of oil and/or gas within thick sequences of sedimentary strata, termed sedimentary basins. Within the mapped region only the northern Hjort Trench could be considered a sedimentary basin, containing up to 1500-2000 m of sediment. However, several factors strongly indicate that it is unlikely to be petroliferous:

- although containing a considerable amount of sediment the northern Hjort Trench is restricted in area, meaning that the total volume of sediment and, therefore, possible hydrocarbons generated is minor;
- due to its location along a mobile plate boundary the sedimentary pile is heavily faulted and disturbed, thereby providing ready pathways for the escape into the water column of generated hydrocarbons; and
- most conclusively, the entire depositional regime is unfavourable for the development of a petroleum system. The region is too remote from continental sources of both organic plant material and large influxes of terrigenous sediment to provide rapid burial in anaerobic conditions.

The seismic and 3.5 kHz data provide no evidence of bottom-simulating reflectors that might indicate the presence of gas hydrates within the sediments of Hjort Trench, and such methane deposits are not known to exist in the great water depths involved (ie 5500-6500 m).

AUSTRALIA'S MARINE JURISDICTION IN THE SOUTHERN MACQUARIE RIDGE REGION

An important objective of the AUSTREA-2 survey was to acquire the necessary data to support definition of extended Continental Shelf (ECS) south of the Australian EEZ around Macquarie Island. This built on previous examinations of the area by Symonds and Wilcox (1989), and internal AGSO desktop studies throughout the late 1990's.

The United Nations Convention on the Law of the Sea

The adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 marked the culmination of more than ten years of negotiations involving over 150 countries. The Convention established a comprehensive legal framework for the regulation of all ocean space. It covers a diverse range of issues such as the limits of national jurisdiction over ocean space, access to the seas, navigation, protection and preservation of the marine environment, exploitation and conservation of living resources, exploitation of non-living resources, sea-bed mining, scientific research, and the settlement of disputes.

An important aspect of UNCLOS is that it provides for the establishment of a series of new or revised marine jurisdictional zones, that extend over the continental margin and ocean basins adjacent to maritime nations (Fig. 28). The seaward limits of most of these zones are measured from the Territorial Sea Baseline (TSB), which is made up of a series of components that are defined under provisions set out in UNCLOS (United Nations, 1983) and are dependent upon the shape of the coastline at any given location. The 'normal' baseline corresponds with the low-water line (the level of Lowest Astronomic Tide in Australia's case) along the coast, including the coasts of islands. The TSB can also consist of straight bay and river closing lines, and a system of straight baselines, which may be used where the coastline is deeply indented, or where there is a fringe of islands along the coast in its immediate vicinity. Waters that lie landward of the TSB are generally designated internal waters for the purposes of international law.

The arrangement of the various UNCLOS zones is shown in Figure 28, and are as follows:

- Territorial Sea **-** extends to not more than 12 nautical miles (M) from the TSB. A coastal State's sovereignty extends throughout this zone, and includes the water column, seabed and subsoil, as well as the airspace above it. However, foreign ships have the right of innocent passage through the zone;

- Contiguous Zone - outer limit extends to not more than 24 M from the TSB. A zone extending beyond the Territorial Sea in which a coastal State may exercise control necessary to prevent and punish infringement of its customs, immigration or sanitary laws and regulations within its territory or Territorial Sea;

- Exclusive Economic Zone (EEZ) - outer limit extends to not more than 200 M from the TSB. A zone extending beyond the Territorial Sea in which a coastal State has sovereign rights for the purposes of exploring and exploiting, conserving and managing the natural resources (living or non-living) of the water column, seabed and subsoil. A State also has jurisdiction with regard to marine scientific research, and the protection and preservation of the marine environment, as well as other rights and duties;

- Continental Shelf - outer limit is 200 M from the TSB, or beyond that to the outer edge of the continental margin as defined in Article 76 of UNCLOS (Appendix 2). A zone that extends beyond the Territorial Sea, and overlaps with the EEZ out to 200 M, in which a coastal State has sovereign rights for the purposes of exploring and exploiting its mineral and other non-living resources of the seabed and subsoil, together with sedentary living organisms. A State also has jurisdiction with regard to marine scientific research, and protection and preservation of the marine environment in its continental shelf, as well as other rights and duties.

The outer limit of seabed and subsoil jurisdiction of a coastal State is defined by its Continental Shelf, and therefore it is this zone that also defines the full national jurisdiction over the environment and resources of everything that lies beneath the water column.

Definition of the Continental Shelf

The concept of a 'legal' Continental Shelf, defined by a series of rules or formulae, is quite distinct and different from the morphologically defined continental shelf of a geographer. The rights associated with a Continental Shelf have remained essentially unchanged over the years - a coastal State has sovereign rights over its legal Shelf for the purposes of exploring and exploiting the natural resources of its seabed and subsoil. The inner (landward) limit of the Continental Shelf has long been regarded as the outer limit of the Territorial Sea; however, the definition of the outer limit has been considerably more contentious.

The 1982 UNCLOS brought with it a new definition of the ‘legal’ Continental Shelf that was very different in concept from that contained in the previous 1958 Geneva Convention on the Continental Shelf. Under the 1958 Convention the outer limit of the Continental Shelf was defined as extending to a depth of 200 m, or beyond that limit beneath the superjacent waters to a depth where exploitation of the natural resources is possible. Effectively, this definition stated that a coastal State could claim as much of the deeper waters beyond a geomorphic shelf as it was capable of exploiting; however, gradually it became customary that rights over the Continental Shelf did not extend beyond the geomorphological continental margin - the outer edge of the continental rise. Despite this theoretical, absolute outer limit based on geomorphology the definition remained imprecise and tied to continuing technological developments.

Article 76 of UNCLOS (Appendix 2) provides a much clearer definition of the outer limit of the Continental Shelf which accommodates the geomorphologically different circumstances of coastal nations around the world. It defines the Continental Shelf as comprising:

> '*...the sea-bed and subsoil of the submarine areas that extend...throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles...where the outer edge of the continental margin does not extend up to that distance*' (Article 76(1)).

It goes on to define the term continental margin as comprising:

> '*...the submerged prolongation of the land mass of the coastal State, and consists of the sea-bed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges...*' (Article 76(3)).

Article 76 of UNCLOS provides two methods for establishing the outer edge of the continental margin wherever the margin extends more than 200 M from the TSB, and both of these are based on measurements from foot-of-continental-slope (FoS) reference points. In absence of evidence to the contrary, Article 76 defines the FoS as the point of maximum change in the gradient at its base. The first of these methods - *the sediment thickness formula* - produces a line delineated by the outermost fixed points at each of which the thickness of sedimentary rocks is at least one percent of the shortest distance from the FoS (Fig. 29). Application of this method requires information on the morphology of the seafloor so that FoS points can be determined, as well as knowledge of sediment thickness beyond the FoS to at least the edge of the continental rise.

The second method - *the Hedberg formula* (so-called) - produces a line delineated by reference to fixed points not more than 60 M from the FoS (Fig. 29). Application of this method only requires information on the morphology of the seafloor so that FoS points can be determined.

Both the 1% sediment thickness and Hedberg lines are formed by straight lines not exceeding 60 M in length connecting either the 1% sediment thickness points, or selected points on the 60 M radius Hedberg arcs, respectively. Either of these lines can become the outer limit of the Continental Shelf provided that they do not extend beyond either of two cut-off limits: 350 M from the TSB, or 100 M beyond the 2500 m isobath - referred to here as the isobath cut-off (Fig. 29).

It is apparent from the above discussion that the outer limit of the Continental Shelf will ultimately be formed by a combination of five possibilities, which can be selected to maximise the jurisdiction - the 200 M line, the 1% sediment thickness line, the Hedberg line, the 350 M cut-off, and the 100 M beyond the 2500 m isobath cut-off. The composite outer limit of the Continental Shelf extending beyond 200 M must be delineated by straight lines not exceeding 60 M in length. Figure 29a illustrates the case in which the outermost edge of the continental margin is defined by the 1% sediment thickness line. This line lies beyond both cut-offs, and thus the outermost cut-off - the 350 M line - defines the outer limit of the Continental Shelf in this case. The area of Continental Shelf lying between 200 M and the outer limit of the Shelf is commonly referred to as the 'extended' Continental Shelf (ECS). In the case of an area of extended Continental Shelf that is common to countries with opposite or adjacent coasts, there is a need to negotiate an equitable solution to its delimitation on the basis of international law.

Full application of Article 76 requires information on the morphology of the margin to define the FoS, knowledge of sediment thickness beyond the FoS, the location of the TSB, and good bathymetric information defining the 2500 m isobath. The outer limit of the Continental Shelf must be defined at least every 60 M around parts of the margin extending beyond 200 M, and thus a considerable technical data base is needed consisting of high quality bathymetric and seismic reflection data. These, and associated data sets, provide an improved understanding of the geology, environment and resource potential of the area being delineated, and can be used to enhance rights to ECS by providing support for the extent of natural prolongation and the location of the continent-ocean boundary.

Where a coastal State intends to establish the outer limits of its Continental Shelf beyond 200 M using Article 76 of UNCLOS, it must submit details of such limits, along with supporting scientific and technical data, to the Commission on the Limits of the Continental Shelf within ten years on entry into force of the Convention for that State (i.e. originally by 16 November 2004 for Australia). At a May 2001 meeting of States that are party to UNCLOS the initial deadline for submissions was changed to 13 May 2009 (ten years from the date on which the CLCS adopted its Scientific and Technical Guidelines) for States for which UNCLOS entered into force before May 1999. Although the general form of the technical data required for Continental Shelf definition is apparent from Article 76 and the Scientific and Technical Guidelines of the CLCS (Commission on the Limits of the Continental Shelf, 1999), the exact requirements and approaches are likely to remain uncertain until the CLCS has had an opportunity to consider submissions.

Australia's Marine Jurisdiction

The beginning of the UNCLOS regime was an important milestone for Australia, because it provided rules for defining its vast new marine zones, as well as setting out rights and obligations for managing the environment and resources within them.

With the proclamation of the 200 M Australian EEZ, and new UNCLOS definition for the Continental Shelf, Australia will have an area of ocean under its jurisdiction greater than the landmass (Fig. 30). Symonds and Willcox (1988, 1989) estimated that the Australian EEZ has an area of about 8.6 million km² (about 11.1 million km² including the EEZ adjacent to the Australian Antarctic Territory (AAT)), and the area of the Continental Shelf will be about 12.3 million km² (about 16.5 million km² including the area adjacent to the AAT) - more than one and a half times the size of the continent and one of the world's biggest. About 20% of this Continental Shelf is geomorphic shelf (< 200 m water depth), about 45% is deep continental margin (shelf, slope and rise; 200 - 4000 m), and the remaining 35% is deep-ocean floor.

The Symonds and Willcox (1988, 1989) studies used about 200 000 km of early 1970s seismic data to define eight areas of ECS totalling about 3.7 million km² (Table 4); however, more recent work has indicated a ninth area to the east of the Australian EEZ around Norfolk Island (Fig. 30), with an area of about 0.1 million km² (Table 4), and a tenth area adjacent to the AAT, giving a total ECS area of about 5.6 million km². To support ECS definition under UNCLOS, Australia needs information about the physiography and sediment thickness of parts of its continental margin extending beyond 200 M. A preliminary study of existing datasets showed that further survey work was required in at least seven areas, including the Macquarie Ridge area, for Australia to be able to fully define the outer limit of its ECS. Recently, the Australian Government also decided to carry out the necessary work to place Australia in a position to be able to prepare a submission delineating the ECS off the AAT, should it choose to do so.

EXTENDED CONTINENTAL SHELF ZONE	AREA (10^6 KM^2)
Lord Howe Rise/Norfolk Ridge	0.87
South Tasman Rise	0.54
Macquarie Ridge	***0.11***
Great Australian Bight	0.09
Naturaliste Plateau	0.19
Exmouth/Wallaby Plateaus	0.60
Argo Abyssal Plain	0.02
Kerguelen Plateau (to AEEZ adjacent to AAT)	1.24
East of Norfolk Ridge	0.10
Australian Antarctic Territory (AAT) (based on 350 n mile cut-off)	1.80

Table 4. Areas of extended Continental Shelf around Australia and its territories (modified from Symonds & Willcox, 1989). The area in the Macquarie Ridge region is shown in bold italics.

Other Australian marine boundaries and zones

There are several areas where Australia has negotiated maritime boundaries with neighbouring coastal States (Papua New Guinea, the Solomon Islands, France and Indonesia). Further negotiations may be necessary with France, and negotiations with New Zealand regarding the Lord Howe Rise, Norfolk Ridge, Three Kings Ridge and Macquarie Ridge (Fig. 30) have commenced.

Apart from the various international UNCLOS zones discussed above, there are other national marine zones that are peculiar to Australian legislation. These national zones are generally the result of the division of responsibilities between the Commonwealth Government and the State/Northern Territory Governments under the Australian

Constitution and certain agreements between the Commonwealth, the States and the Northern Territory.

Coastal Waters include the water and subjacent seabed between the TSB and a line 3 M seaward. They also include waters on the landward side of straight baseline components of the TSB, but exclude waters lying within State limits on 1 January 1901 and which remain within those limits. Title to the seabed within this zone is vested in the adjacent State or Territory as if that area formed part of the State or Territory. Responsibility for offshore areas beyond 3 M rests with the Commonwealth. Thus, for Australia, the UNCLOS 12 M Territorial Sea is divided into a 3 M State or Territory jurisdiction (Coastal Waters) and a 9 M zone of Commonwealth jurisdiction extending beyond the Coastal Waters.

Other important zones - the Adjacent Areas - are defined by *Australia's Petroleum (Submerged Lands) Act 1967*. Adjacent Areas are 'picture frames' extending beyond the Coastal Waters adjacent to Australia's States and the Northern Territory within which the outer limit of the seabed and subsoil resource regime (the Continental Shelf) will lie. The importance of this zone is that it defines the offshore jurisdictional boundary extending out from the coast between adjacent States. The outer boundaries of the Adjacent Areas have been adjusted several times since 1967 to ensure that they include all potential areas of Australia's Continental Shelf. In the case of Macquarie Island, which is part of Tasmania, the adjacent area boundary extends southeast of Tasmania to include Australia's marine jurisdiction associated with Macquarie Island.

Marine jurisdiction associated with Macquarie Island

Macquarie Island and its associated islets of Judge and Clerk, located approximately 11 km to the north, and Bishop and Clerk, located approximately 37 km to the south, are parts of the State of Tasmania. Thus, there is a 3 M Tasmanian Coastal Waters zone forming the inner part of the Territorial Sea associated with Macquarie Island and a 9 M Commonwealth part beyond it.

The area of Australian EEZ and extended Continental Shelf in the region between Australia and New Zealand is more extensive than shown in Figures 1, 2, 30 and 31. However, for the purposes of this paper, and pending completion of maritime boundary negotiations, the areas of the AEEZ and extended Shelf have been drawn back to the point of equidistance (the median lines) between the two countries in those areas where New Zealand has competing claims.

The AEEZ around Macquarie Island extends from the 12 M Territorial Sea around each of the exposed outcrops related to the above islands/islets out to 200 M in nearly all directions. To the northeast, where the 200 M limit overlaps with those from New Zealand's Auckland and Campbell Islands, the AEEZ is likely to be somewhat less than 200 M. The AEEZ extends to the median line with respect to these jurisdictions to take account of pending maritime delimitation with New Zealand. The area of the AEEZ around Macquarie Island is about 0.470 million km^2 (Table 5). The whole southeastern quadrant of the AEEZ coincides with the 16.2 million hectare (0.162 million km^2) Macquarie Island Marine Park that was declared in October 1999.

Symonds and Willcox (1989) considered that the ECS south of the AEEZ around Macquarie Island could extend as far south as the 350 M cut-off, and have an area of about 0.11 million km² (Table 4). A later AGSO desktop study confirmed the likelihood of ECS existing, but suggested that given the complexity and variability of Macquarie Ridge normal bathymetric surveying along individual profiles was unlikely to unambiguously prove continuity of the ridge to the south beyond the AEEZ, and that swath seafloor mapping should be utilised if possible.

Outer limit of extended Continental Shelf over Macquarie Ridge

Macquarie Ridge is a submarine elevation composed of uplifted oceanic crust surmounted by an island (Macquarie Island) that is composed of similar rock types. This configuration adds an extra degree of complexity to the definition of ECS on Macquarie Ridge. Article 76 of UNCLOS mentions ridges and related submarine elevations in three places (emphasis has been added to such terms in the following):

1. Article 76.3 - "The continental margin … does not include the deep ocean floor with its ***oceanic ridges*** …". That is, on such features the continental shelf cannot extend beyond 200 M.
2. Article 76.6 - "… on ***submarine ridges***, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines …". That is, on such features the continental shelf cannot extend beyond 350 M.
3. Article 76.6 - "This paragraph does not apply to ***submarine elevations*** that are natural components of the continental margin …". That is, on such features the continental shelf can continue to the full extent allowed by all aspects of Article 76, including beyond 350 M to the 2500 m + 100 M isobath cut-off if it is applicable.

The interpretation of these provisions of Article 76 can be complex, and therefore the definition of extended Shelf over such features is commonly difficult and controversial (Symonds *et al.* 2000). Clarification of these issues will have to await the outcome of considerations and recommendations made by the CLCS once claims of coastal States associated with ridge-like features have been submitted.

Another important consideration here is whether UNCLOS draws any distinction between continental landmasses and islands. The answer is found in Article 121, which indicates that islands, with the exception of rocks, have the same entitlements (and limitations) as other land territory. Hence, the provisions of UNCLOS apply to Macquarie Island just as they would to any other land territory, and it can, therefore, generate an EEZ and ECS. Further discussion here is beyond the scope of this report. In the following section, Article 76 is applied to Macquarie Ridge just as it would be to any other part of Australia.

The 1997 AGSO desktop study compiled and examined all existing bathymetric surveys and associated seismic data in the Macquarie Ridge region, including the more recent swath data sets from AGSO RV *Rig Seismic* Survey 124 and the RV *Ewing*, but could not unambiguously establish continuity of the ridge to the south up to and beyond the AEEZ. Following the AUSTREA-2 survey, the new swath data was compiled with all existing data in the region to produce the integrated bathymetric grid used in the following analysis (Fig. 31). Sparse seismic data in the region indicates that sediment overlying the relatively young oceanic crust adjacent to the southern Macquarie Ridge is too thin to enable use of the sediment thickness formula. That is, in this area the outer edge of the 'legal' continental margin will be given by the Hedberg line constructed from 60 M arcs beyond the FoS.

As a result of the availability of high-resolution bathymetric grids for the southern Macquarie Ridge (grid cell size of 0.001°, or about 110 m), a combined approach was used to select FoS points based on both single-beam bathymetric profiles along survey tracks, and synthetic profiles derived from the bathymetric grids using ARCView™ tools specifically developed for the purpose. Both types of profiles were analysed using AGSO's standard ARCView™ approach (Borissova et al., 1999) to derive preferred FoS positions at the point of maximum change in gradient at the base of the slope (Article 76, UNCLOS; Appendix 2). All FoS positions were plotted on the combined terrain image, as well as on slope, curvature and aspect images (see Figs 33 & 34 for examples of terrain, slope and aspect 3D displays) derived from the bathymetric model of the newly-swathed seafloor. This approach was used to check the locations and consistency of the FoSs, and to derive a FoS line joining the various FoS picks. The slope and aspect images were found to be the most useful for this purpose, with aspect providing a particularly clear indication of the FoS location in areas of steep slope such as in the Hjort Trench. Near the southern end of the Hjort Trench, at its intersection with the transform fault, and in the vicinity of the most southerly part of the southeastern seamount chain, two possible FoS lines were derived: a conservative one, and a maximised one. As a result of this approach two series of 60 M Hedberg arcs (Appendix 3) were buffered from the two different locations of the FoS line using ARCView™. These are only preliminary Hedberg arcs, and final computations will be conducted by the Australian Surveying and Land Information Group (AUSLIG; now the National Mapping Division of Geoscience Australia) using a rigorous geodetic approach.

The two versions of the Hedberg arcs (not incorporating straight-line segments to produce a final Hedberg Line; Appendix 3) are shown in Figure 31. The conservative Hedberg arcs lie inside the 350 M cut-off, however, the maximised ones extend just beyond it, and may need to be cut-off at 350 M to form the outer limit of the ECS. The conservative arcs add about 0.081 million km² of ECS jurisdiction south of the AEEZ around Macquarie Island, and the maximised arcs about 0.106 million km², giving full Continental Shelf jurisdictions of about 0.551 and 0.576 million km², respectively (Table 5). The potential outer limits of the 'legal' Continental Shelf shown in Figure 31 are preliminary only, and are not necessarily indicative or representative of the final outer limit of the Continental Shelf that might be used by Australia in any submission it makes to the Commission on the Limits of the Continental Shelf.

The areas of the various marine jurisdictional elements associated with Macquarie Island are given in Table 5. The maximum area of ECS is about twice the size of Tasmania, and the full area of marine jurisdiction off Macquarie Island is about 0.580 million km² - about twice the size of Victoria and Tasmania combined, or about three-quarters the size of New South Wales. This area of ECS does not include a small area of potential ECS to the northwest of the intersection of the AEEZ and the New Zealand EEZ (see Symonds et al., 2001).

FEATURE / ZONE[1]	AREA[2] (10^6 KM^2)
Australian landmass	7.683017
Macquarie Island: Landmass	 0.000124
Coastal waters (3 M)	0.000795
Territorial Sea (Commonwealth 9 M)	0.003799
Territorial Sea (12 M)	**0.004594**
AEEZ (200 M)	**0.469587**
Extended Continental Shelf (ECS) beyond AEEZ Conservative ECS Extra ECS area **Maximum ECS**	 0.081115 0.024973 **0.106088**
Continental Shelf (including AEEZ) – conservative **– maximum**	**0.550703** **0.575675**
Adjacent area off Tasmania	2.135275
Total marine jurisdiction (maximum) **Total jurisdiction (onshore and offshore)**	**0.580269** **0.580394**

[1]The various zones are shown on Figure 28.
[2]Areas were calculated using an Albers Equal Area projection in ArcView™.

Table 5. Areas of zones making up Australia's marine jurisdiction around Macquarie Island.

The area of ECS covers the southernmost part of the Macquarie Ridge complex, and the most easterly and shallowest (~400 m) seamount of the Hjort Ridge seamount province (Fig. 11) that lies beyond the AEEZ.

CONCLUSIONS

The geophysical mapping of the seafloor over the Hjort region of the southern Macquarie Ridge provides the means to investigate its form, character and economic potential, as well as to understand the nature of the marine environment.

Mapping by swath bathymetry provided a detailed high-resolution view of the seafloor morphology (Figs 11 & 12). Terrain analysis reveals:

- a 5500-6700 m deep arcuate-shaped oceanic trench flanked by gently sloping abyssal floor to its west and the moderate-to-steep rise of a bounding ridge to its east;
- a long, narrow elevated axial valley feature of complex internal sinuous form revealing the typical releasing-restraining system of physiographic depressions and hills along a strike-slip fracture zone;
- a broad, deep ridge-like section of elevated seafloor retaining the continuous ridge-valley system of relict seafloor spreading formation;

- an eastern province dominated by several very large seamounts rising from abyssal depths;
- a converging series of large-scale right-lateral moving oceanic fractures, which segment and offset sections of oceanic crust;
- a spread of seamounts and probable volcanic conical features over and to the east of the Hjort Ridge suggesting past and/or current volcanic activity at the seafloor, possibly related to hotspot activity or subduction to the west; and
- a dominant east-west alignment of moats and contourites evident in the sediment cover suggesting the current-shaping influences of the Antarctic Circumpolar Current and subsidiary eddies developed by the topography.

Mapping by swath reflectivity and echosounder sub-bottom profiling enabled an interpretation of sediment facies distribution (Figs 13, 14, 17, 18a, 18b and 19). The facies distribution analysis highlights:

- a Hjort Trench floor covered largely by undisturbed mostly pelagic sedimentation;
- an approximate 30% coverage of both disturbed and undisturbed sediment facies across the Hjort Ridge;
- abyssal seafloor about the large eastern seamounts hosting mixed sedimentation styles, including well-developed contourites and a large debris-flow deposit due to the slumping of the northeast flank of a large seamount; and
- both sediment cover and contourite mounding in the trenches formed along the segmented oceanic crust fractures.

Sparse bottom-sampling of manganese nodules indicates the potential for seafloor mineral deposits. The diversity of topography may promote an equivalent diversity in fishing habitat and benthic fauna, while widespread volcanism may host hydrothermal and fumarole type mineralisation. In contrast, the depositional and tectonic framework of the region is unfavourable for hydrocarbon deposits.

The existence of several primary and derived spatial data sets (ie grids), which model various seafloor parameters (Figs 15 & 16), provides the means to construct a knowledge-based query so as to identify the spatial distribution of the desired phenomenon (Figs 22 & 24). Such queries are also able to statistically classify the seafloor.

An analysis of the new swath bathymetry data, integrated with existing data sets, for marine jurisdiction purposes, indicates that an area of ECS exists south of Macquarie Island over the southern Macquarie Ridge Complex. The swath data, and its use in a combined grid and ship-track based approach to the definition of a foot-of-slope line, has allowed us to optimise the outer limit of the ECS. The maximum extent of this preliminary ECS is about 0.106 million km², roughly twice the size of Tasmania, and the full area of marine jurisdiction off Macquarie Island, subject to a successful submission to the CLCS, will be approximately 0.580 million km² - about three-quarters the size of New South Wales.

RECOMMENDATIONS

The material presented in this report is essentially a first-pass analysis of the seafloor data acquired over the Hjort region of the southern Macquarie Ridge Complex. Other large data sets, such as seismic, magnetic and gravity profiles, and those documenting a suite of oceanographic parameters, have not been examined. Furthermore, certain interpretations made rely on several assumptions for the data used.

Given the amount of data acquired, the complexity of the region's morphology and underlying crustal structure, the present paucity of data both on ocean current activity and on bottom-geology as well as the time required to consider the region in a wider plate boundary context it is certain that further study will reveal a greater wealth of information into the region's characteristics. The following are suggestions for further work:

- A complete interpretation of the region's seismic, incorporated with gravity, magnetics and seafloor characteristics data sets, will, most importantly, address the following questions:

  - Has there been, and is there still, subduction along the Hjort Trench?
  - How is plate boundary strain partitioned between the main zone of strike-slip movement along the Macquarie Fault Zone and possible subduction and transcurrent motion in the Hjort Trench to its west?
  - Can the distribution of seamounts and smaller volcanic edifices provide some insight into possible subduction processes and/or the genesis of a local hot spot?
  - How is plate motion transferred from the Macquarie Fault Zone and Hjort Trench regions to the segmented transform province?
  - Are there sequences present in the northern Hjort Trench sedimentary pile and, if so, do they provide some insight into the chronology of current activity or regional tectonic movements?

- The removal of the effects of terrain slope from the multibeam backscatter signal will provide a less ambiguous estimate of seafloor sediment distribution and related interpretations.

- The acoustic facies classification presented rests on the calibration with bottom samples south of Tasmania (Whitmore & Belton, 1997), which may not be wholly representative for the sedimentation regime along the southern Macquarie Ridge. Therefore, once a larger suite of bottom samples is collected over the swathed area a re-interpretation of seafloor sediment type should be attempted.

- The highly-detailed nature of the swath-sampled topography provides the means to attempt modelling of Antarctic Circumpolar Current movement and associated eddy generation across the region. This may provide significant input into sediment facies and associated mineral distributions, benthic habitat and fishing stocks.

- As above, the highly detailed nature of the swath-sampled topography provides the data density required by finite element modelling techniques, which may aid in unravelling the evolution of plate boundary motion and associated tectonic deformation.

- A presentation was made using two examples of the query capabilities of distributed data sets, such as, for example, with the primary grid of bathymetry and derived grids of slope and aspect. Clearly, provided a rule-base of conditions exists, the data sets can be examined for the spatial distribution of any parameter. For example:

    - Determining the distribution of a fish species ‘X’, which spawn in deep quiet waters away from the known distribution of fish species ‘Y’;
    - Knowing the distribution of water-bottom current axes determine the distribution of bottom feeders for a certain depth and substratum regime; and
    - Knowing the historical distribution of earthquakes and terrain slope determine the probable locations for future slumping and possible tsunami directions.

- The definition of the outer limit of ECS over the southern Macquarie Ridge Complex given in this report should be considered preliminary only, and is not necessarily indicative or representative of the final outer limit of the Continental Shelf that might be used by Australia in any submission it makes to the Commission on the Limits of the Continental Shelf. It will need to be re-visited following a re-compilation of all existing ship-track bathymetry data in the region.

- The ECS covers the southernmost part of the Macquarie Ridge Complex, and the most easterly and shallowest (~400 m) seamount of the Hjort Ridge seamount province that lies beyond the AEEZ.

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APPENDICES

Appendix 1

Digital Products

A listing of all the primary and derived digital data sets constructed, as a result of the study leading to this report, is given. These data sets form the basis for most of the images presented in the figures.

This is not a listing of the full suite of geophysical and navigational data produced by the crew of the N/O *l'Atalante* (see Bernardel et al., 2000).

Spatial Grided Data Sets (Arc/INFO™ grid format)

- Merged bathymetry - merge of all existing swath and satellite predicted bathymetry (Smith & Sandwell, 1997) for the Macquarie region bounded by the coordinates 51°-62° S and 153°-163° E.
- Backscatter - for AUSTREA-2 survey Macquarie coverage and stored as values between 0 and 255 reflecting intensity levels.
- Terrain slope - for AUSTREA-2 survey Macquarie coverage and storing values representing rate of maximum change in depth values across AUSTREA-2 bathymetry coverage.
- Terrain aspect - for AUSTREA-2 survey Macquarie coverage and storing values identifying the direction of maximum rate of change in depth values across AUSTREA-2 bathymetry coverage.
- Terrain flow accumulation - for AUSTREA-2 survey Macquarie coverage and storing values representing the requested accumulated weight of all cells that flow into each downslope cell.

Spatial Vector Data Sets (Arc/INFO™ cover format)

- Contours - line contours of any depth contour interval constructed on demand from the bathymetry grid.
- Pseudo-drainage - line network, constructed from terrain flow accumulation grid, specifying the linear form of those cells with the requested number of accumulated downslope cells flowing into them.
- Volcanics distribution - polygons outlining the distribution of interpreted volcanic features.
- Sediments distribution - polygons outlining the interpreted distribution of seafloor sediment accumulations.

Appendix 2

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

Article 76: Definition of the continental shelf

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appendix 3

Informal Terms relating to Article 76

Application of Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) (Appendix 1) raises several concepts and terms that 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 M, 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 M, 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 M 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 M 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 M long. This would normally be done in a manner so as to maximise the size of the enclosed 'legal' Continental Margin.

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 M in length.

Finally, the fixed points (not more than 60 M apart) comprising the line that defines the outer limits of the CS, may not lie beyond one or other of two cut-offs. The first cut-off is 350 M from the baseline (informally called the *350 M cut-off line*), and the second is 100 M 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.

Appendix 4

Regional Earthquake Database

Earthquakes for the Macquarie Ridge region between latitudes 51°S to 62°S and longitudes 153°E to 163°E. These earthquakes are shown on Figure 10.

This information is extracted from AGSO's Australian Seismological Centre earthquake database. Only earthquakes of greater than magnitude 3 and less than magnitude 9.99 are shown.

Source	Date	UTC	Lat	Long	Depth	mb	Ms	MD	MN	ML	auth	unsp	auth	Mw	obs	stat
GUTE	19240626	13734.0	-56.000	157.500	0							7.8	PAS			
GUTE	19290522	200615.0	-62.000	155.000	0							6.5	PAS			
GUTE	19291216	4531.0	-55.000	155.400	10		5.6						PAS			
GUTE	19331202	51718.0	-52.000	161.000	0							6.0	PAS			
GUTE	19341025	102317.0	-54.000	160.000	0							5.6	PAS			
GUTE	19351209	72330.0	-55.000	162.000	0							6.3	PAS			
GUTE	19381009	163640.0	-62.000	160.000	0							6.0	PAS			
GUTE	19391110	164940.0	-53.000	160.000	0							6.0	PAS			
GUTE	19401001	213820.0	-62.000	160.000	0							6.5	PAS			
GUTE	19430906	34130.0	-53.000	159.000	0							7.8	PAS			
GUTE	19450323	231413.0	-62.000	153.000	0							7.1	PAS			
GUTE	19511028	64742.0	-58.000	158.000	0							6.8	PAS			
SYKES	19600310	4025.2	-61.350	155.000	0		5.1									8
ISS	19600322	23119.0	-61.240	154.420	0		6.4									86
SYKES	19600322	134843.1	-60.440	153.580	0		5.7									14
ISS	19621025	200604.0	-61.700	154.730	0		6.0									106
SYKES	19630128	100313.8	-52.330	160.170	0	5.6										9
MOS	19630512	94258.3	-57.500	159.400	44							6.2	PMG			
ISS	19630512	94300.0	-57.560	159.780	70	6.2	6.4									127
ISS	19630805	153905.0	-60.650	154.020	13	5.2	5.7									84
SYKES	19630811	13418.6	-60.390	154.350	0	5.4	4.9									18
SYKES	19631224	210549.8	-53.040	159.450	0	5.8	5.7									22
ISC	19640105	162550.0	-61.400	155.000	6		5.9									34

ISC	19650802	131957.5	-55.900	157.700	33				6.2	ISC	242
ISC	19650816	170126.2	-61.410	154.500	33				5.4	ISC	49
USCGS	19651025	175346.2	-60.500	153.900	49				5.2	ISC	20
ISC	19651111	25127.0	-60.600	153.500	33				5.0	ISC	72
ISC	19660109	120821.0	-56.690	159.100	5	5.6					24
ISC	19660405	115740.4	-55.060	158.700	33				5.4	ISC	53
ISC	19660525	132056.6	-52.770	160.170	33				6.0	ISC	217
ISC	19670721	22218.3	-54.300	159.060	25				5.2	ISC	28
ISC	19670731	224835.5	-59.910	159.200	33				5.1	ISC	39
ISC	19670801	90548.6	-59.890	159.600	33				5.5	ISC	95
ISC	19680421	164314.0	-56.370	157.860	2				5.6	ISC	79
ISC	19680508	110007.0	-57.960	157.570	25				5.5	ISC	182
ISC	19681130	41333.0	-61.400	160.800	33				5.0	ISC	21
ISC	19681130	42513.8	-61.350	160.300	15				5.2	ISC	19
ISC	19681130	60731.0	-61.720	160.900	6				5.1	ISC	33
ISC	19690617	235810.4	-52.530	159.700	33				5.8		236
ISC	19690824	93124.0	-61.280	154.300	1				4.9		55
ISC	19700611	164643.7	-58.860	157.600	64				6.0		303
ISC	19700618	63902.9	-61.230	160.300	33				5.2		96
ISC	19700623	40743.1	-59.270	159.400	30				5.2		108
ISC	19710927	165449.6	-54.740	158.699	33	5.2					31
ISC	19711128	145823.9	-60.289	153.822	37	5.2					45
ISC	19720407	305.3	-53.520	159.080	33		5.9	MOS			175
ISC	19720620	14154.0	-60.446	153.807	33	5.2					156
ISC	19720906	180941.6	-51.158	161.141	33	5.3					49
ISC	19721211	180620.7	-61.899	162.506	33	5.1					21
ISC	19721224	203100.1	-52.375	160.494	33	5.5					102
ISC	19730319	64225.9	-53.049	159.751	33	5.4					42
ISC	19730607	24330.9	-53.998	159.349	33	5.8					119
ISC	19730615	213359.0	-61.311	154.329	33	5.1					44
ISC	19730924	233057.7	-52.217	160.781	10	5.6					49
ISC	19731019	1300.7	-54.689	158.539	33	5.5					168
ISC	19740413	41942.5	-52.731	160.388	33	4.9					13
ISC	19740602	130021.9	-61.157	153.854	17	5.3					35
ISC	19740604	44530.6	-60.524	153.605	34	5.3					38
ISC	19740605	114421.1	-54.513	158.568	33	5.5					36
ISC	19741011	60013.6	-60.672	153.914	33	5.2					57
ISC	19741011	83352.7	-60.701	153.945	33	5.1					169
WYS	19750926	0.0	-53.240	156.470		5.6					

ISC	19760125	132205.2	-61.335	154.324	33	5.2	48
ISC	19760518	60444.5	-60.394	154.351	33	5.3	143
ISC	19760519	152647.4	-61.590	154.493	33	5.4	62
ISC	19770721	115322.3	-53.817	158.844	33	6.2	458
ISC	19770721	123429.4	-53.668	159.457	33	5.5	39
ISC	19780317	144059.0	-55.397	157.967	33	4.1	8
ISC	19780402	55518.2	-61.315	154.567	33	5.2	35
ISC	19780514	120627.1	-61.519	154.589	33	5.2	92
ISC	19780524	61200.9	-52.949	160.053	33	5.6	69
ISC	19790313	140418.8	-60.463	153.503	160	4.8	31
ISC	19790423	215435.6	-52.931	159.842	10	5.5	278
ISC	19790811	51434.4	-51.940	161.456	10	5.6	104
ISC	19790811	64940.3	-52.040	161.562	10	4.1	11
ISC	19790904	191123.4	-51.282	162.143	33	4.2	7
ISC	19791012	124735.3	-53.188	160.004	10	4.8	13
ISC	19791017	101412.4	-61.299	154.223	10	5.2	74
ISC	19800118	215527.8	-53.857	158.902	10	5.1	82
ISC	19800207	104905.9	-53.934	158.962	10	4.9	73
ISC	19800207	104916.3	-54.212	158.784	0	6.0	246
ISC	19800207	105909.0	-54.266	158.796	1	5.7	162
ISC	19800328	131516.6	-60.278	153.097	10	4.1	26
ISC	19800502	174406.6	-54.784	158.430	10	5.1	35
ISC	19800527	22611.9	-60.026	160.730	33	5.3	124
ISC	19800608	202826.7	-59.076	158.675	10	5.1	126
ISC	19800608	205832.9	-59.424	159.036	33	4.3	11
ISC	19800608	210741.5	-59.199	158.263	33	4.8	15
ISC	19800711	171432.6	-59.055	158.814	33	4.4	16
ISC	19800713	215324.4	-54.427	158.738	11	5.4	82
ISC	19800805	173804.5	-53.076	159.844	10	4.5	17
ISC	19800827	130604.4	-57.574	157.797	33	4.6	11
ISC	19801012	112159.5	-61.305	154.004	10	5.1	28
ISC	19810128	192533.3	-54.641	157.768	10	5.4	139
ISC	19810210	21836.3	-51.125	162.170	33	4.2	11
ISC	19810221	35440.5	-61.757	154.866	10	5.2	93
ISC	19810503	80118.5	-53.292	159.702	33	4.4	15
ISC	19810613	12601.7	-60.409	153.430	0	5.1	149
ISC	19810714	202410.9	-52.681	160.504	10	5.0	47
ISC	19810815	1933.8	-55.322	158.564	33	4.6	12
ISC	19820112	224858.3	-51.583	160.108	0	4.1	5

ISC	19820211	1042.5	-60.322	153.095	10	4.6					10
ISC	19820420	74535.3	-55.013	158.530	10	4.6					13
ISC	19820607	2415.3	-60.890	154.112	10	5.1					35
ISC	19820624	155530.3	-55.226	158.719	0	4.5					12
ISC	19820627	161714.8	-55.422	160.226	10	5.9					379
ISC	19820707	104304.0	-51.151	160.642	10	6.2					503
ISC	19820707	105815.3	-51.408	160.925	33			4.9	WEL		14
ISC	19820707	111514.9	-51.471	160.860	33	5.0					25
ISC	19820707	121656.1	-51.386	160.828	10	5.4					102
ISC	19820710	95357.6	-51.367	161.146	33	3.8					9
ISC	19820720	92237.3	-51.157	161.247	33	3.9					8
ISC	19820722	174505.3	-51.158	161.394	10	5.3					72
ISC	19820927	114836.6	-59.165	158.993	33	4.3					17
NEIS	19830509	134528.0	-61.865	161.283	10	5.5	5.3				33
NEIS	19830509	150635.9	-61.662	161.138	10	5.0	5.1				21
NEIS	19830509	224132.2	-61.733	161.139	10	4.9	5.3				14
NEIS	19831129	130848.6	-61.071	153.810	10	4.7					9
NEIS	19840218	150639.5	-61.962	154.669	10	4.6					13
NEIS	19840523	51633.1	-51.950	161.089	10	5.9	5.9				240
NEIS	19840702	142526.1	-54.871	158.889	10	5.1	5.0				40
NEIS	19841231	214210.5	-60.135	153.192	10	5.4	5.2				45
ISC	19850103	224410.9	-54.410	155.072	10	5.2				45	
ISC	19850125	124805.1	-58.667	157.529	33	4.7				13	
ISC	19850318	144957.2	-51.232	162.776	12	4.1				10	
ISC	19850424	162157.6	-51.114	160.973	10	4.8				18	
ISC	19850425	90640.1	-60.656	153.660	10	5.0	5.4			59	
ISC	19850808	222617.8	-61.477	154.292	10	5.3	5.2			63	
ISC	19851002	84854.1	-53.334	159.149	0	4.5				11	
ISC	19851026	85547.8	-61.264	154.132	10	5.2				31	
ISC	19860428	51106.9	-60.209	159.975	10	4.3				8	
ISC	19860705	195741.7	-60.383	153.469	10	5.4	5.6			144	
ISC	19860723	73527.6	-61.894	154.866	10	5.3	5.7			151	
ISC	19861116	65655.3	-61.370	153.853	10	4.9	5.1			56	
ISC	19870128	201437.9	-61.045	153.870	10	5.4	5.5			117	
ISC	19870207	104620.9	-59.067	158.910	15	5.4	5.4			110	
ISC	19870309	84751.2	-54.617	158.537	10	4.5				12	
ISC	19870421	105401.5	-61.801	153.563	10	4.6				19	
ISC	19870501	4609.2	-57.904	157.826	17	4.9				38	
ISC	19870505	100028.3	-57.631	157.893	11	4.7				26	

ISC	19870808	54151.9	-58.698	158.162	15	5.3	4.5			98	
AUST	19870808	54155.0	-58.119	158.774	13			5.4	AUST		9
ISC	19870903	64011.8	-58.859	158.476	15	5.9	7.2			555	
ISC	19870903	80134.1	-59.498	158.928	15	6.1	6.9			494	
ISC	19870903	83615.8	-59.546	159.064	33	5.3				101	
ISC	19870903	92006.9	-59.437	159.121	33	4.6				15	
ISC	19870903	94229.7	-59.451	158.924	33	5.0				96	
ISC	19870903	110817.9	-59.559	159.226	0	5.5	5.9			209	
ISC	19870903	113112.9	-59.448	159.190	33	4.6				19	
ISC	19870903	140844.1	-59.222	159.920	33	4.4				8	
ISC	19870905	25948.0	-59.588	158.396	15	4.5				27	
ISC	19870909	192040.0	-59.201	159.185	33	4.6				19	
ISC	19870917	92815.0	-53.401	159.741	10	4.5				17	
ISC	19870921	203918.8	-59.518	159.077	10	4.6	3.9			9	
ISC	19871004	231257.3	-61.712	161.030	10	5.2	4.6			36	
ISC	19871212	41956.9	-58.797	159.749	10	4.0				10	
ISC	19880106	163110.7	-51.188	162.202	33	4.0				7	
ISC	19880113	114030.8	-61.673	154.753	10	5.2	5.0			41	
ISC	19880116	54651.7	-60.497	153.533	10	5.5	5.5			180	
ISC	19880223	15841.8	-60.623	159.643	10	5.5	5.5			176	
ISC	19880908	110639.8	-60.865	153.672	10	4.7	5.1			34	
ISC	19881120	105442.1	-51.451	161.719	10	4.8				11	
ISC	19890127	62352.3	-61.205	153.678	10	4.5	4.0			18	
ISC	19890130	210118.1	-60.476	153.274	10	4.6	4.2			21	
ISC	19890421	201315.7	-51.123	161.935	10	4.3				10	
ISC	19890509	153409.2	-52.983	159.540	10	5.2	4.9			77	
ISC	19890517	161255.8	-61.946	154.242	10	4.9	5.4			71	
ISC	19890523	105446.2	-52.371	160.642	10	6.4	8.1			702	
ISC	19890523	133523.6	-51.998	160.161	10	4.9				11	
ISC	19890523	140935.7	-52.050	161.033	10	5.3				80	
ISC	19890523	150455.1	-51.914	161.921	10	4.8				8	
ISC	19890523	151420.6	-51.885	159.143	10	5.0				17	
ISC	19890523	160755.3	-52.103	160.825	10	5.3	5.5			127	
ISC	19890523	162515.6	-52.635	160.467	10	5.1				36	
ISC	19890523	165933.2	-51.422	160.125	10	4.8				11	
ISC	19890523	171142.8	-51.875	160.566	10	5.8	5.9			393	
ISC	19890524	21505.0	-52.144	159.903	10	4.8				62	
ISC	19890524	21658.4	-52.402	160.560	10	5.6	5.3			286	
ISC	19890524	35542.6	-51.965	161.029	10	4.5				7	

ISC	19890524	70011.1	-53.288	159.837	10	4.7	4.5		14
ISC	19890524	74418.3	-52.159	159.593	10	5.1	5.1		94
ISC	19890524	95610.9	-52.079	160.785	10	3.8			9
ISC	19890524	152104.1	-51.806	161.460	10	5.3	4.8		79
ISC	19890524	165651.3	-52.619	160.367	10	4.1			12
ISC	19890524	170046.3	-51.774	161.358	10	4.8			12
ISC	19890524	173020.4	-52.485	159.920	10	4.6	4.3		26
ISC	19890524	234122.5	-52.731	160.544	10	5.0			39
ISC	19890525	5453.3	-52.129	159.789	10	5.6	5.6		358
ISC	19890525	30905.7	-52.626	160.737	10	4.2	4.1		17
ISC	19890525	44311.7	-52.183	160.756	10	5.4	4.8		137
ISC	19890525	93926.0	-52.015	159.985	10	5.3	5.5		206
ISC	19890525	113733.4	-52.192	160.952	10	5.3	5.0		87
ISC	19890526	15416.1	-53.252	159.209	10	5.2	4.5		40
ISC	19890526	61534.4	-51.919	161.212	10	4.6	4.0		5
ISC	19890526	65736.6	-52.698	160.501	10	4.9			28
ISC	19890526	70002.2	-52.485	160.170	10	5.5	5.4		153
ISC	19890526	125618.4	-51.888	161.401	10	5.0	4.9		51
ISC	19890528	15435.1	-53.265	160.306	10	4.4			11
ISC	19890528	32345.2	-51.091	159.683	10	4.8	4.3		31
WYS	19890528	42620.0	-51.290	160.060		4.8			
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ISC	19890531	194859.4	-53.369	159.861	10	5.2	4.0		10
ISC	19890601	72506.2	-52.119	159.525	10	5.2	4.8		103
ISC	19890604	70739.1	-51.878	160.681	10	5.1	4.9		18
ISC	19890604	202946.5	-52.790	160.557	10	5.2	4.6		33
ISC	19890606	140425.0	-53.192	160.026	10	4.8			15
ISC	19890611	122146.9	-51.874	159.567	10	5.2	5.1		98
ISC	19890617	194659.9	-52.380	160.511	10	4.8	4.5		31
ISC	19890621	85819.2	-52.250	160.335	10	5.1	4.7		45
WYS	19890621	172847.0	-53.590	156.740		5.0			
WYS	19890701	21220.0	-51.420	159.450		5.1			
ISC	19890703	170230.2	-53.150	160.197	10	4.8	5.6		45
ISC	19890706	42850.0	-52.095	160.066	10	4.8	4.2		23
ISC	19890707	105019.9	-51.671	161.257	10	4.6	4.6		13
ISC	19890709	105103.6	-52.510	159.526	10	4.8	4.8		37
ISC	19890722	44142.7	-53.246	159.934	10	4.9			6
ISC	19890810	104436.7	-61.887	154.479	10	5.2	5.5		119
ISC	19890813	1551.0	-51.702	161.417	10	5.0	4.6		34

ISC	19890917	54802.3	-61.397	154.060	10	5.4	5.6	121	
ISC	19890918	225238.1	-52.628	160.842	10	4.1		8	
ISC	19890919	54502.9	-52.289	160.060	10	4.4	4.7	16	
ISC	19891015	101808.0	-52.597	160.484	10	5.0		15	
ISC	19891109	194959.8	-52.175	161.082	10	5.0	4.7	29	
ISC	19891109	220534.5	-61.326	154.030	10	5.2	5.1	54	
ISC	19891115	191957.2	-52.339	160.070	10	5.7	5.4	188	
ISC	19891220	15034.6	-52.876	160.478	10	4.9		8	
ISC	19900109	83028.2	-53.178	160.241	10	4.8	4.6	19	
ISC	19900126	64051.9	-52.476	160.000	10	4.4	4.2	8	
ISC	19900217	112415.1	-58.212	158.821	10	3.5		8	
ISC	19900314	100606.2	-53.340	160.000	33	4.7	3.9	13	
ISC	19900509	223819.3	-61.953	161.391	10	4.9	5.7	116	
ISC	19900806	135911.2	-59.174	159.036	10	5.0	4.6	22	
ISC	19900812	30417.5	-59.105	158.810	10	4.8	4.6	32	
ISC	19900917	134726.7	-53.170	159.638	10	5.9	6.0	445	
ISC	19910105	113947.6	-61.522	158.563	10	4.7		14	
ISC	19910114	153030.7	-51.076	162.290	33	4.9		27	
ISC	19910208	224307.8	-61.883	154.516	10	4.7	4.3	19	
ISC	19910211	33527.8	-61.686	158.300	10	4.6	4.4	10	
ISC	19910223	230742.0	-51.624	161.501	10	5.1		43	
ISC	19910701	141527.3	-54.729	158.634	10	4.4		20	
ISC	19910702	175023.8	-51.965	161.527	10	4.1		9	
ISC	19910819	32327.7	-51.085	159.376	10	4.8	4.3	31	
ISC	19910903	130934.5	-53.206	160.081	10	4.6		20	
ISC	19910905	52454.3	-53.425	160.331	33	4.2		13	
ISC	19920121	173416.3	-51.300	160.494	10	4.0	3.9	9	
ISC	19920217	43728.8	-56.032	157.928	10	5.3	5.7	162	
NEIC	19920217	43731.4	-55.979	158.123	33	5.5	5.5		66
ISC	19920222	91538.7	-51.186	159.185	10	4.3	4.2	17	
ISC	19920311	83643.4	-52.801	159.926	10	5.1		71	
NEIC	19920311	83644.7	-52.970	160.091	33	5.2			32
ISC	19920320	235815.7	-52.879	160.316	10	4.3	5.0	35	
NEIC	19920320	235817.6	-52.896	160.526	33	4.6	5.0		21
ISC	19920420	190327.3	-61.156	154.161	10	4.3		9	
ISC	19920503	85414.3	-53.012	161.172	10	3.4		10	
NEIC	19920503	85416.4	-52.969	161.026	33	3.5			8
ISC	19920509	23960.0	-51.840	159.759	12	5.1	4.9	103	
NEIC	19920509	24000.4	-51.773	159.720	10	5.0	4.9		47

ISC	19920511	204344.5	-51.244	160.338	10	4.7		38	
NEIC	19920511	204347.2	-51.269	160.348	33	4.7			23
NEIC	19920530	152655.4	-61.534	161.444	10	4.1			6
ISC	19920530	152656.6	-61.735	161.213	10	4.1		18	
NEIC	19920602	184844.1	-51.432	160.537	10	3.2			11
ISC	19920602	184844.1	-51.435	160.541	10	3.2		11	
ISC	19920615	141647.7	-60.791	153.977	15	5.1	5.2	60	
NEIC	19920615	141650.1	-60.774	154.040	33	5.2	5.1		38
ISC	19920623	230513.2	-61.420	160.760	10	4.3		19	
NEIC	19920623	230513.4	-61.314	161.186	10	4.5			11
NEIC	19920715	111950.4	-58.156	158.305	33	4.3			6
ISC	19920715	111950.7	-58.144	158.229	33	3.2		8	
NEIC	19920807	210549.2	-51.205	160.349	10	4.7	5.4		28
ISC	19920807	210551.0	-51.015	160.350	10	4.3	5.4	41	
NEIC	19920924	181711.0	-61.220	154.359	10	5.5	5.8		89
ISC	19920924	181711.7	-61.221	154.088	10	5.4	5.8	268	
ISC	19920927	2314.3	-52.500	160.595	10	4.2		14	
NEIC	19920927	2315.1	-52.860	159.587	10	4.5			7
ISC	19921104	15927.1	-61.581	154.780	10	5.7	6.2	306	
NEIC	19921130	72522.6	-54.425	158.724	10	4.9		6	
NEIC	19921130	72522.7	-54.425	158.724	10	4.9			6
ISC	19930101	213639.4	-60.959	153.965	10	5.2	5.4	102	
HDR	19930214	101600.2	-57.137	157.760	10	4.5			8
ISC	19930214	101600.6	-57.109	157.769	10	4.4		11	
ISC	19930422	221519.0	-53.169	159.725	10	5.4	5.2	185	
HDR	19930422	221519.0	-53.350	159.394	10	5.5	5.2		71
HDR	19930427	81227.4	-53.975	159.403	10	4.5			21
ISC	19930427	81227.5	-53.988	159.427	10	4.3		27	
ISC	19930519	232511.4	-51.651	162.622	10	4.3		9	
ISC	19930627	202021.4	-52.929	160.875	33	3.9	4.2	17	
HDR	19930627	202021.5	-53.048	161.106	33	4.0			9
HDR	19930804	222920.5	-51.929	160.171	10	4.9			35
ISC	19930804	222920.9	-51.857	160.153	10	4.9	4.1	96	
HDR	19930906	220035.4	-54.867	159.283	33	4.5			9
ISC	19930906	220035.6	-54.873	159.246	33	4.4		14	
ISC	19931107	202423.0	-61.972	154.530	10	4.5	4.9	19	
ISC	19940123	2044.9	-60.699	153.636	10	4.6	5.3	29	
ISC	19940129	191003.3	-56.796	159.044	33	3.7		6	
ISC	19940305	111239.8	-61.247	153.731	10	4.5	5.5	48	

ISC	19940316	94407.2	-51.967	161.148	33	4.2		26
ISC	19940317	185818.6	-52.893	160.586	33	3.4		6
ISC	19940409	60147.0	-58.438	157.911	10	3.6		8
ISC	19940430	170116.2	-54.329	159.162	10	3.4		32
ISC	19941007	170246.0	-59.088	159.067	33	3.6		7
ISC	19941015	64801.3	-58.789	158.359	33	4.7	5.0	82
ISC	19941105	21602.7	-57.252	157.627	18	6.0	6.1	473
ISC	19941105	142509.1	-57.024	157.401	10	4.2		17
ISC	19941123	55650.6	-52.893	160.214	10	5.0	4.7	41
ISC	19950307	110715.2	-58.261	157.868	0	3.9		9
ISC	19950502	235245.0	-60.455	153.564	10	5.1	5.8	205
ISC	19950621	152851.1	-61.749	154.554	10	5.7	6.7	431
ISC	19950829	181855.0	-59.593	153.626	33	4.0		9
ISC	19950904	12907.2	-59.673	154.453	0	3.9		8
ISC	19950924	191449.4	-58.357	162.116	10	4.4		11
ISC	19951001	181453.7	-56.506	158.176	10	4.0		15
ISC	19951001	182947.2	-56.474	158.086	10	4.5		31
ISC	19951006	183942.3	-55.051	158.610	10	4.7		31
ISC	19951013	152224.9	-58.870	158.218	14	5.6	5.8	470
ISC	19951014	4756.6	-58.380	161.955	33	4.3		16
ISC	19951017	22238.0	-61.266	159.635	10	4.1		12
ISC	19951222	134038.0	-61.306	153.452	10	4.4	5.5	35
ISC	19951226	95559.4	-59.231	158.941	0	3.8		12
ISC	19960111	202052.9	-58.709	158.415	29	4.1		27
ISC	19960118	200207.7	-58.245	157.835	19	5.3	5.2	198
ISC	19960127	84931.3	-59.203	158.682	0	4.1		17
EIDC	19960206	125709.7	-51.910	159.020	0	3.9		3
EIDC	19960206	130952.9	-54.590	158.900	0	3.8		3
ISC	19960206	222819.1	-51.015	160.488	77	3.7		19
ISC	19960308	182531.9	-57.891	157.929	19	4.3		28
EIDC	19960317	84647.9	-61.840	155.140	0	3.9		4
ISC	19960510	160130.7	-61.739	160.917	10	4.5		30
ISC	19960528	82626.4	-61.805	154.427	20	4.4		43
ISC	19960528	222222.2	-61.036	161.921	33	4.2		9
ISC	19960606	194744.2	-61.961	162.674	41	4.3		50
ISC	19960729	94722.9	-60.176	159.319	10	4.5		31
ISC	19960905	60210.0	-56.144	157.777		4.3		21
ISC	19961022	105125.8	-60.899	154.036	10	4.8		41
NEIC	19970409	165013.8	-60.980	160.916	10	4.1		7

ISC	19970511	93333.9	-57.103	157.557	10	4.8	4.2				78
EIDC	19970605	130939.2	-61.287	154.483	0	4.1					3
ISC	19970606	84045.6	-57.590	157.818	10	4.7	5.0				86
EIDC	19970702	20524.5	-54.998	158.059	0	4.0	4.4				3
EIDC	19970702	83617.6	-53.467	159.878	0	3.8	3.4				5
EIDC	19970811	15630.0	-61.853	158.916	0	3.7		4.4	EIDC		3
ISC	19970905	5122.4	-61.170	159.446	10	4.0	4.1				8
EIDC	19971026	102047.9	-57.647	160.963	0	3.8					
EIDC	19971125	75824.1	-60.096	153.176	0	3.7					
ISC	19971127	173048.4	-61.854	155.663	10	4.3	4.2				14
QED	19980616	93512.3	-52.906	160.011	10	4.9	5.7			6.2	
QED	20000101	55819.7	-60.779	153.648	10	5.5	5.6			6.0	

Seismic Parameters:

Source : contributing agency
Date : date of earthquake
UTC : Universal Coordinated Time
Lat : decimal latitude
Long : decimal longitude
Depth : focal depth in km
mb : body wave magnitude
Ms : surface wave magnitude
MD : duration magnitude
MN : Nuttli magnitude
ML : local magnitude
auth : agency that assigned the magnitude
unsp : unspecified magnitude
Mw : moment magnitude
obs : number of observations
stat : number of stations

Appendix 5

Seafloor Sample Database

These samples are taken from published sources, and may not represent the full complement existing in the region. Their distribution for the Hjort region study area is shown on Figure 13.

"Site" is generally indicative of both vessel (also found under "Alias"), survey number and actual site number on survey.
"Depth" is in metres.
"Type" is a generalised sample description.

Site	Device	Alias	Latitude	Longitude	Depth	Report*	Recovery	Type	Short Description
Eltanin 16-4-1	Piston Core		-55.6000	160.2000	691.9	1	1280cm	Sand	Sand, foraminiferal
Eltanin 16-5-1	Piston Core		-56.0833	159.0833	641.6	1	300cm	Sand	Ooze, diatomaceous
Eltanin 16-6-1	Piston Core		-58.9833	161.9167	772.7	1	817cm	Mud	Ooze, diatomaceous
Eltanin 27-24-1	Piston Core		-59.0867	157.0483	516.6	1	576cm	Mud	Ooze, siliceous, foraminiferal
Eltanin 27-26-1	Piston Core		-54.4950	158.9733	5.2	1	240cm	Sand	Sand
XXVII	Unknown	AAE[1]	-53.7500	158.2000	1463	2		Mud	Diatom ooze
XXXIV	Unknown	AAE[1]	-53.1333	157.0050	4498.8	2		Mud	Gloigerina ooze
LXIV	Unknown	AAE[1]	-54.3667	157.3333	3986.8	2		Rock	Quartz pebble encrusted with iron
LXVII	Unknown	AAE[1]	-58.3250	155.6500	3657.6	2		Rock	Pebble with Foraminifer attached
Eltanin 34-4	Piston Core		-60.2500	159.8833	520.6	2	389cm	Mud	Mud, sandy, diatom, radiolaria, Mn nodules
Eltanin 34-5	Piston Core		-57.3883	159.9933	632.5	2	1233cm	Mud	Ooze, radiolaria, sandy, spicules
Eltanin 36-29	Piston Core		-53.0000	155.1667	650.8	2	500cm	Mud	Mud, radiolaria, diatom, spicules
Eltanin 36-30	Piston Core		-54.0667	155.0000	681.2	2	577cm	Mud	Ooze, diatom, radiolaria, muddy, spicules
Eltanin 36-31	Piston Core		-55.0000	155.0000	711.7	2	493cm	Mud	Ooze, diatom, spicules, radiolaria
Eltanin 36-32	Piston Core		-56.8833	155.0000	606.6	2	450cm	Mud	Ooze, foram, radiolaria, spines, diatom
Eltanin 36-34	Piston Core		-60.0000	155.0417	465.7	2	609cm	Mud	Ooze, spicules, radiolaria, foram, diatom, sandy
Eltanin 36-35	Piston Core		-62.7517	154.9817	582.2	2	588cm	Mud	Mud, diatom
Eltanin 36-36	Piston Core		-60.3883	157.5333	469.4	2	597cm	Mud	Ooze, spicules, diatom, foram, radiolaria
Eltanin 36-37	Piston Core		-58.6667	159.5167	646.2	2	525cm	Sand	Sand, foram, radiolaria

Eltanin 36-38	Piston Core		-56.4667	161.7583	688.2	2	1209cm	Mud	Ooze, mud, spicules, radiolaria, diatom, foram
Eltanin 37-1	Piston Core		-58.2000	157.5000	944.9	2	102cm	Mud	Ooze, diatom, spicules, radiolaria
Eltanin 44-7	Piston Core		-53.0533	158.2167	554.7	2	862cm	Mud	Ooze and mud, foram, radiolaria, sandy, diatom
Eltanin 44-9	Piston Core		-53.5017	163.5217	448.1	2		Rock	Mn nodules
Eltanin 44-11	Piston Core		-56.0600	160.7517	734.6	2	1059cm	Mud	Ooze and sand, foram, radiolaria, diatom
DSDP 278	Drill Site		-56.5570	160.0715	3708	4	277.8m	Mud	Brown-grey foraminiferal-bearing diatom ooze
V16-118	Piston Core	Vema	-52.8667	158.8833	4306	3	0.4m	Mud	Mn nodules, ooze
V16-119	Piston Core	Vema	-52.8583	158.9167	4338	3	7.85m	Mud	Mn nodules, ooze
C8-69	Piston Core	Robert Conrad	-53.4833	155.6167	4303	3	1.7m	Mud	Diatom ooze
C8-70	Piston Core	Robert Conrad	-58.0500	155.7833	3301	3	10.5m	Mud	Calcareous ooze
Sample 1	Dredge	FVAL	-54.5717	158.7510	1150	5		Rock	Calcarenite with basalt debris
1/84, Leg 2	Dredge	HMAS Cook	-47.8333	164.7833		5	1.4kg	Rock	Basalt
SO136-100	Gravity Core	RV Sonne 1998	-56.4587	162.6030	5009	6	6.26m	Mud	Siliceous oozes
SO136-111	Gravity Core	RV Sonne 1998	-56.6810	160.2415	3912	6	9.61m	Mud	Siliceous oozes
SO136-117	Gravity Core	RV Sonne 1998	-55.6667	159.4177	4460	6	10.69m	Mud	Siliceous oozes
SO136-110	Box Corer	RV Sonne 1998	-56.6812	160.2477	3907	6	33.5cm	Mud	Foraminifers bearing diatom/radiolarian ooze
SO136-116	Box Corer	RV Sonne 1998	-55.6672	159.4167	4450	6	36cm	Mud	Foraminifers bearing diatom/radiolarian ooze

[1] Australian Antarctic Expedition (1911-1914)

* Sources from which descriptions are taken and to which further referral can be made:
1. USNS Eltanin. Core Descriptions Cruises 32 - 45. Antarctic Core Facility, Department of Geology, Florida State University. BASE S55 (26) USN.69
2. Australian Antarctic Expedition (1911-1914). Scientific reports series A, vol. II oceanography. Part I: sea-floor deposits from soundings by F. Chapman, Assoc. Linn. Soc., Lond., F.R.M.S. (palaeontologist to the National Museum, Melbourne, Hon. palaeontologist to the Geol. Survey, Victoria. Base S5 (99) AUS AMG).
3. Pleistocene Manganese Pavement Production: Its Relationship to the Origin of Manganese in the Tasman Sea. Robert R. Payne and John R. Conolly.
4. Initial Reports of the Deep Sea Drilling Project. Volume 14, 1975.
5. Phil O'Brien, c/- Geoscience Australia, Canberra, Australia.
6. Geomar Report. FS Sonne Cruise Report SO136. TASQWA. Quaternary Variability of Water Masses in the Southern Tasman Sea and the Southern Ocean (SW Pacific Sector) Wellington - Hobart, October 16 - November 12, 1998.

Appendix 6

Glossary of terms used

Many of these definitions are taken from *Marine Geology*, by James Kennett, which is a standard text on marine geology and seafloor processes.

ACC: Antarctic Circumpolar Current, the world's most voluminous ocean current, which flows clockwise on its circumnavigation of Antarctica.

AEEZ: Exclusive Economic Zone (see *EEZ* below) about Australian territory.

Acoustic: a sonar signal travelling at the speed of sound in the respective medium.

Accretionary Prism: general wedge-shaped mass of tectonically deformed sediments at a subduction zone formed by the tectonic transfer of strata from the descending plate into the body of the overlying plate.

Anastomosing: branching and rejoining irregularly to produce a net-like pattern.

Antarctic Bottom Water: An important formation of cold, highly saline water produced in the large embayments of Antarctica and flowing north, at great depths, as far as the northern hemisphere mid-latitudes of the Pacific and Atlantic oceans.

Arcuate: a linear feature bent or curved.

Arc/INFO™: trademark product of Environmental Systems Research Institute (ESRI) able to perform a large suite of Geographical Information System (GIS) directed activities.

ArcView™: trademark product of Environmental Systems Research Institute (ESRI) able to perform a large suite of Geographical Information System (GIS) directed activities.

Basalt: fine-grained volcanic rock rich in ferromagnesian minerals. The compositional equivalent to gabbro and dolerite. Forms the upper layers of oceanic crust and so the seafloor interface.

Breakup: the point at which extensional rifting of continental crust results in the appearance of volcanic and igneous material (ie oceanic crust) along an extensive lineament and the commencement of continental drift between the opposing sides.

Conjugate (margins): usually refers to two margins facing each other across an ocean basin, which were once joined prior to continental breakup and subsequent seafloor spreading.

Contour currents: ocean bottom-water circulation, which often follows depth contours. Stratification in the water column tends to force the currents along contours rather than up and over topography. They are best developed in areas of steep topography, especially at the continental margins where the bottom topography extends through the greatest thickness of the water column.

Contourites: sediments deposited by contour currents, which have thin beds defined by sharp contacts and are well laminated, sorted and graded.

Debris flows: gravity-induced, down-slope movements of mixtures of coarse and fine debris and water, resembling the flow of wet concrete.

Dextral: right-handed, or to the right.

Distal: generally something formed distant to its source.

Dolerite: medium-grained igneous rock, which is the compositional equivalent of basalt and gabbro. They often occur as dykes and sills.

Ductile: the ability to maintain strength under a small degree of strain.

Dyke Swarm: high concentration of similar-trending dykes.

Earthquake foci: the sub-surface point from which seismic waves produced by an earthquake originate. The point above, on the earth's surface, is known as the earthquake's epicenter.

EEZ: the Exclusive Economic Zone refers to the marine zone within a 200 nautical mile radius of a coastal state's baseline where the coastal state has complete jurisdiction over the resources of the water column, seabed and subsoil.

En echelon: geologic features that are in an overlapping or staggered arrangement. Each is relatively short, but collectively they form a linear zone, in which the strike of the individual features is oblique to that of the zone as a whole.

Ensonify: process of directing sonar energy onto a surface.

Eocene: geological epoch of the Tertiary period, extending from about 55 to 34 million years in the past.

Facies: The sum total of features such as sedimentary rock type, mineral content, sedimentary structures, bedding characteristics and fossil content, which characterise a sediment as having been deposited in a given environment.

Flood Basalt: thick widespread stratiform sheets of extruded basaltic lava, usually across continental surfaces.

Focal Mechanism: description of type of movements between rocks during an earthquake.

Forearc: region between a subduction-related trench and a volcanic arc.

Forearc Basin: sedimentary basin, usually elongate, lying between the volcanic arc and the shelf break in a convergent plate boundary zone. It is parallel to the arc and closer to it than to the trench-slope basin and the trench.

Fumarole: A vent or fissure, usually volcanic, from which gases and vapors are emitted.

Gabbro: coarse-grained igneous rocks the compositional equivalent to basalt. Comprises the deeper rock layers of oceanic crust.

Guyot: flat-topped seamount usually caused by erosion at the sea surface.
Hot spot: oceanic volcanoes sourced by a magma source beneath the crust in the upper mantle. Generally associated with a lineament of volcanoes representing the direction of plate motion over the stationary volcanic source.

Hydrothermal deposit/mineralisation: mineral deposit formed by precipitation of minerals in fractures, breccia openings, or other spaces, by replacement from aqueous fluids of high temperature and pressure.

KHz: unit of one thousand hertz, referring to the frequency of the respective transmitted signal.

Kinematics: that part of structural and tectonic analysis that deals with the movements that occur during deformation. These movements include rigid-body translation and rotation, and non-rigid movements of distortion and dilation. Commonly refers to movements associated with the Earth's tectonic plates.

M: the term for nautical mile, a unit of distance (1852 m) used primarily in navigation and adopted by the International Hydrographic Organisation.

Ma: millions of years before the present.

Mafic: usually applied to igneous/volcanic rocks containing high quantities of ferromagnesian minerals. *Ultramafic* rocks contain even higher proportions.

Manganese seafloor deposits: the accumulation at the seafloor of primarily manganese, but also iron, copper, nickel and cobalt. These elements are precipitated out of the water column and accrete in an oxidised state as nodules, crusts or thin coatings on rocks. In many areas of the seafloor they exist as pavements of nodules and are in sufficient quantities and of sufficient economic importance to make them of great current interest. Although prevalent at the seabed interface they also exist as buried deposits where sediment accumulation is great.

Miocene: geological epoch of the Tertiary period, extending from about 24 to 5 million years in the past.

Multibeam: the technology of having multiple acoustic transducers spread athwartship so that a swath-like portion of seafloor is acoustically ensonified at each instant of sonar transmission.

Ophiolite: volcanic sequences representing sections of oceanic crust and upper mantle created at mid-oceanic spreading ridges and later uplifted at convergent boundaries.

Patagonian toothfish: fish species *Dissostichus eleginoides* occurring around most sub-Antarctic islands and submarine plateaux. They grow to over 2 m length and 100 kg in weight, and are predatory, feeding mainly on mid-water fish and squid as well as benthic animals.

Peridotite: mantle-derived rock containing high amounts of ferromagnesian minerals.

Pole-of-rotation: imaginary axis point about which a rotation of a plate defines its motion relative to another adjoining plate.

Seamount: large conic-like submarine volcanoes rising above the abyssal floor. Are called guyots if its top is planated.

Sedimentology: the physics and chemistry of sediments and sedimentary rocks. Refers to sediment grain characteristics, mineral composition and a suite of other parameters indicative of the depositional environment.

Sequence Stratigraphic Boundary: boundaries in sedimentary rocks separating different sequences defined by relatively continuous periods of deposition.

Serpentinized: hydrothermal alteration of ferromagnesian rocks, thereby producing the mineral serpentinite.

South Tasman Rise: large elevated section of seafloor south of Tasmania cored by continental rock. Formed as a result of Australian-Antarctic separation.

Spreading fabric: the alternating ridge-valley morphology developed on bare oceanic crust as a result of its formation along linear mid-ocean spreading centres.

Strike-slip: horizontal component of motion along a large-scale fault, termed right-lateral if the opposing side's relative motion is to the right and vice versa for left-lateral motion.

Subduction: the tectonic process whereby a segment of lithosphere is inserted partially or totally beneath another, adjacent one.

Teleseismic: referring to earthquakes.

Terrane: informally refers to a region where a particular rock or group of rocks predominates.

Thermohaline: refers to ocean water circulation that is density-driven.

Tholeiite: basalts marked by about 50 % silica and high alumina content.

Transpression: tectonic strike-slip motion with a component of compression between the opposing segments of crust.

Transtension: tectonic strike-slip motion with a component of extension between the opposing segments of crust.

Turbidites: the sediments deposited by turbidity currents, which are marked by graded bedding, moderate sorting and well-developed primary structures.

Turbidity currents: short-lived, powerful, gravity-driven currents consisting of dilute mixtures of sediment and water of density greater than the surrounding water, the motion of which is maintained by internal turbulence.

UNCLOS: acronym for the *United Nations Convention on the Law of the Sea*, a 1982 treaty providing for the means to define and regulate a coastal state's marine jurisdiction. Australia ratified it in 1994, thereby giving it until 2004 to justify its relevant claim. See Appendix 2.

Volcanic Arc: the linear front of volcanoes forming inland of a trench along a subduction zone.

Volcanogenic: marine sediments of volcanic origin.

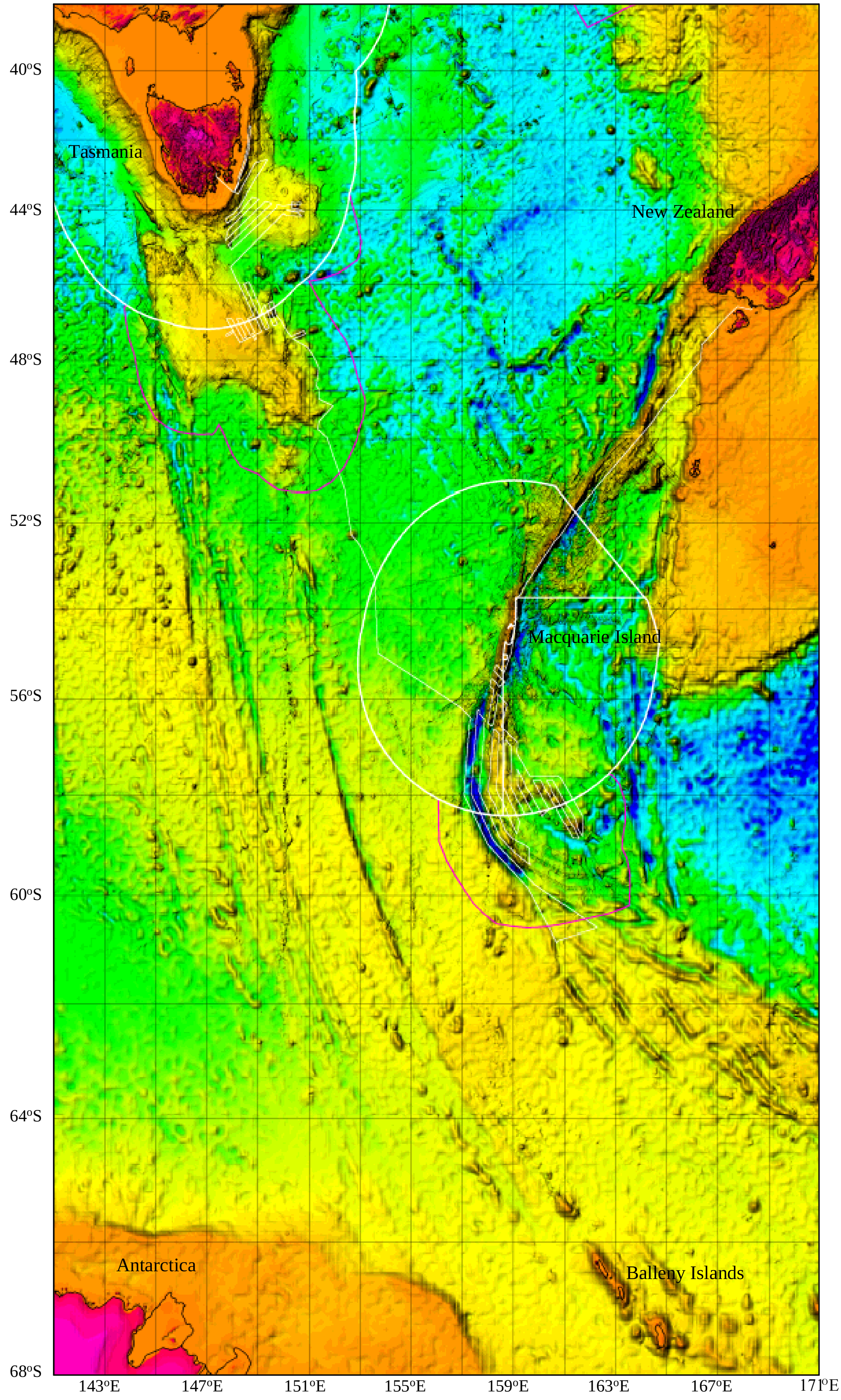


Figure 1. Regional hill-shaded view of terrain showing AUSTREA-2 survey coverage. The 200 M Australian Exclusive Economic Zone (white), Macquarie Island Marine Park (white) and pre-existing extended Continental Shelf limits (magenta) are also shown. The projection on this, and all following figures employing hill-shaded views of terrain, is Mercator.

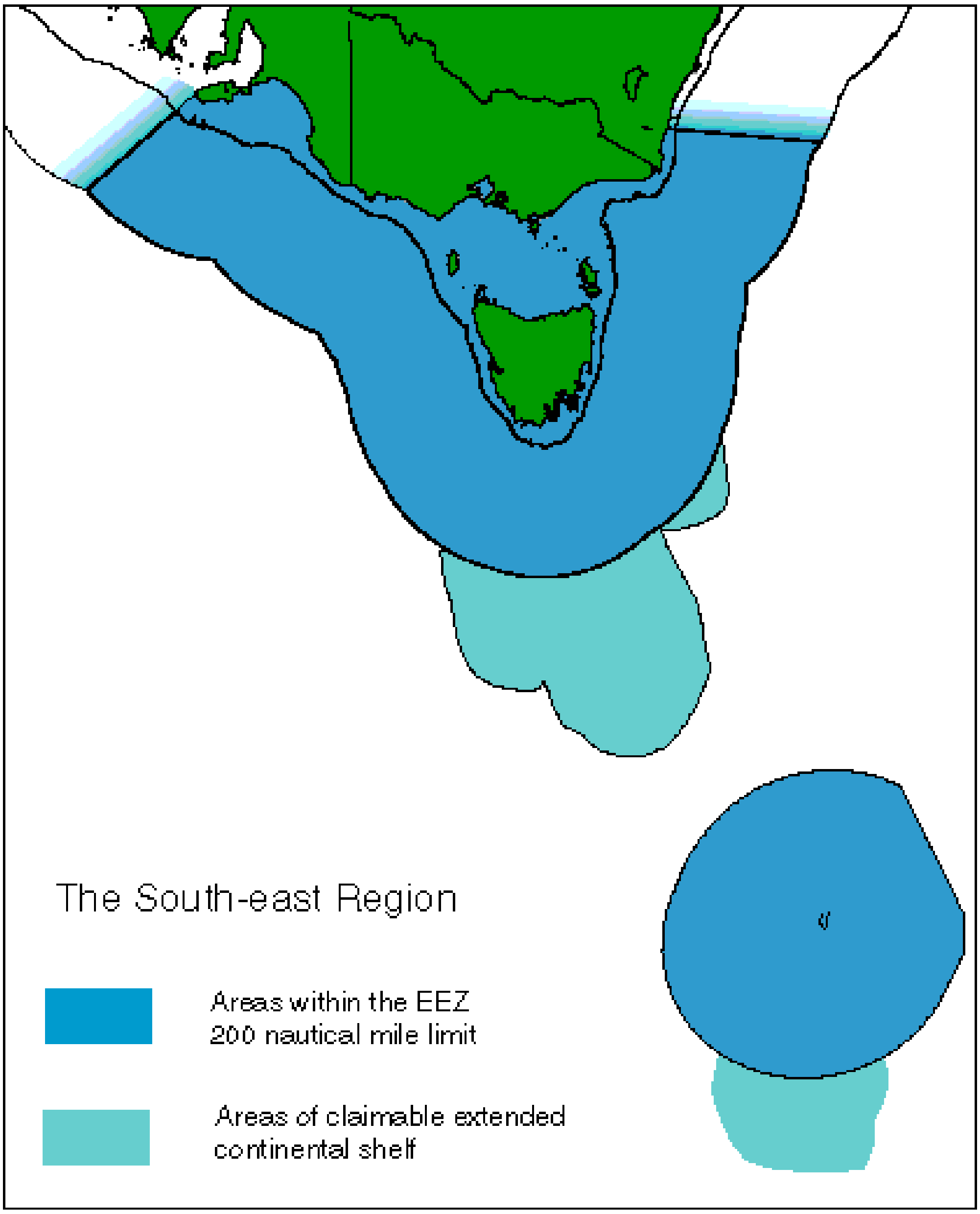


Figure 2. Location of the South-east Marine Region that will be the focus of the first regional marine planning process. After the National Oceans Advisory Group (2000).

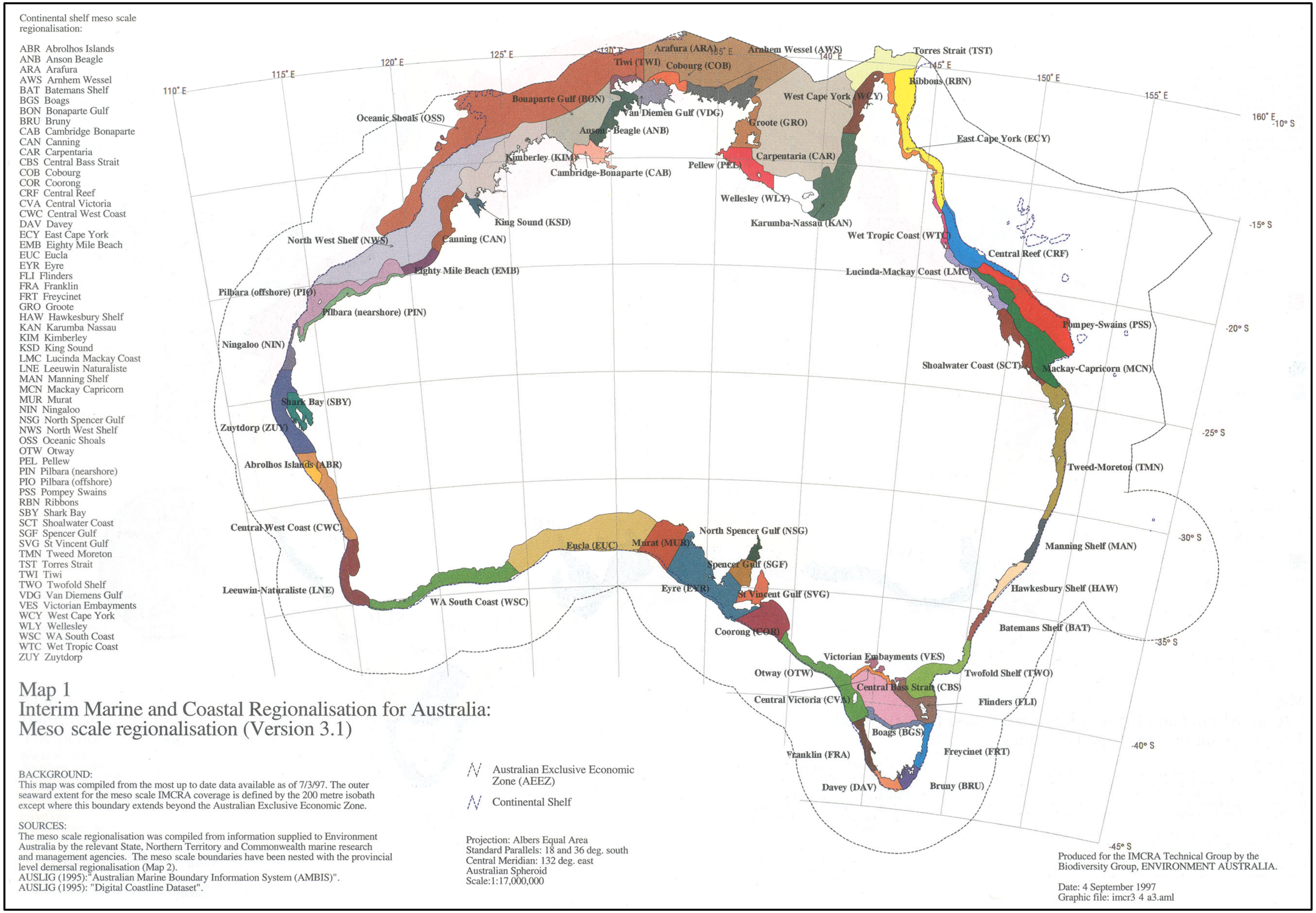


Figure 3. Map showing the continental shelf meso-scale regions for Australia (taken from IMCRA, 1997).

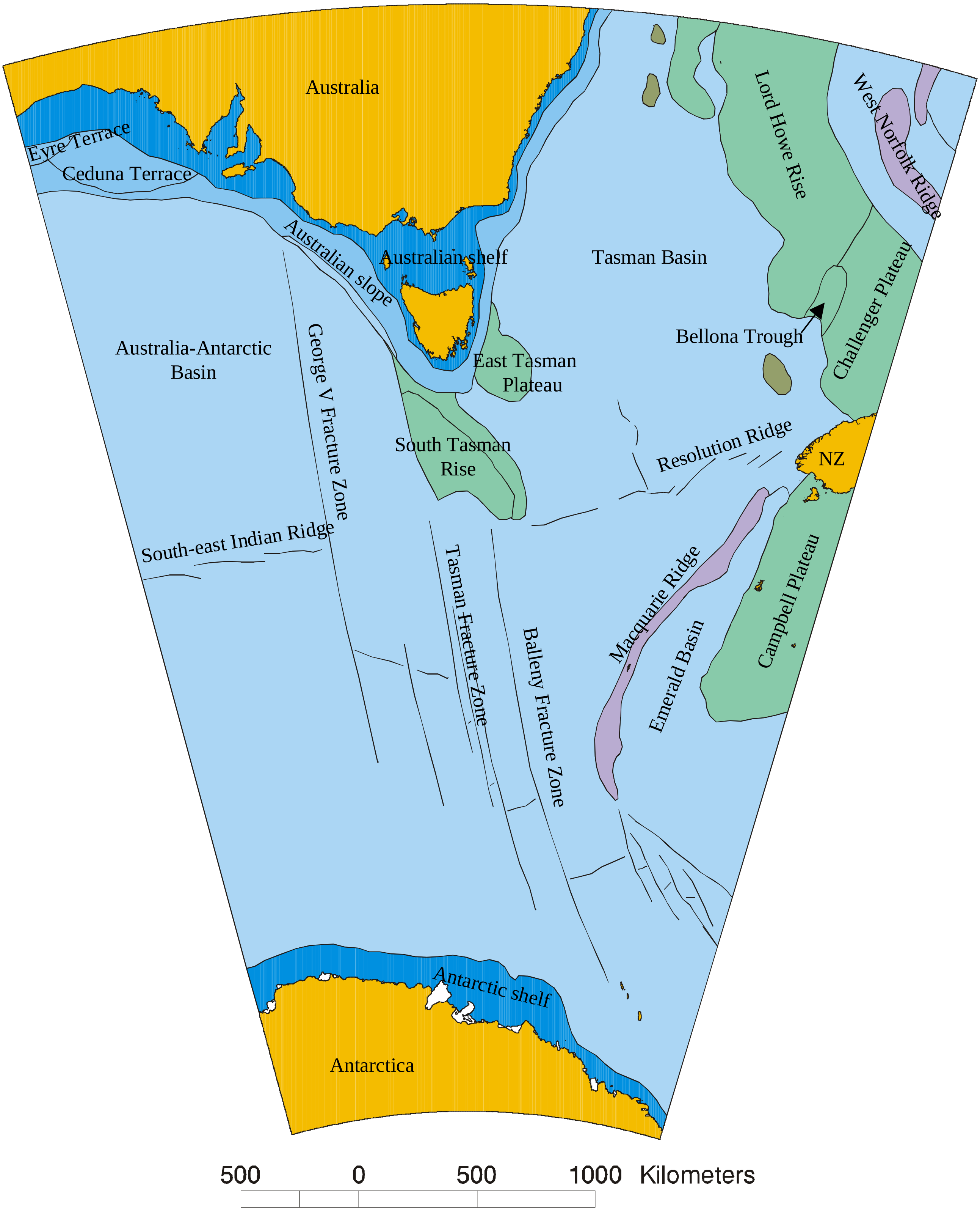


Figure 4. Physiographic provinces map of the South-east Region.

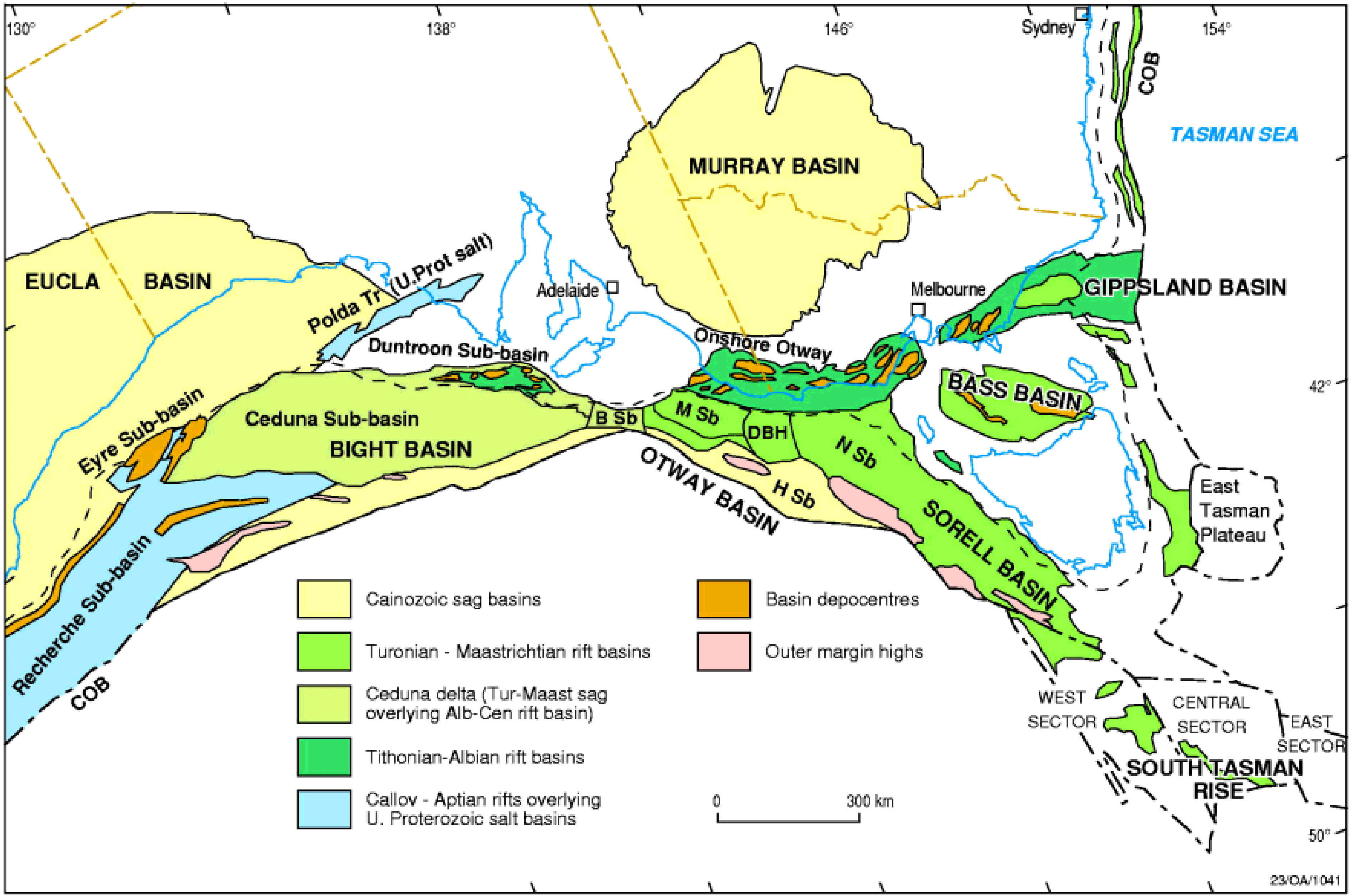


Figure 5. Structural elements of the southern and southeastern margins of Australia showing the distribution of Early and Late Cretaceous rift basins. COB - continent-ocean boundary; B Sb - Beachport Sub-basin; M Sb - Morum Sub-basin; DBH - Discovery Bay High; N Sb - Nelson Sub-basin; H Sb - Hunter Sub-basin. After Moore et al. (2000).

a.

b.

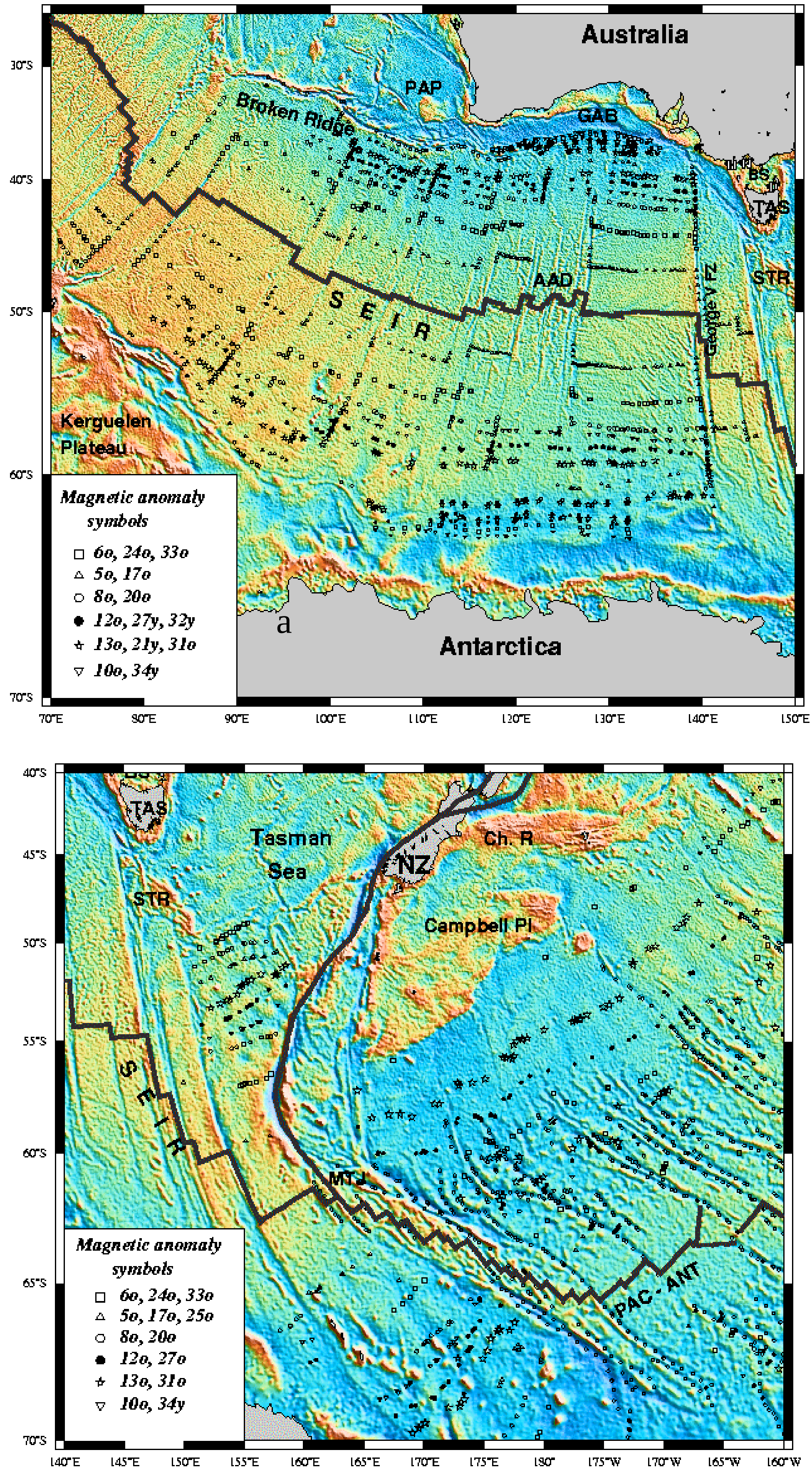


Figure 6. Gravity anomalies from satellite altimetry overlain by seafloor spreading magnetic anomaly and fracture zone identifications for (a) the region between Australia and Antarctica and (b) the Macquarie Ridge region. After Müller (2000).

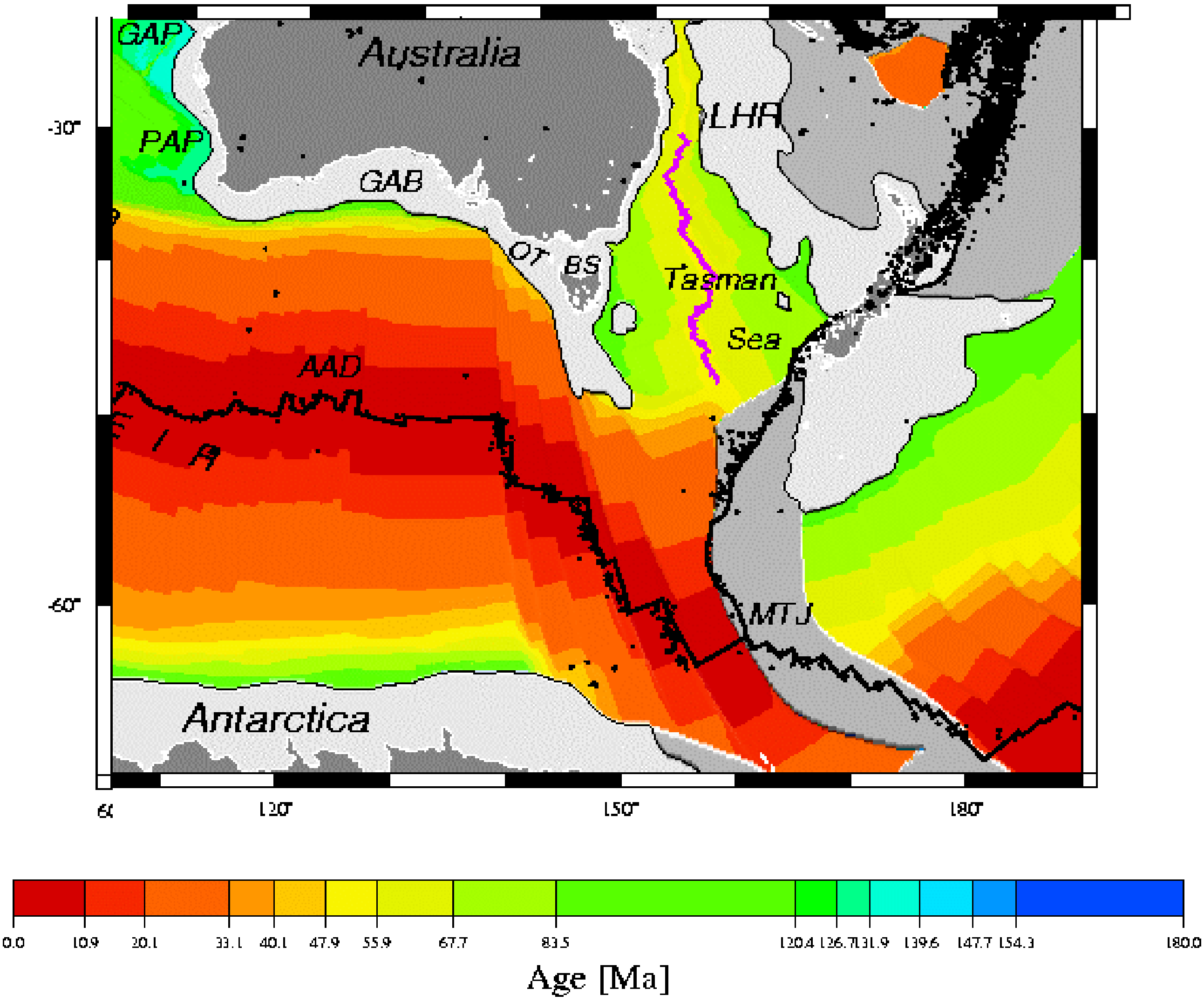


Figure 7. The age of the ocean floor off southern and eastern Australia. Shows extinct (pink line) and active (black line) seafloor spreading ridges and earthquakes (black dots). GAP - Gascoyne Abyssal Plain; PAP - Perth Abyssal Plain; GAB - Great Australian Bight; OT - Otway Basin; BS - Bass Strait; LHR - Lord Howe Rise; SEIR - South East Indian Ridge; AAD - Australian-Antarctic Discordance; MTJ - Macquarie Triple Junction. Modified from Müller et al. (1997).

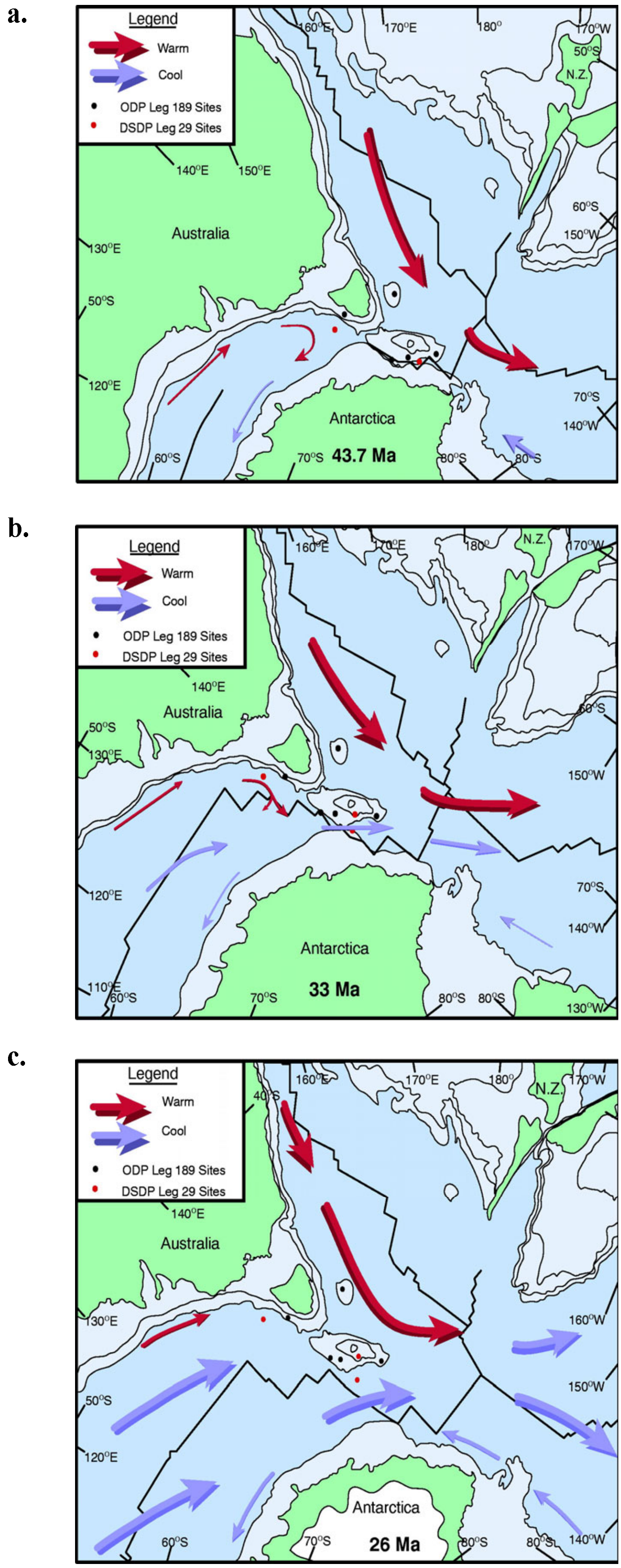


Figure 8. Plate reconstructions of the Australian-Antarctic region at 43.7, 33 and 26 million years modified from Cande et al. (2000). Shows the inferred surface-water circulation of the Australian -Antarctic region from the (a) middle Eocene (43.7 Ma) with the Tasmanian Gateway closed; (b) earliest Oligocene (33 Ma) with the Gateway starting to open; and (c) late Oligocene (26 Ma) with the Gateway open and expansion of the Antarctic Circumpolar Current. After Shipboard Scientific Party (2000).

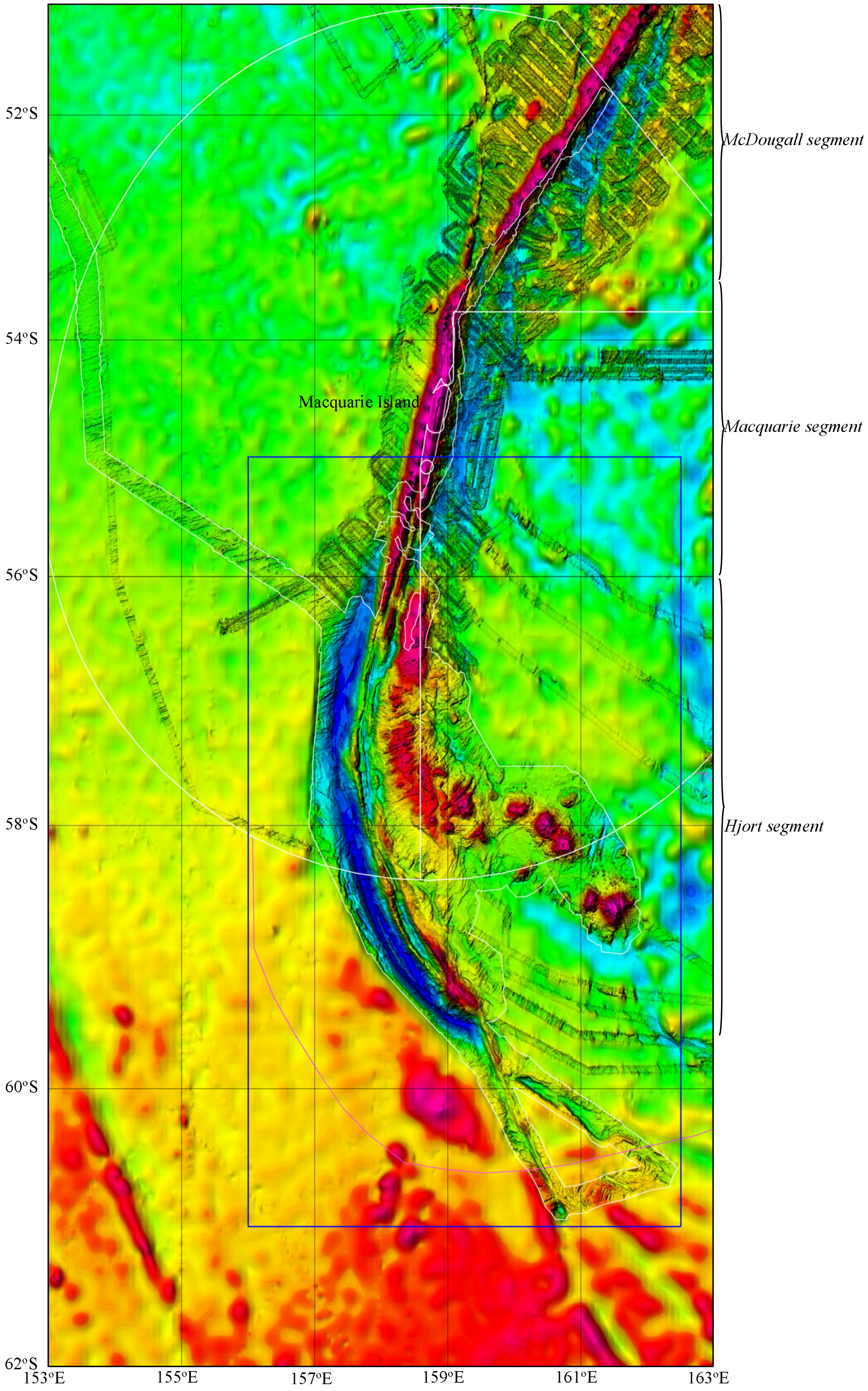


Figure 9. Hill-shaded view of terrain for the central and southern Macquarie Ridge region. Image represents merge of predicted bathymetry and swath bathymetry from AUSTREA-2, AGSO Survey 124 in the north and sparse tracks of R/V Ewing. The study area is shown by the blue box and the coverage of the AUSTREA-2 survey by the white polygon. The 200 M Australian Exclusive Economic Zone (white), Macquarie Island Marine Park (white) and pre-existing extended Continental Shelf limits (magenta) are also shown. Indicated segments refer to descriptive partitioning of the entire Macquarie Ridge Complex - Puysegur segment to the north not shown.

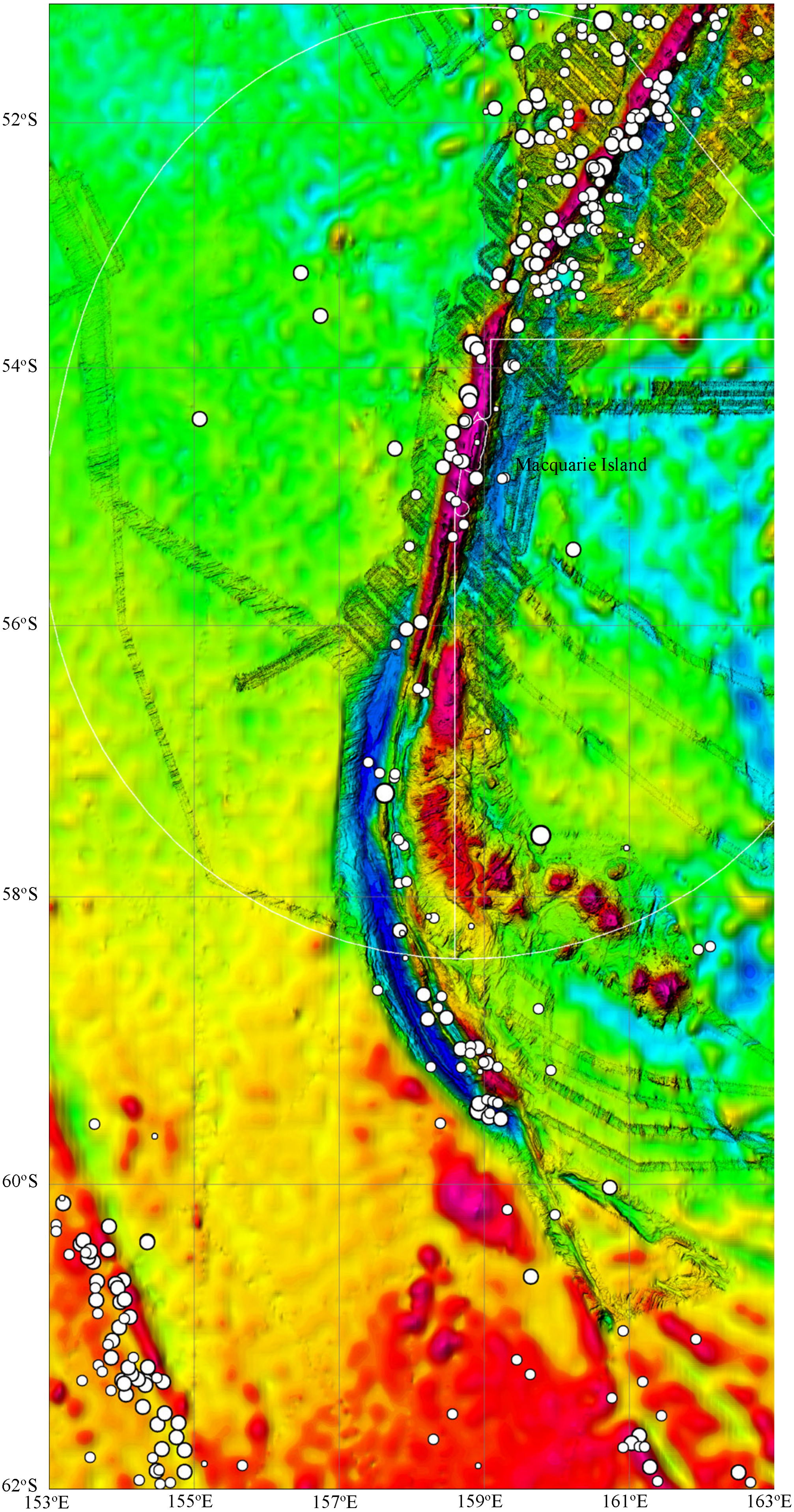


Figure 10. Hill-shaded view of terrain for the central and southern Macquarie Ridge region with earthquake epicentres (Appendix 4) marked as filled circles. Smallest to largest circles represent magnitudes less than 4, between 4 and 5, between 5 and 6 and greater than 6, respectively.

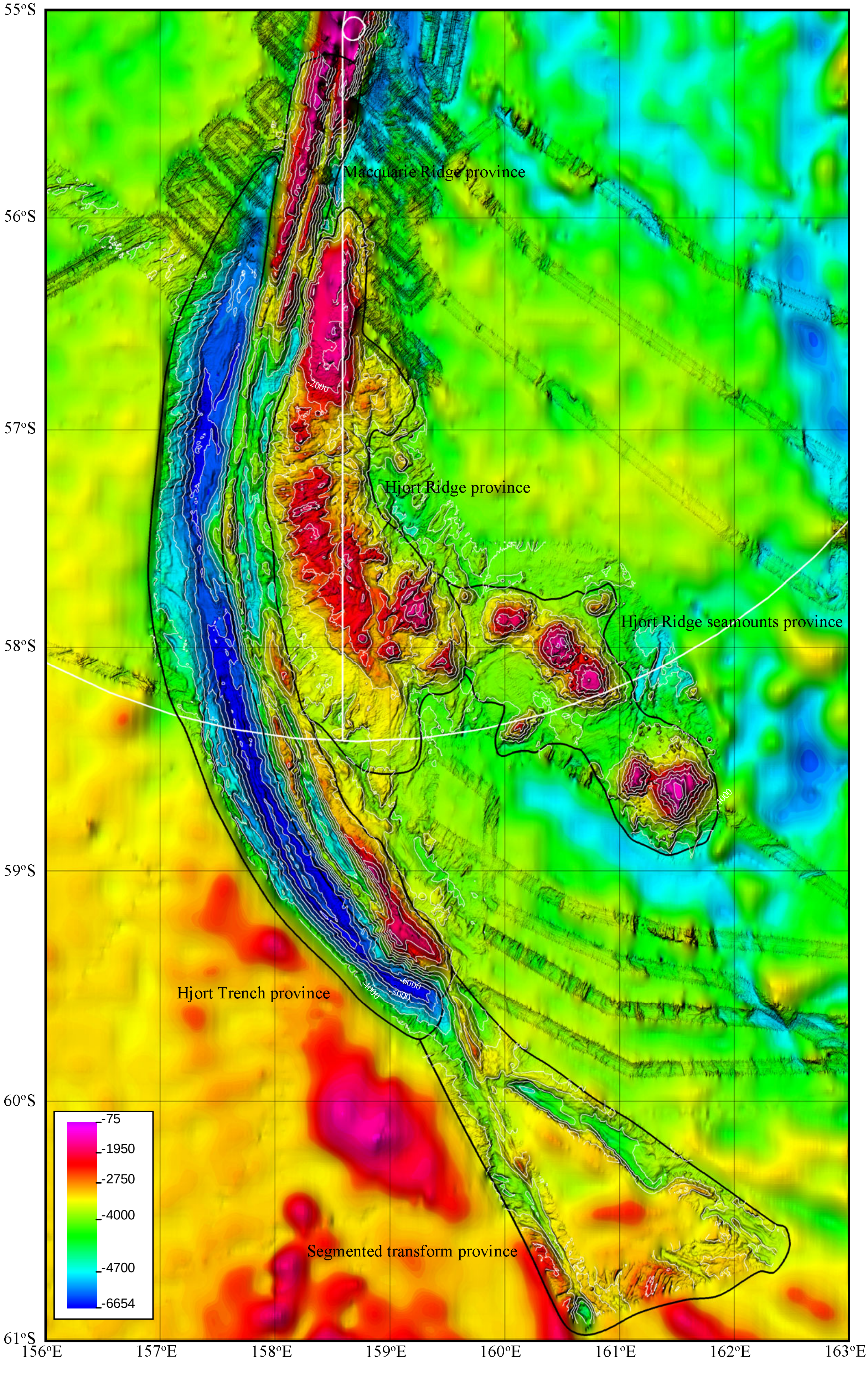


Figure 11. Hill-shaded view of terrain in the Hjort region study area. Black polygons represent subdivision of newly swath-mapped seafloor into physiographic provinces. Bathymetric contour (white) interval is 500 m and colour bar represents depth range in metres. The AEEZ (white) and the Macquarie Island Marine Park (white) are also shown on this and following maps.

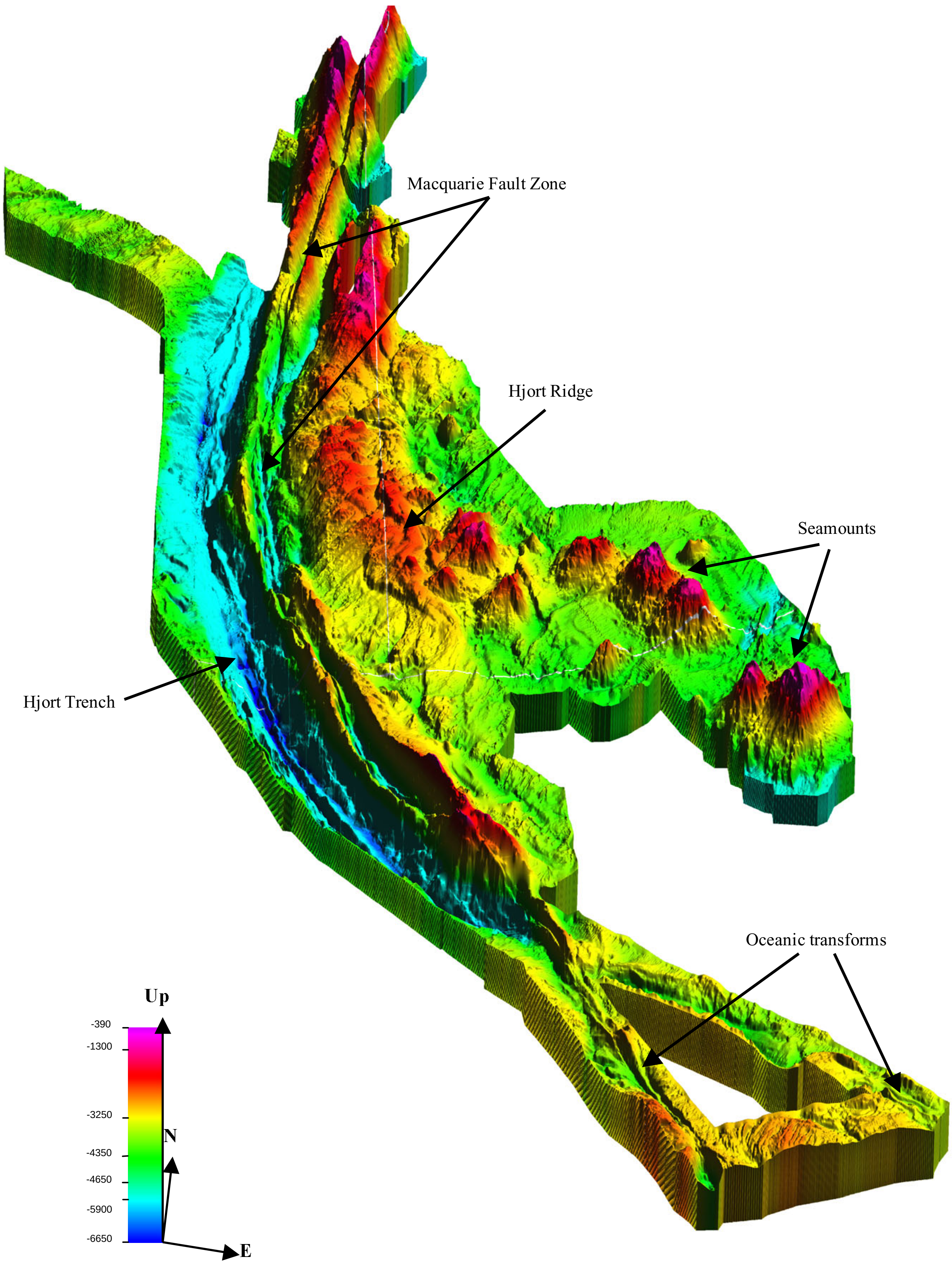


Figure 12. 3D perspective view from the south of the newly swath-mapped seafloor in the Hjort region study area. The AEEZ (white) and the Macquarie Island Marine Park (white) are shown draped over the seafloor. Colour bar represents depth range in metres.

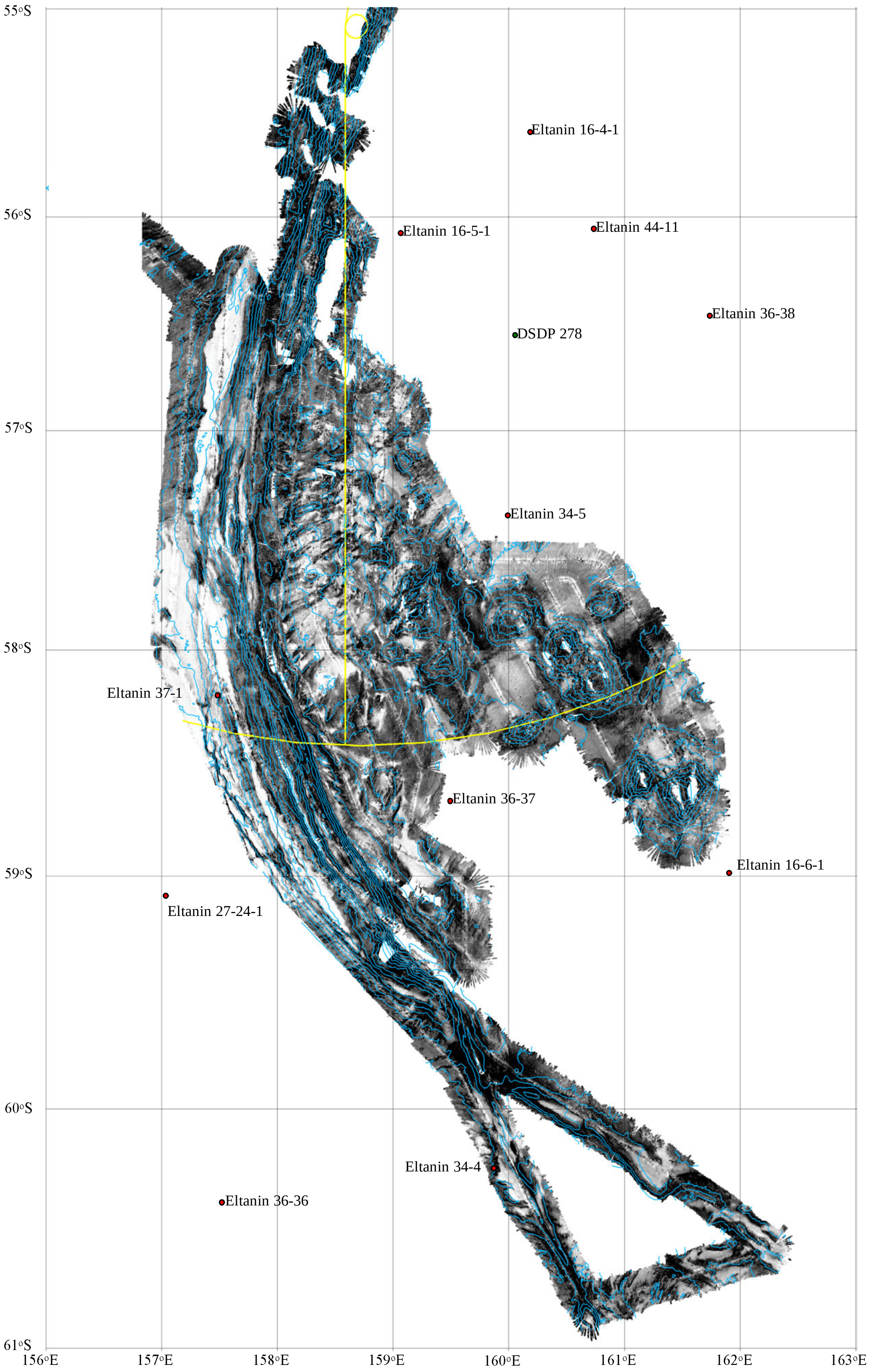


Figure 13. Seafloor backscatter for the Hjort region study area. Seafloor sample sites and Deep Sea Drilling Project site are also indicated (see Appendix 5). Bathymetric contour (blue) interval is 500 m.

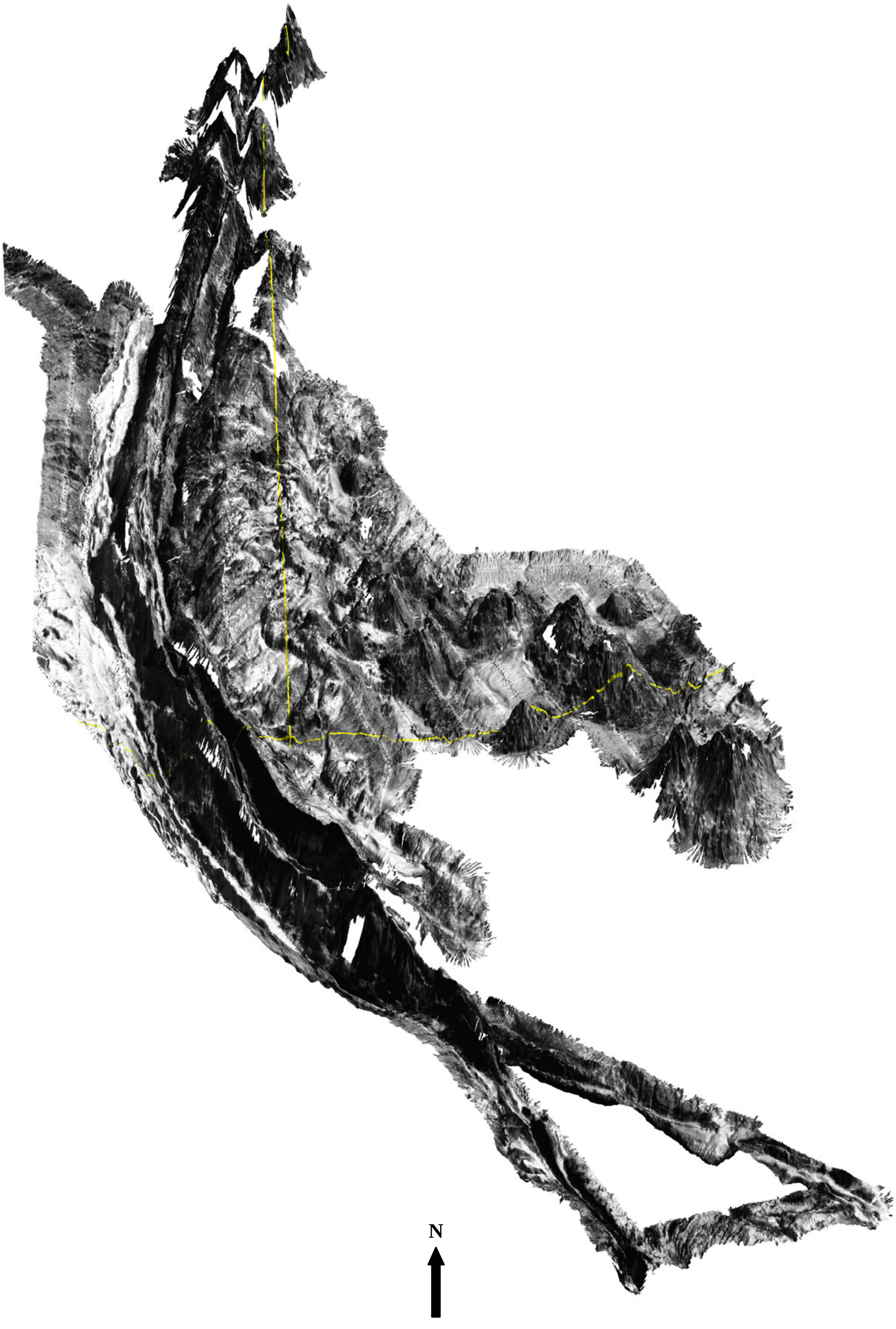


Figure 14. 3D perspective view from the south of the newly-mapped seafloor backscatter in the Hjort region study area. The backscatter signal is draped over swath bathymetry. Also shows the AEEZ (yellow) and the Macquarie Island Marine Park (yellow) draped over the seafloor.

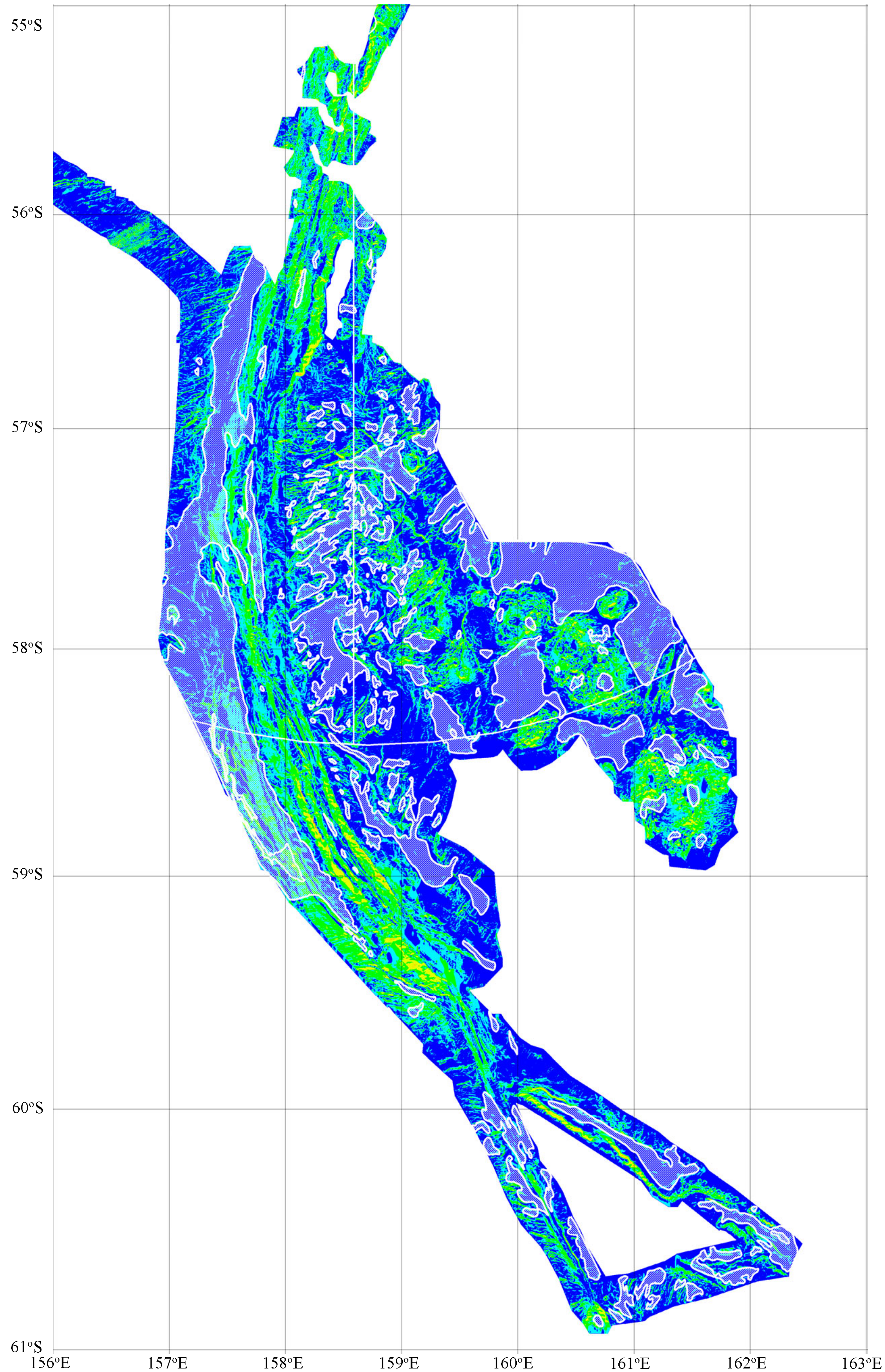


Figure 15. Terrain slope image of the newly-mapped seafloor in the Hjort region study area. Areas of interpreted sediment cover are shown as white hachured polygons. Slope ranges are: dark blue - 0-5°; light blue - 5-10°; green - 10-20°; yellow - 20-30°; orange - 30-40°; and red - 40-60°.

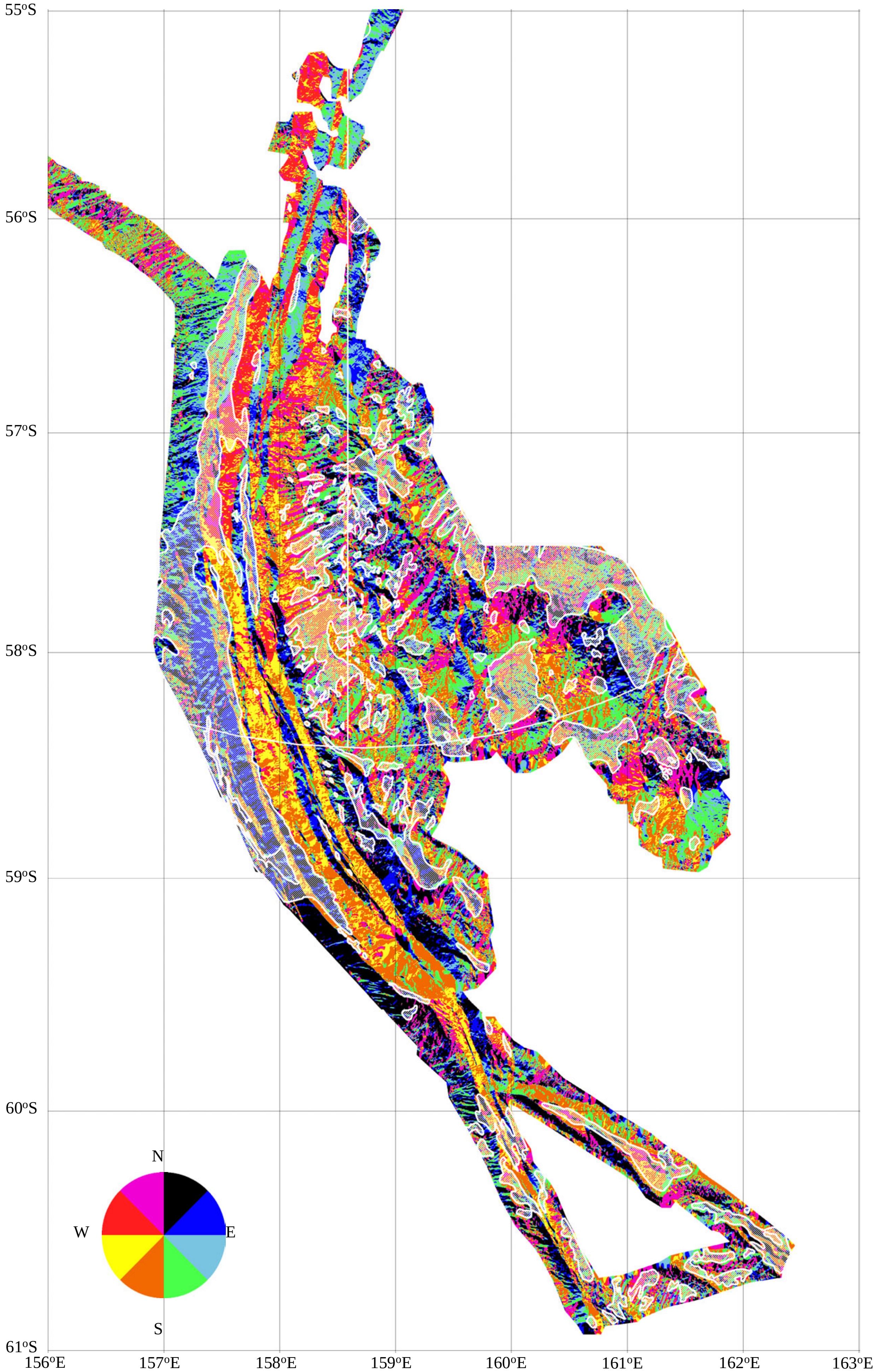


Figure 16. Terrain aspect image of the newly-mapped seafloor in the Hjort region study area. Areas of interpreted sediment cover are shown as white hachured polygons. Aspect azimuths are divided into 45° sectors as indicated on the colour wheel.

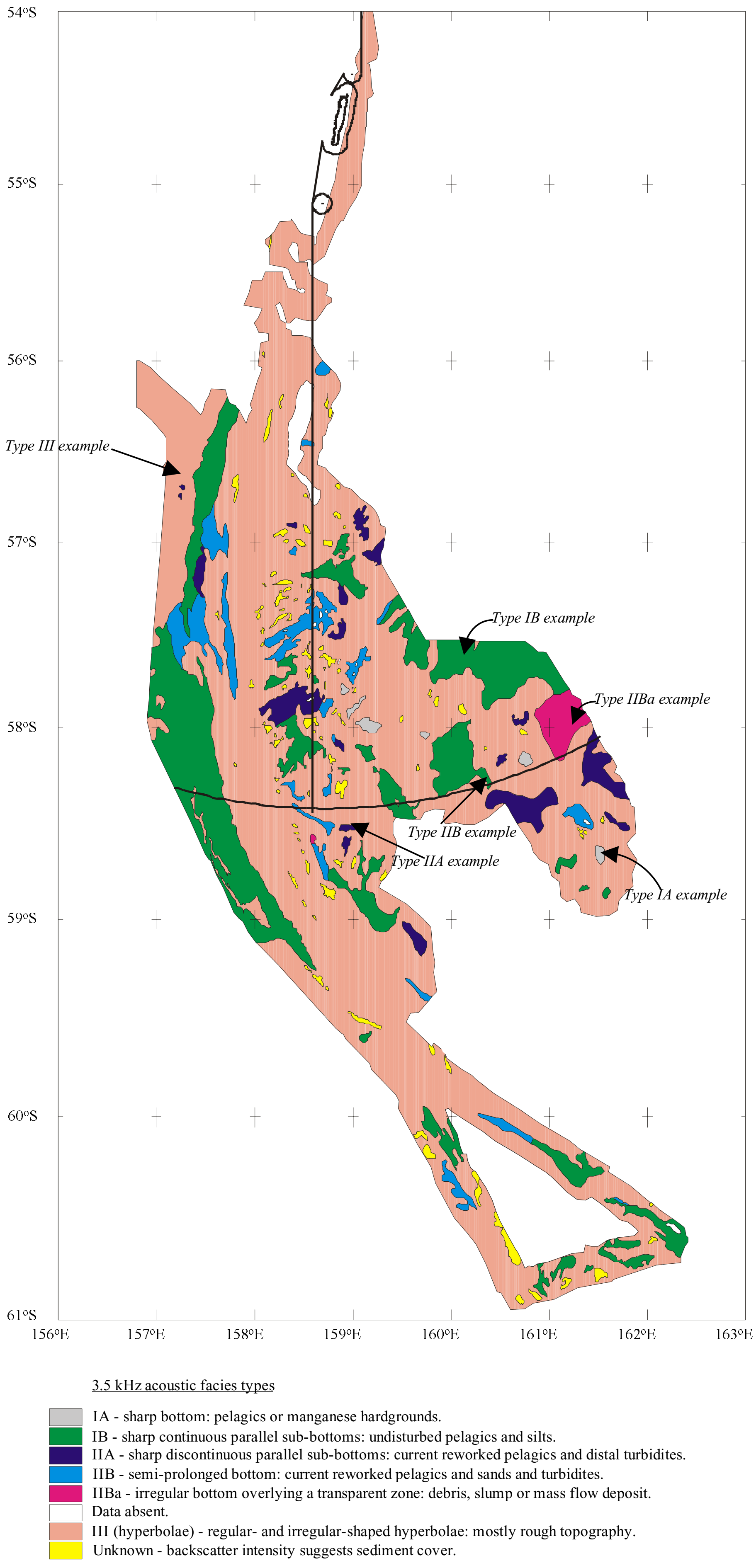
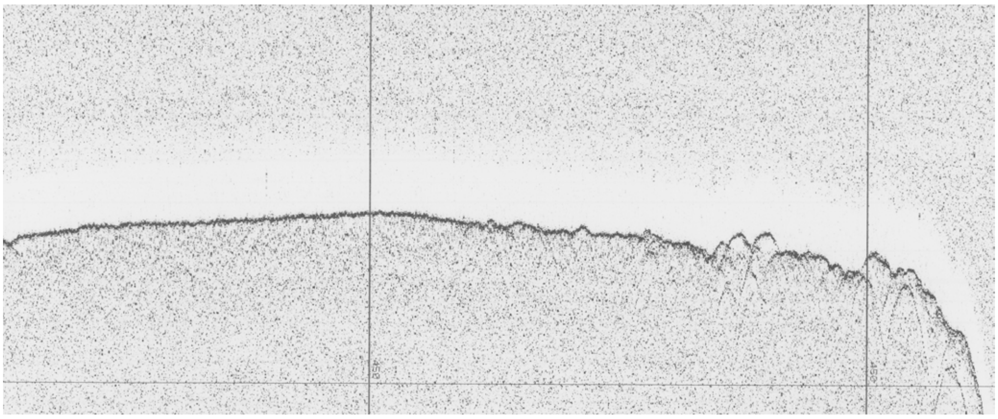
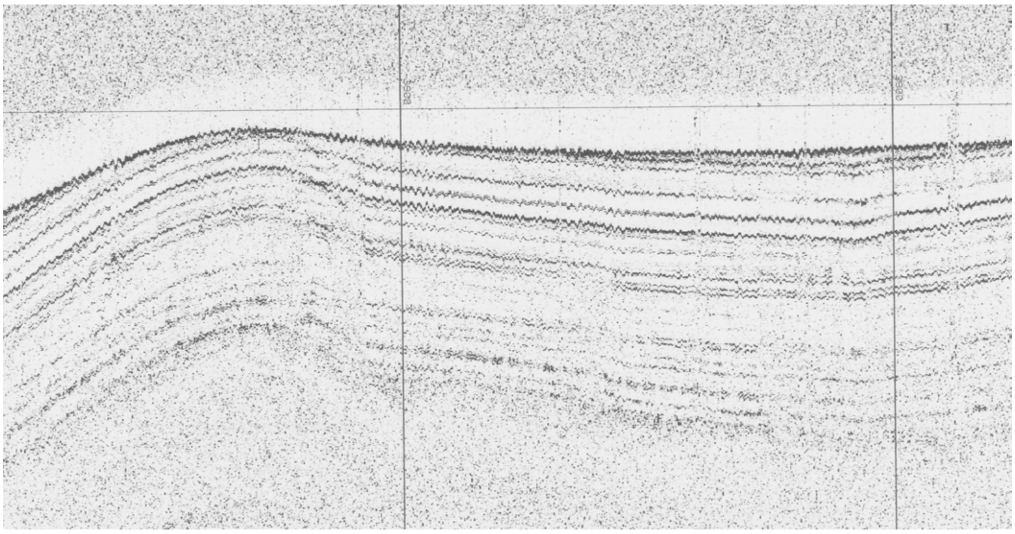


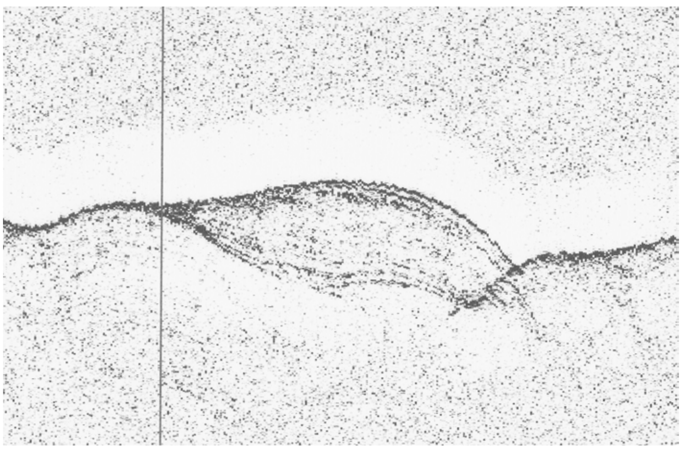
Figure 17. Acoustic facies distribution in the Hjort region study area based on the classification of Whitmore and Belton (1997). See Figure 19 for the acoustic facies types along survey track and Figures 18a and 18b for echosounder signatures of the marked examples.



Type IA, on top of seamount, at ~ 161°31’ E, 58°40’ S.

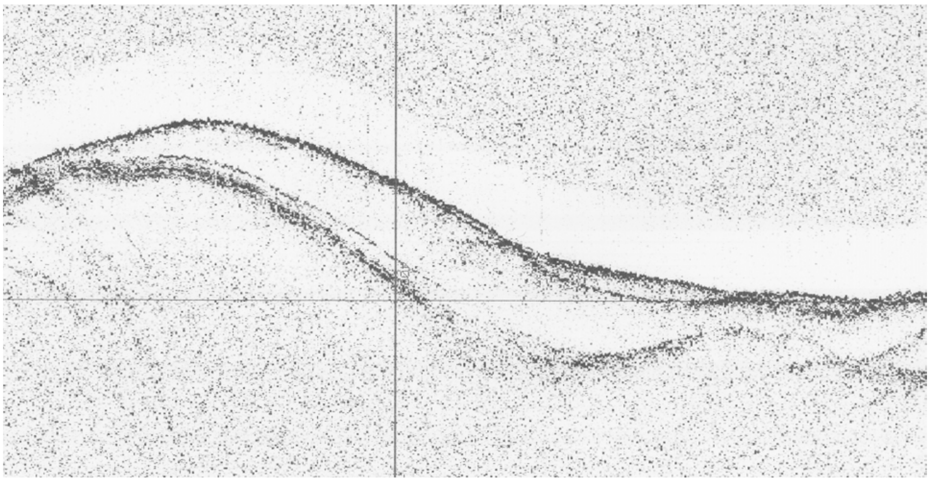


Type IB, sedimentation cycles in a contourite, at ~ 160°7’ E, 57°36’ S.

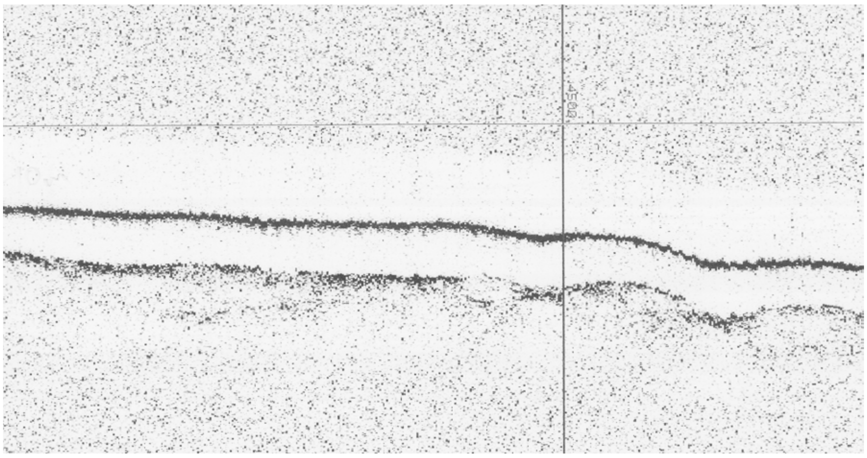


Type IIA, embedded in constricted contourite, at ~ 158°54.25’ E, 58°31.3’ S.

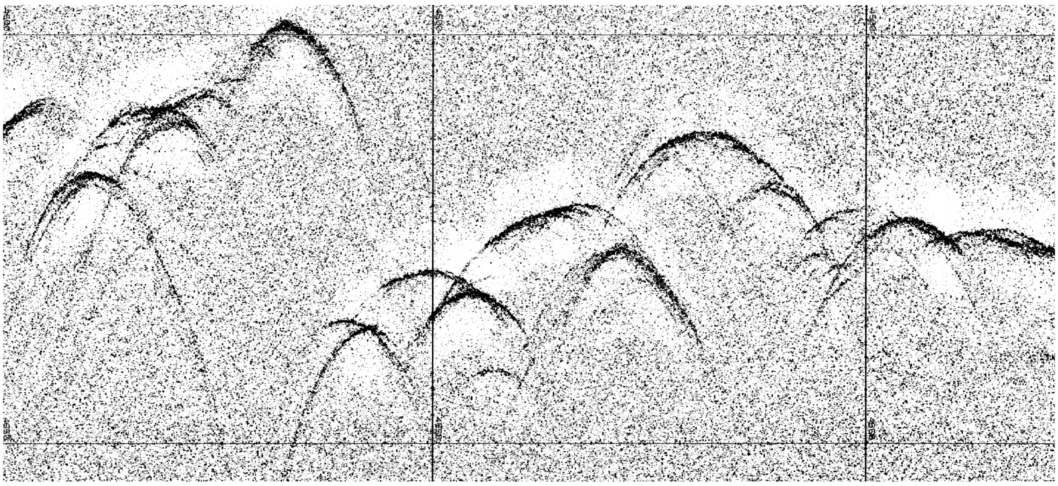
Figure 18a. Examples of 3.5 kHz acoustic facies echo types based on Whitmore and Belton (1997). Echo types IA on the top of a seamount; IB and IIA associated with contourites.



Type IIB, at base of seamount, at ~ 160°20.6’ E, 58°14.7’ S.



Type IIBa, to northeast of large seamount, at ~ 161°13.1’ E, 57°59.1’ S.



Type III (combines IIIA, B and D hyperbolae types of Whitmore & Belton, 1997) on barren oceanic crust, at ~ 157°16’ E, 56°33’ S.

Figure 18b. Examples of 3.5 kHz acoustic facies echo types based on Whitmore and Belton (1997). Echo types IIB associated with sediments at the base of a seamount; IIBa sediments distant from seamounts; and III (combines hyperbolae types IIIA, IIIC and IIID of Whitmore & Belton, 1997) on barren oceanic crust.

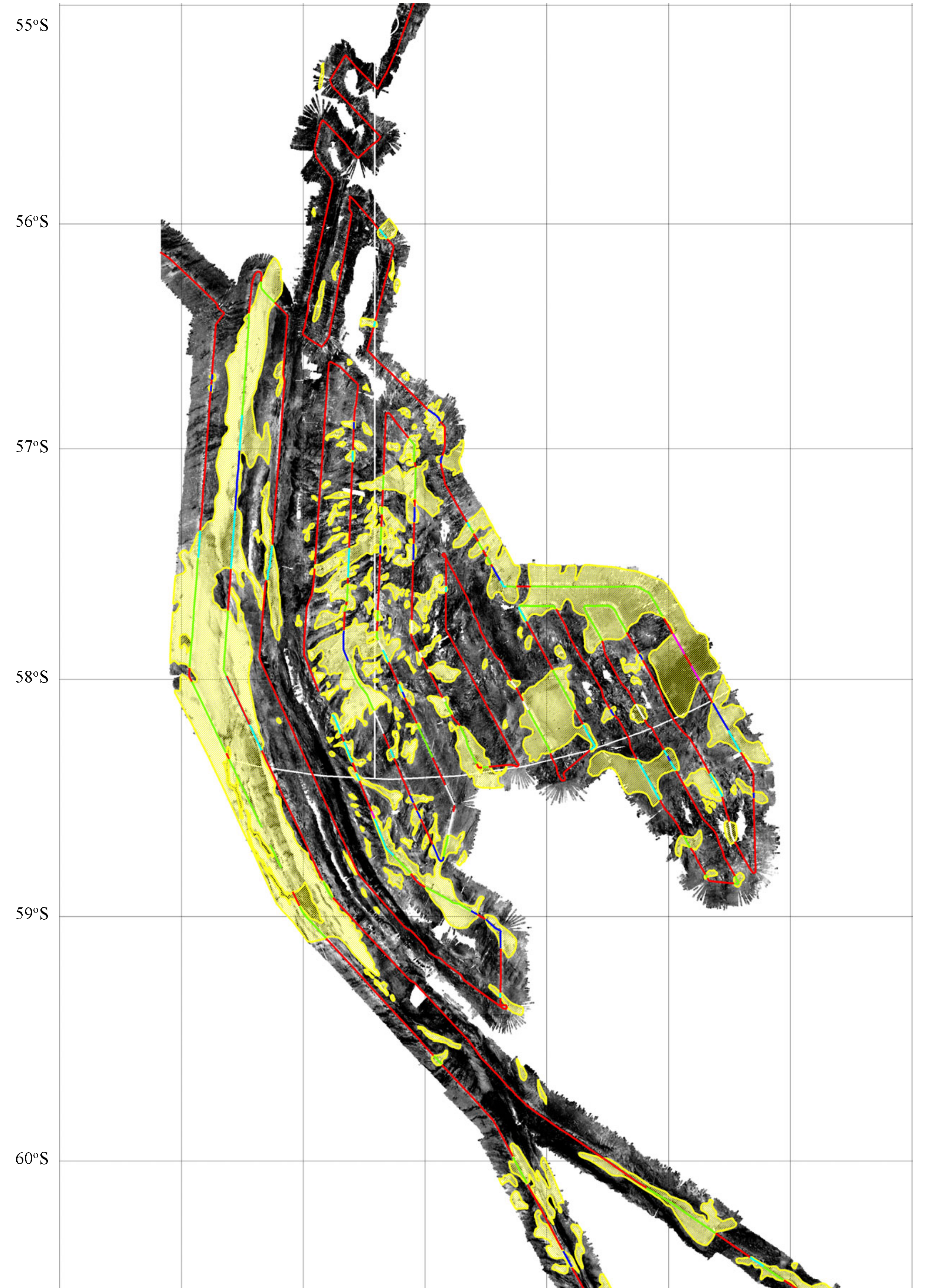


Figure 19. Acoustic facies correlated with seafloor backscatter signal to extrapolate sediment cover in the Hjort region study area. Acoustic facies types along track are (based on the classification of Whitmore & Belton, 1997) : red - III (hyperbolae); white - IA; green - IB; dark blue - IIA; light blue - IIB; pink - IIBa; and absent - indeterminate.

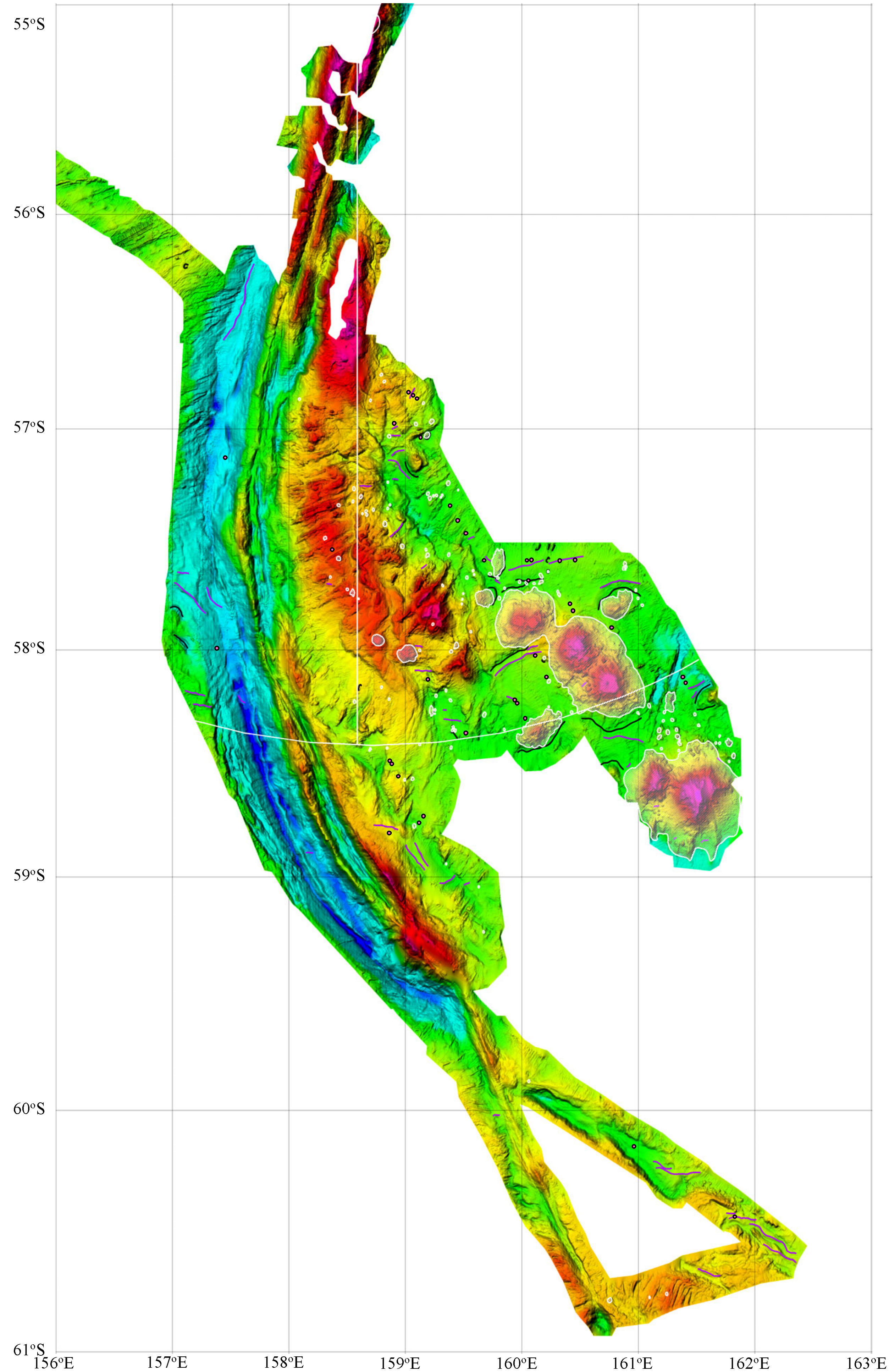


Figure 20. Hill-shaded view of the seafloor in the Hjort region study area showing the distribution of volcanic features and current effects. Shown are volcanic features (hachured white polygons), contourites (purple lines), moat features (black lines) and evidence of current scour (pink dots).

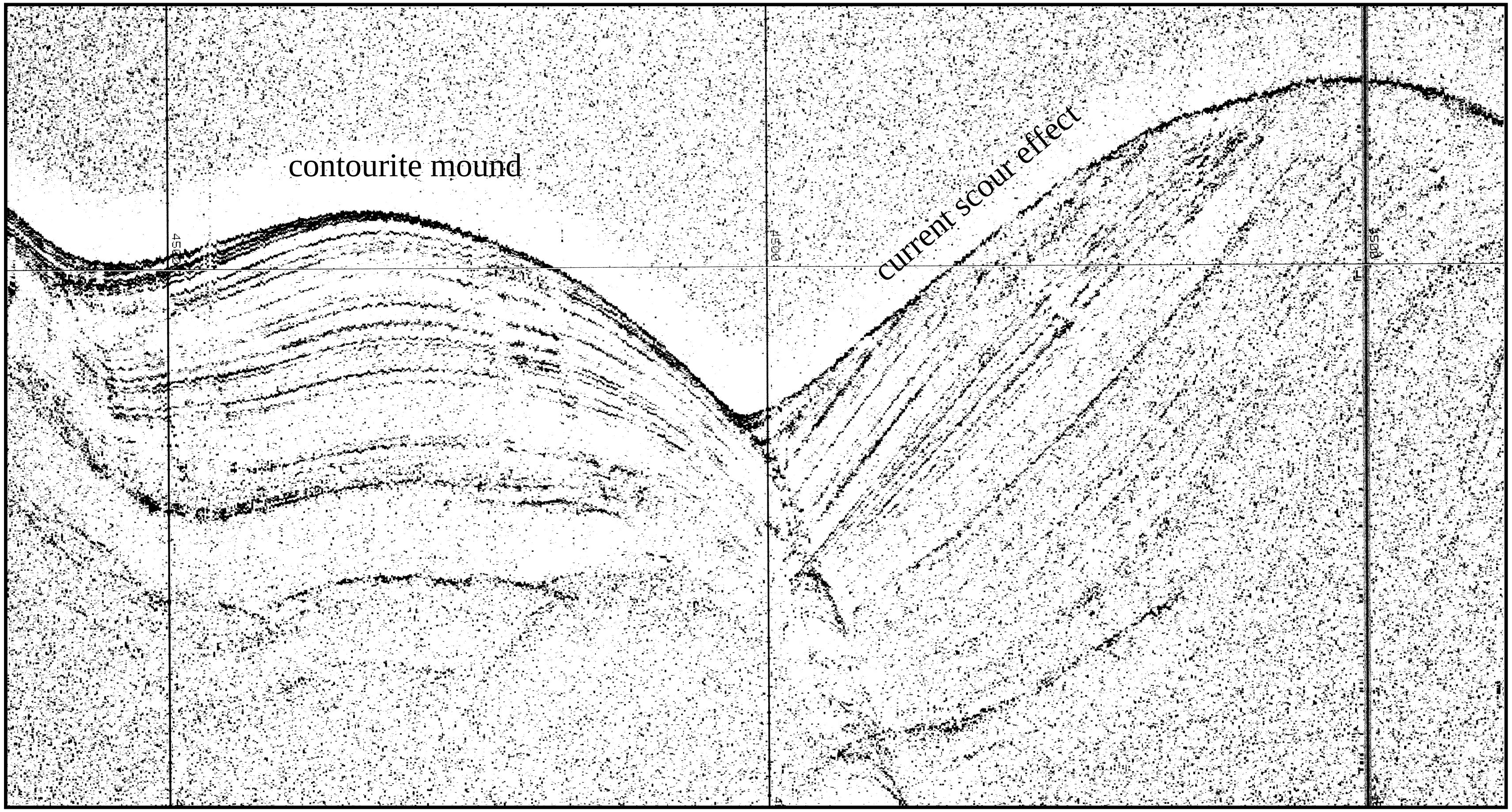


Figure 21. Example of 3.5 kHz echosounder record of contourite mound. Location is along survey track at approximately 161°22.3' E, 58°7.25' S.

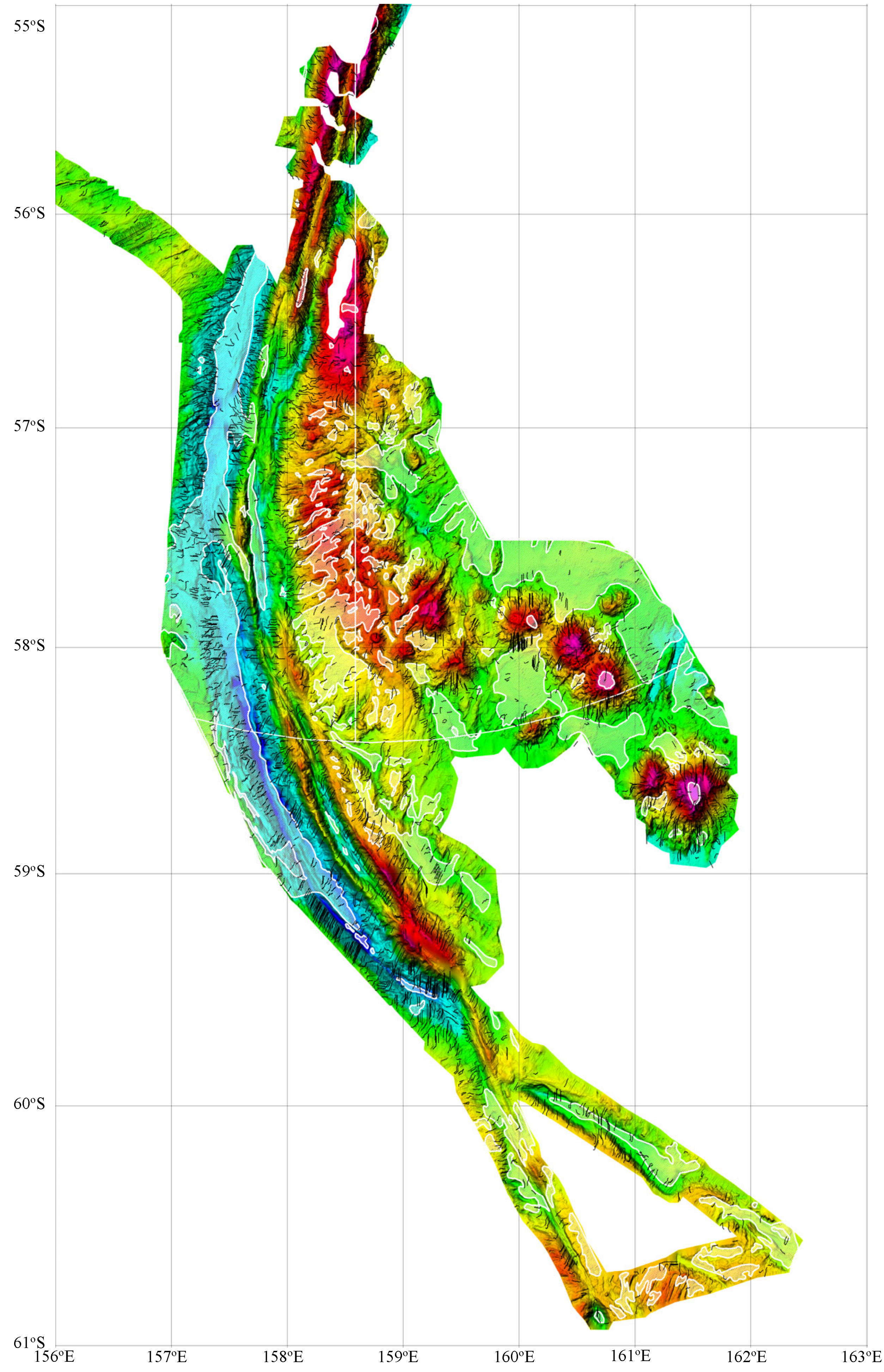


Figure 22. Hill-shaded view of the seafloor in the Hjort region study area showing modelled 'drainage' into sedimented areas derived from the bathymetric grid. Sediment cover is shown as hachured white polygons and the downslope flow network as black lines.

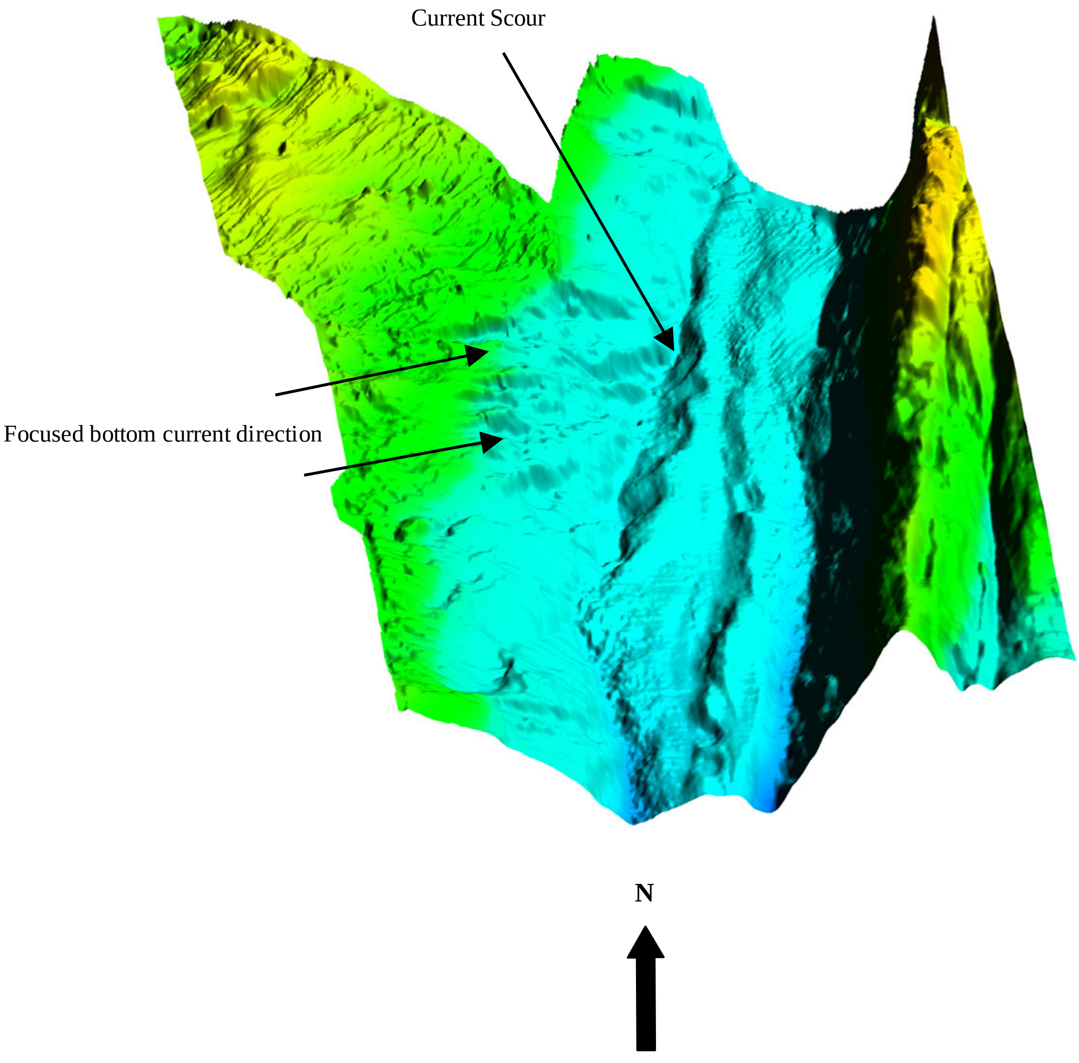


Figure 23. 3D perspective view from the south of the northern Hjort Trench terrain, centred at 157°30’ E, 56°30’ S, showing interpreted scouring effects related to an eastward flowing ocean-bottom current.

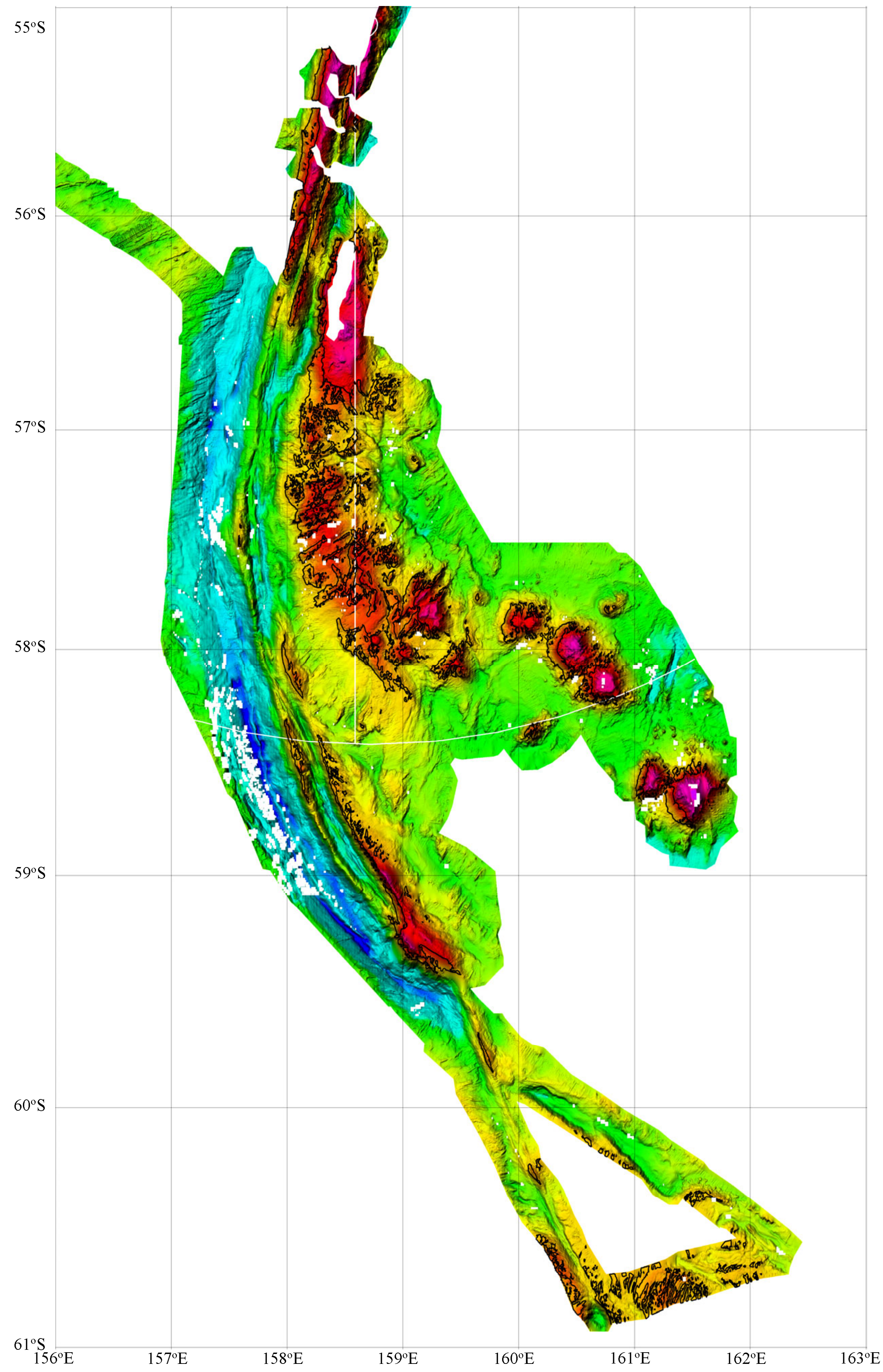


Figure 24. Hill-shaded view of the seafloor in the Hjort region study area showing modelled source regions for turbidites (white areas) and the distribution of a hypothetical benthic species X (see text) (black polygons).

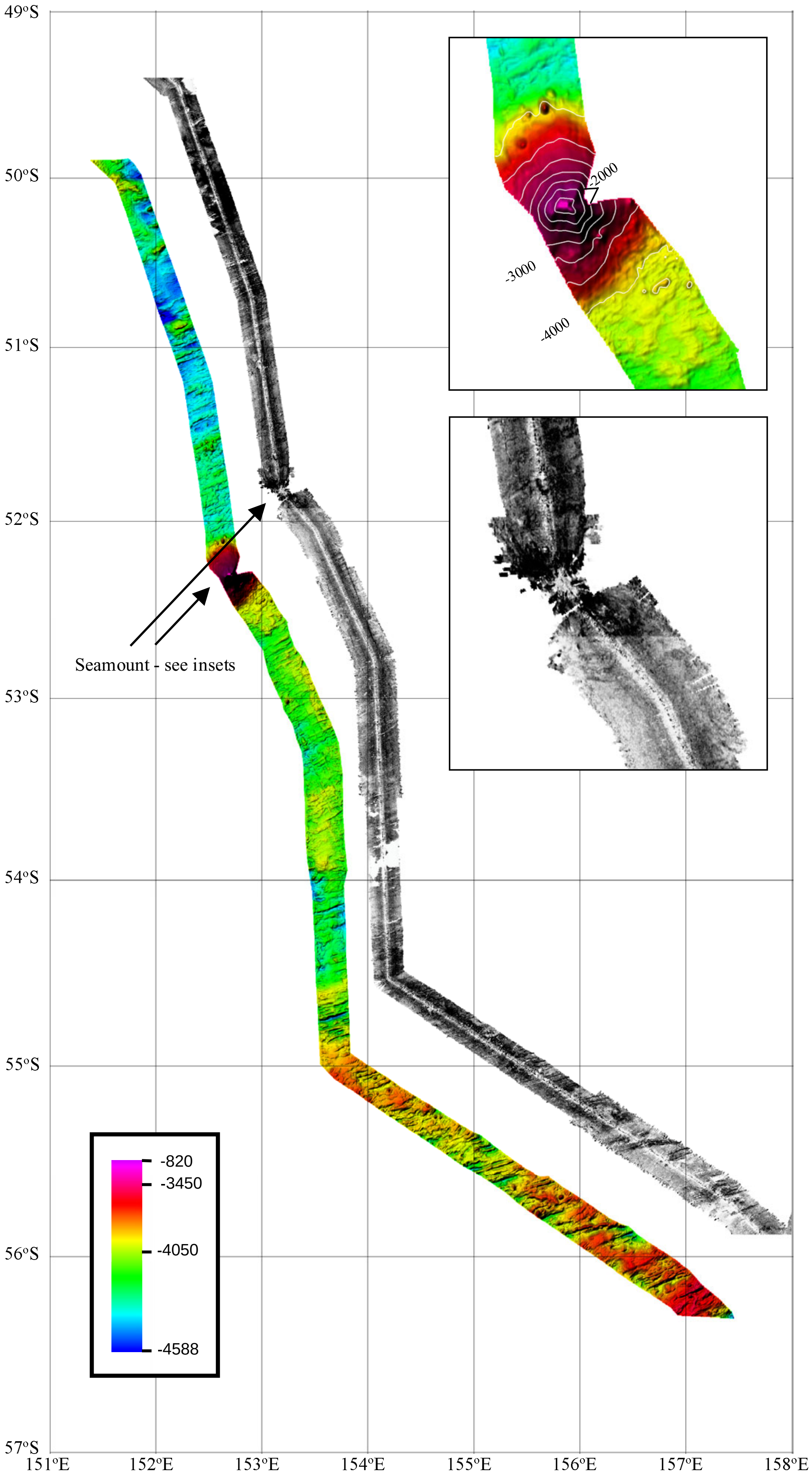


Figure 25. Hill-shaded view of terrain and grayscale backscatter along the transit from the South Tasman Rise to the southern Macquarie Ridge survey area showing a detail (insets) of a mid-ocean seamount. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter and insets are offset for display purposes. Colour bar represents depth range in metres.

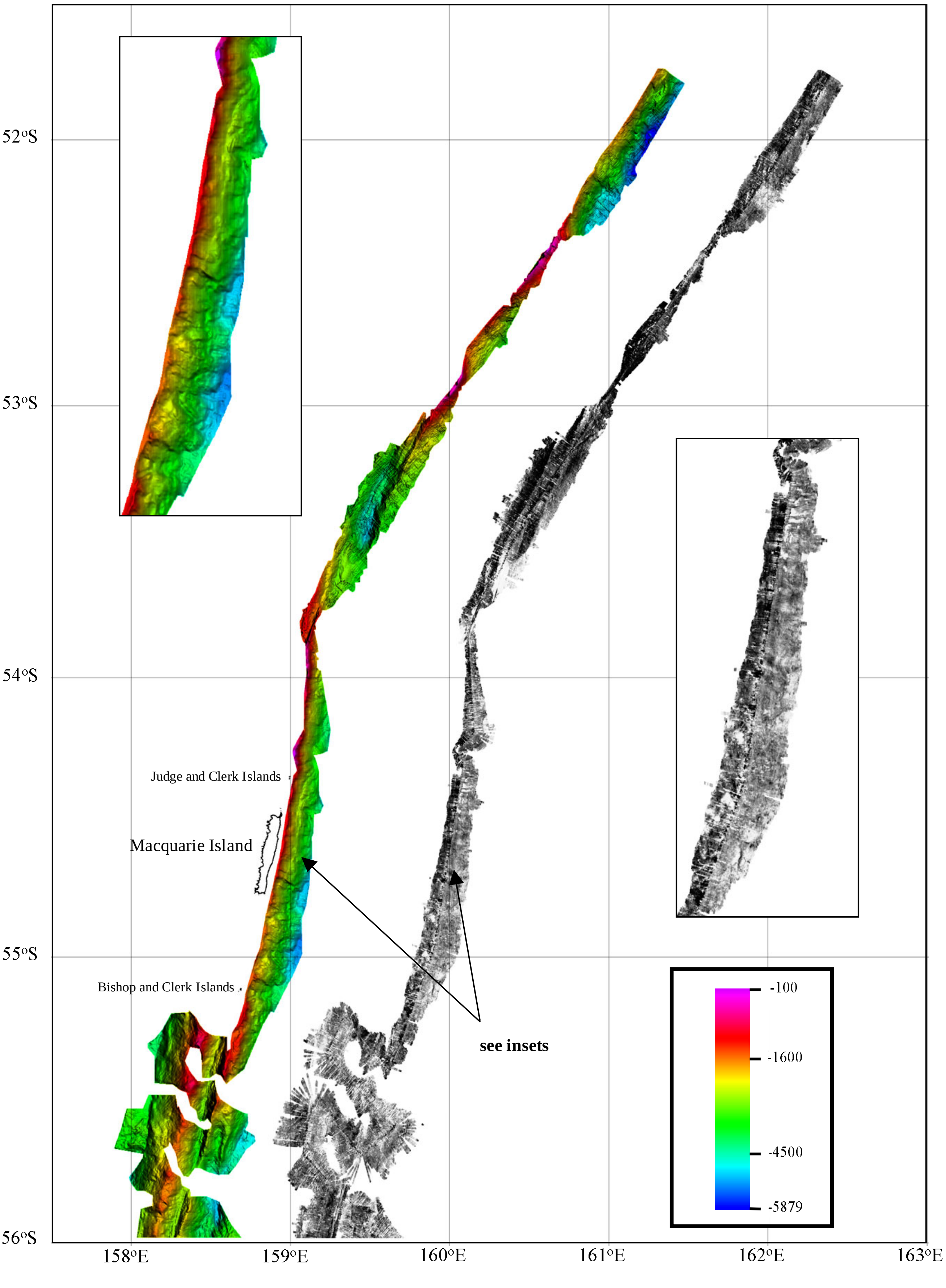


Figure 26. Hill-shaded view of terrain and grayscale backscatter along the transit from the Hjort region study area to the AEEZ boundary north of Macquarie Island showing a detail (insets) of the area east of Macquarie Island. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter and insets are offset for display purposes. Colour bar represents depth range in metres.

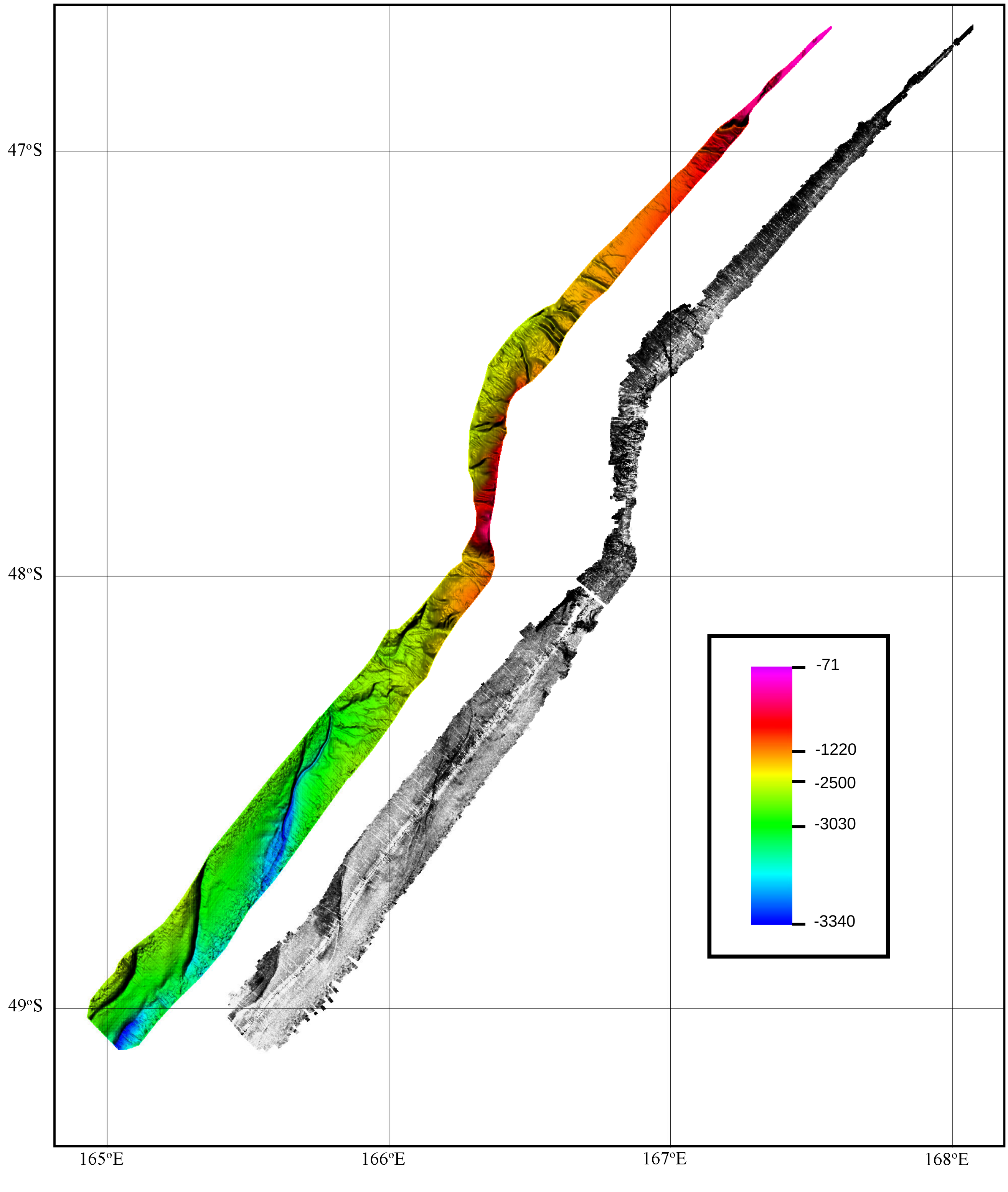


Figure 27. Hill-shaded view of terrain and grayscale backscatter along the transit from the eastern base of the northern Macquarie Ridge to New Zealand. See Figure 1 for location of the transit. Note that only the terrain image is geographically referenced - the backscatter is offset for display purposes. Colour bar represents depth range in metres.

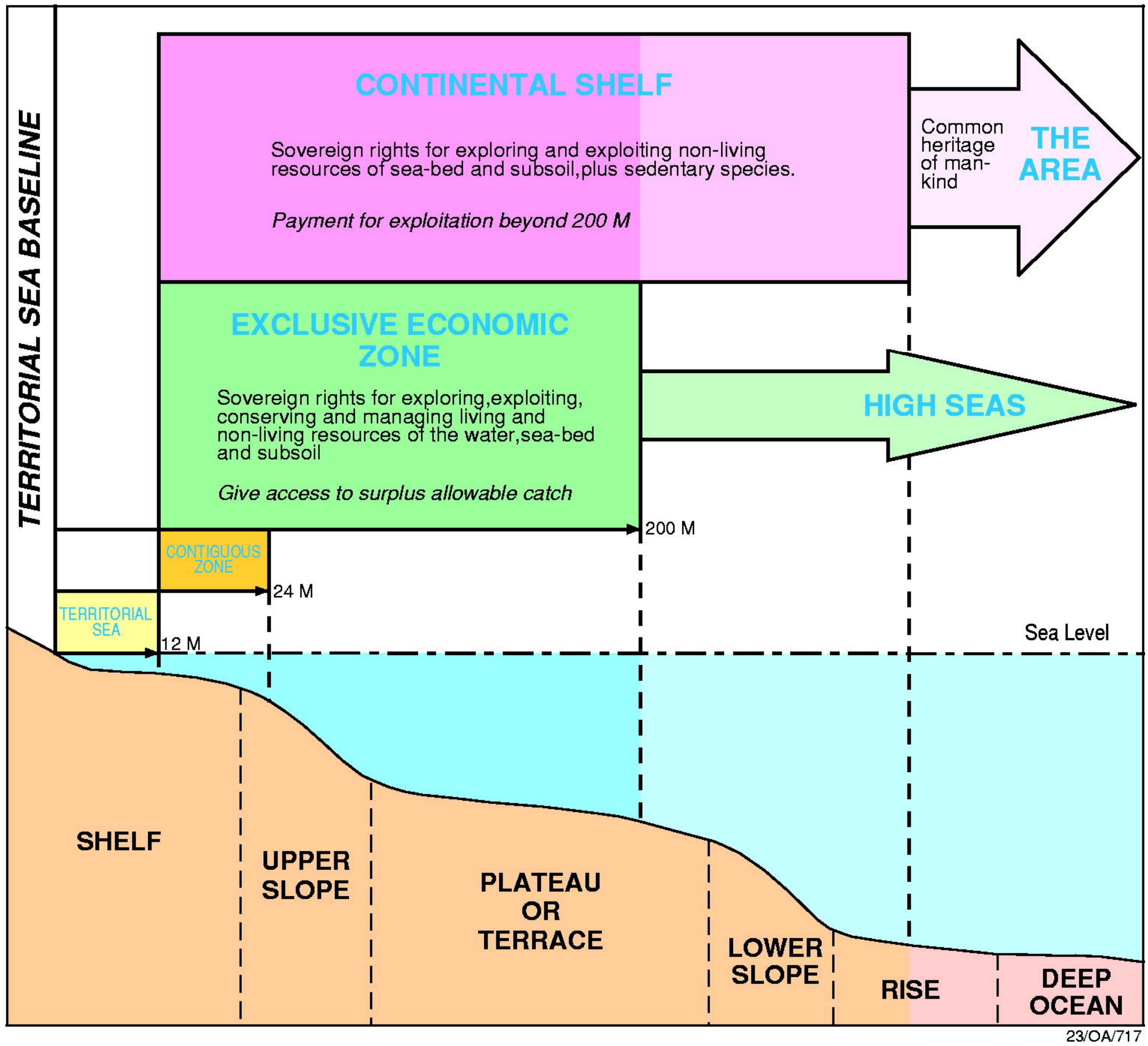


Figure 28. Marine jurisdictional zones contained in the 1982 United Nations Convention on the Law of the Sea. Note that M refers to nautical mile. After Symonds et al. (1998).

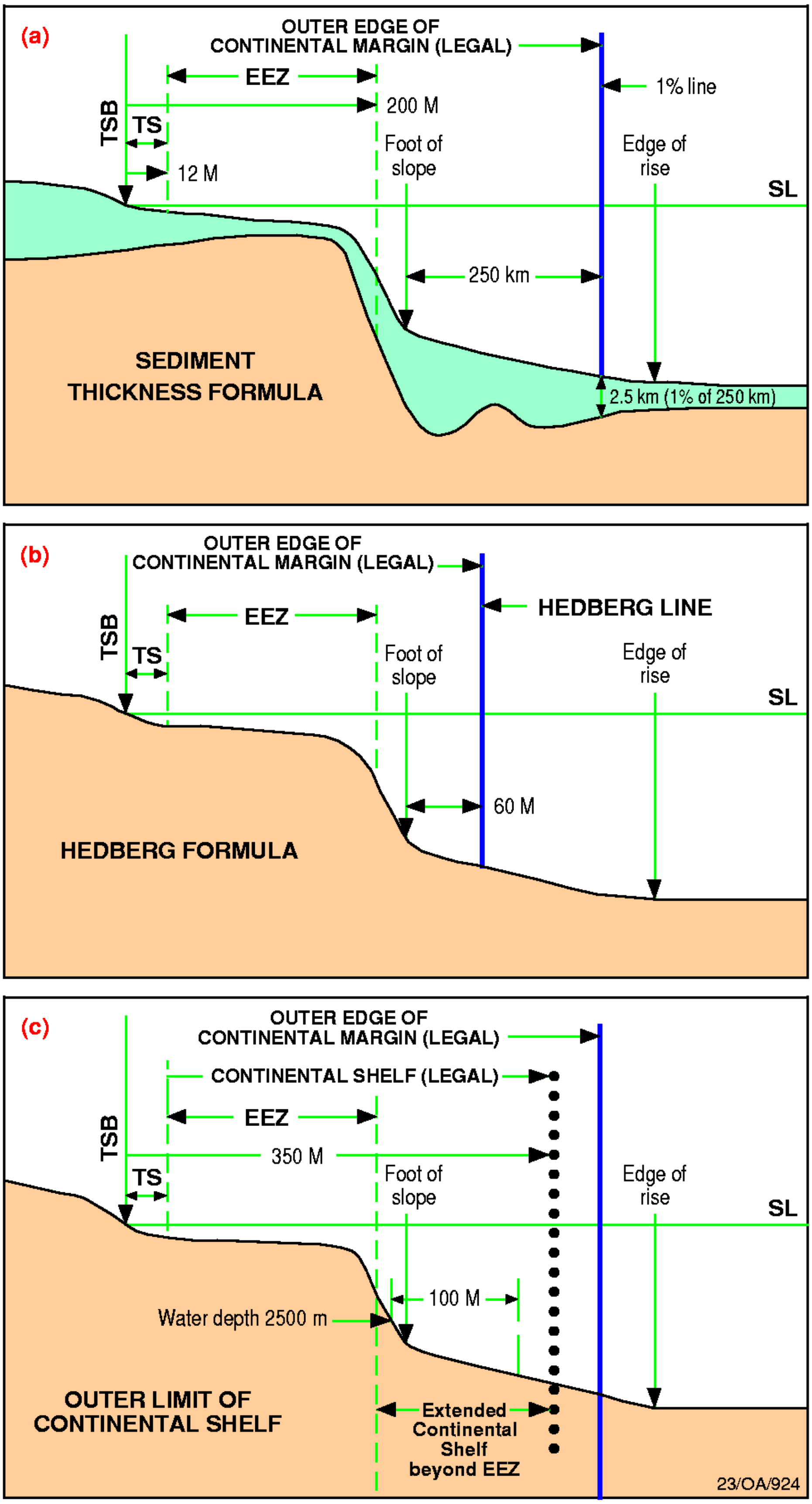


Figure 29. Procedures for determining the outer limit of the Continental Shelf under Article 76 of the 1982 United Nations Convention on the Law of the Sea. (c) shows application of the two cut-offs, showing the zone of extended Continental Shelf that lies beyond the 200 nautical mile Exclusive Economic Zone. After Symonds et al. (1998).

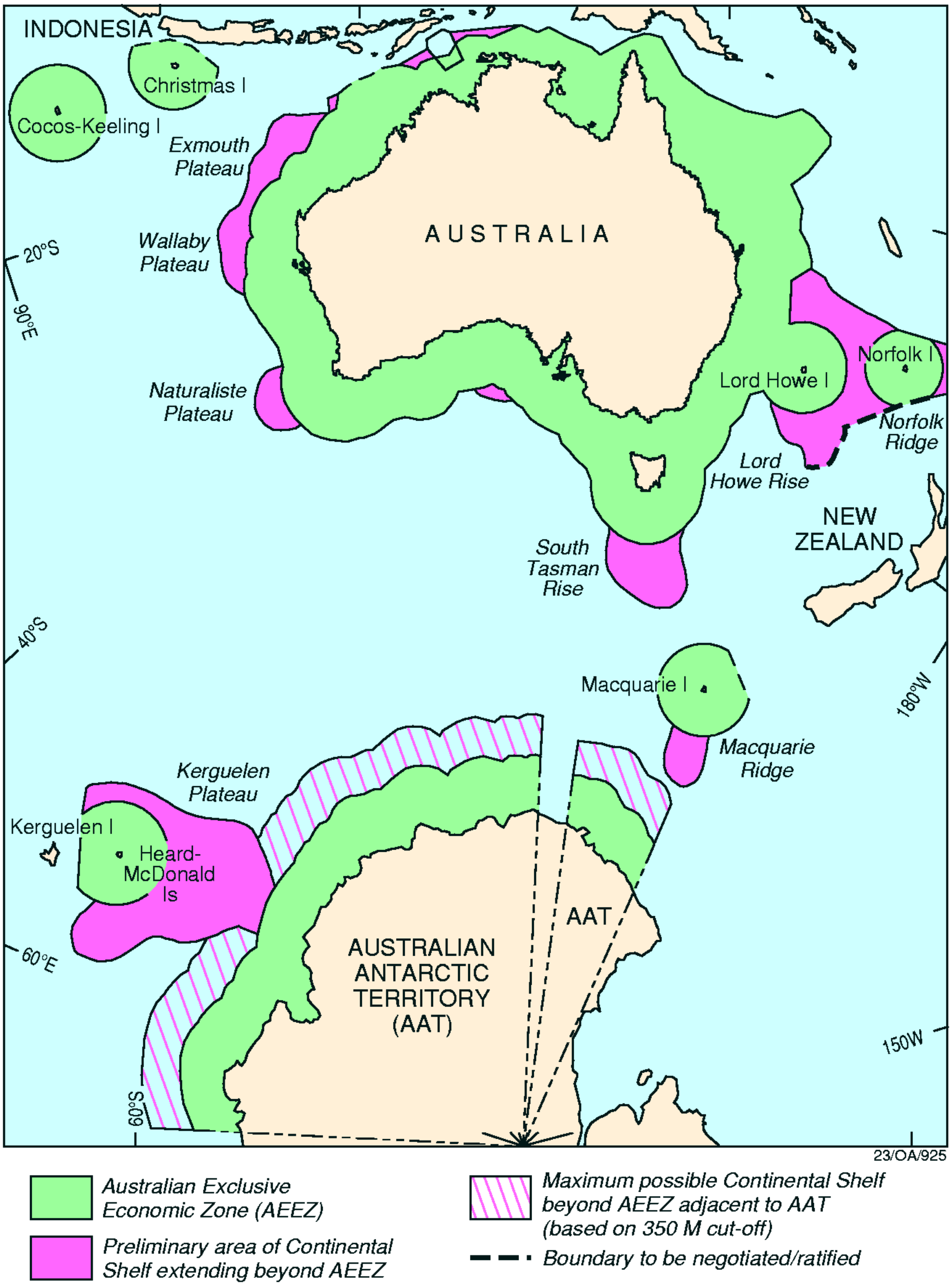


Figure 30. Sketch map showing the main marine jurisdictional zones around Australia and its territories. After Symonds et al. (1998).

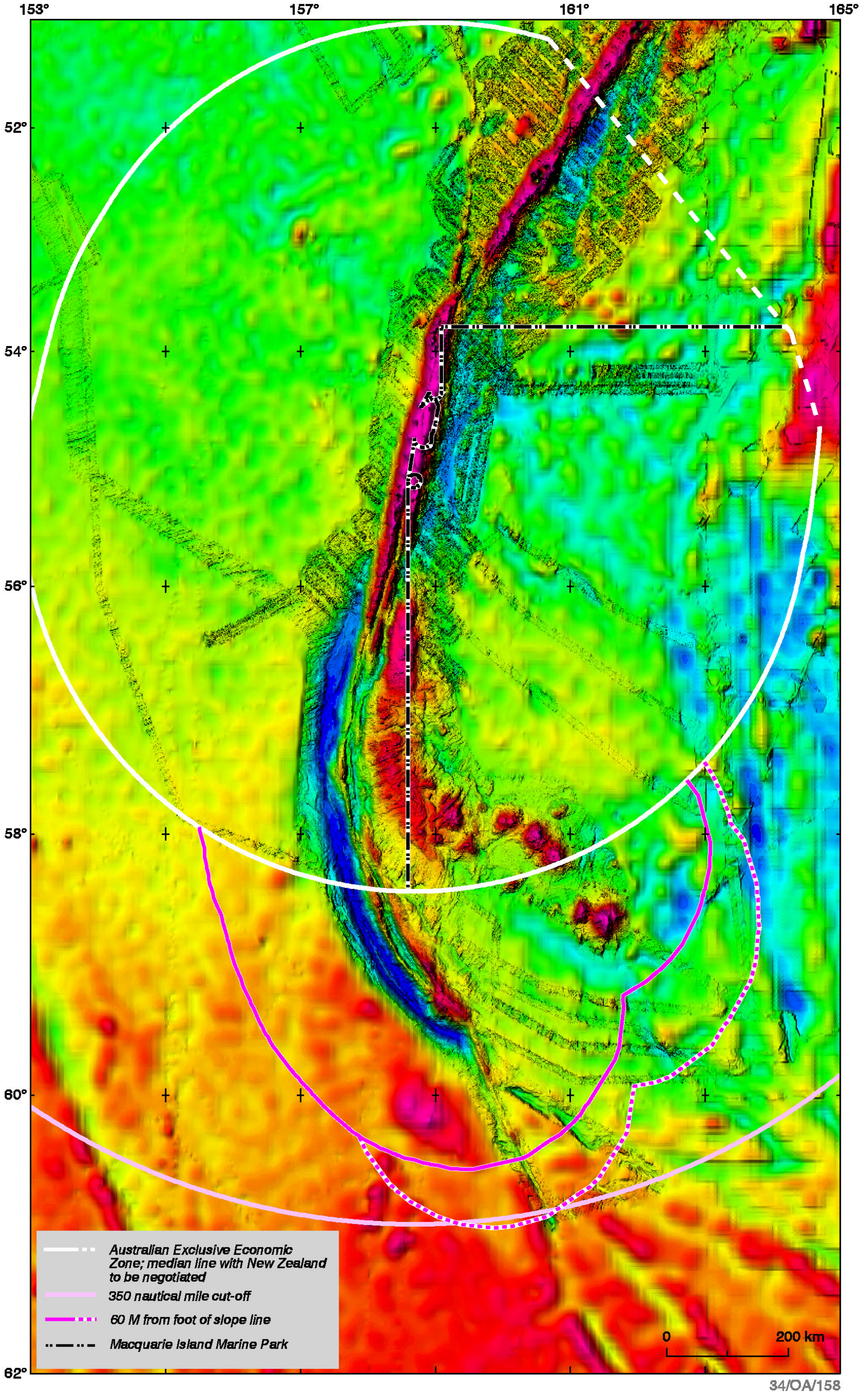


Figure 31. Hill-shaded view of terrain for the central and southern Macquarie Ridge showing various options for the so-called Hedberg line drawn 60 nautical miles (M) from the FoS. These preliminary lines are not necessarily indicative or representative of the information that Australia might use to define the final outer limit of the Continental Shelf in any submission it makes to the Commission on the Limits of the Continental Shelf.

Recent Swath Mapping in the southern Macquarie Ridge Complex: Seafloor Characteristics and Tectonic Development

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Petroleum & Marine Division

Introduction

As part of the process of developing a Regional Marine Plan for South-east Australia, and to aid definition of Australia's marine jurisdiction south of Macquarie Island, the Australian Geological Survey Organisation conducted a seafloor swath-mapping survey in the region from Jan.-Feb. 2000, on behalf of the National Oceans Office.

A total of about 60,000 km^2 of multibeam bathymetry and backscatter, and some 4,300 km of 6-channel seismic reflection, gravity, magnetics and 3.5 kHz sub-bottom profiling data were acquired over the arcuate-shaped Hjort Trench and adjoining Hjort Ridge - the southern extension of the 1600 km-long Macquarie Ridge Complex (Fig. 2).

Significant features of the seafloor morphology in the area include:

- The deep (6600 m), mostly sedimented, Hjort Trench - the best developed trench along the entire ridge complex;
- A southward broadening and deepening of the Hjort Ridge segment of the complex;
- A southward change in the character of the Macquarie Ridge, and the presence of a broader, high-relief axial valley in the region between and parallel to the Hjort Trench and Hjort Ridge (Figs 1 and 4);
- A chain of large seamounts approximately 180 km northeast of the deepest portion of the Hjort Trench; and
- A N-NW trending linear feature that obliquely truncates the southern Hjort Trench and adjoining axial valley.

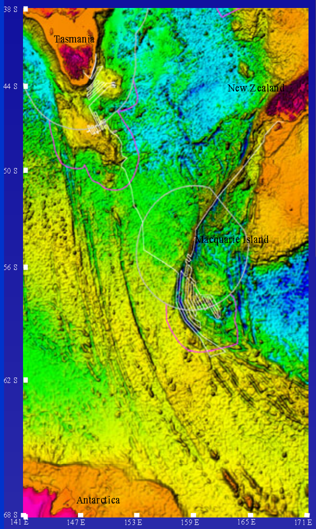

Fig. 2. Track map of survey. Grey boundaries are EEZ and pink lines are limits of legal extended Continental Shelf.

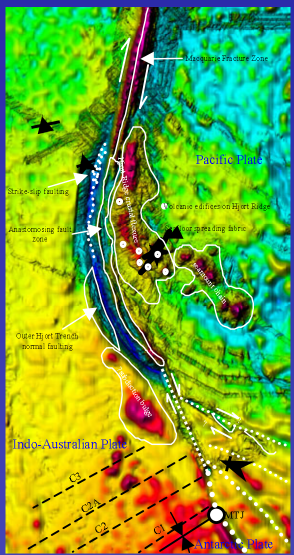

Fig. 3. Reproduction of Fig. 1 with superimposed initial tectonic interpretation.

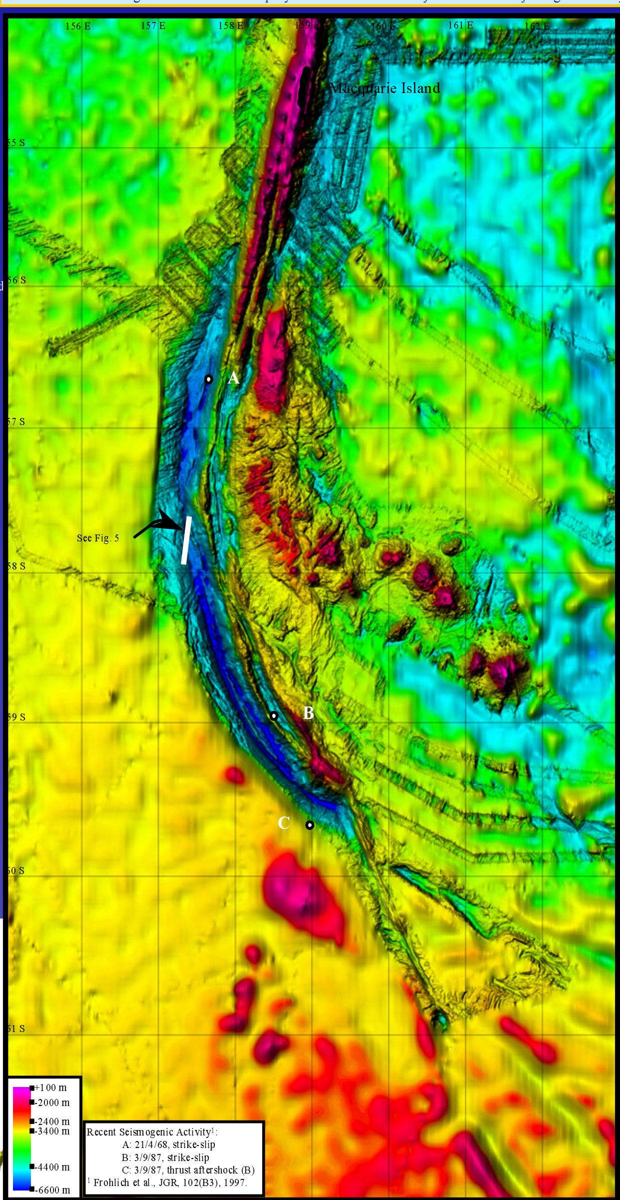

Fig. 1. Terrain model for the southern Macquarie Ridge region. Image is hill-shaded colour bathymetry. Grid is merge of new data with previous swath data (*Ewing*-Atlas and *Rig Seismic*-HMR1) and predicted bathymetry.

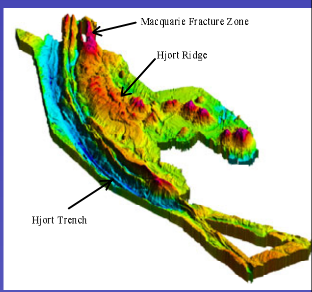

Fig. 4. South-westerly perspective view of new swath bathymetry over the southern Macquarie region.

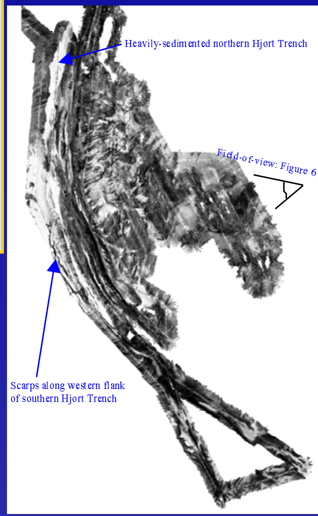

Fig. 7. Grey-scale image of multibeam backscatter data.

Seafloor Characterisation

The image in Fig. 7 represents the intensity levels of the reflected multibeam signal - termed backscatter. An initial first-pass analysis relates intensity to sub-bottom hardness. That is, the darker the region then the stronger the reflectivity coefficient of the seafloor. For example, dark zones may define bare or thinly-covered volcanic rock, or highly consolidated sediment. Morphology, however, can further refine this analysis. Dark zones on seamount features probably represent exposed volcanics - compare figs 4 and 7.

Integrated interpretation of backscatter data and morphology can be best achieved via 3-dimensional visualisation. Fig. 6 presents grey-scale backscatter levels draped over swath bathymetry. The overall darker character of the seamounts supports their volcanic composition. Note also the much darker zone spreading out from the base of the seamount in a NE direction (Fig. 7). The 3.5 kHz echo-sounder data across this zone shows a thin transparent layer between two strong reflecting surfaces. These characteristics suggest it is an area of debris, slump or mass flow deposits[1]. Associating this interpretation with the spatial correlation afforded by the respective multibeam datasets suggests a relatively recent massive slumping on the E-NE flank of the seamount. This is also confirmed by a closer examination of the morphology of the seamount, which shows a smooth and slightly concave character on this flank. Such mass movement of volcanic material points to large-scale, recent seismogenic activity in the region.

[1] Whitmore & Belton, Australian Journal of Earth Sciences 44, 1997.

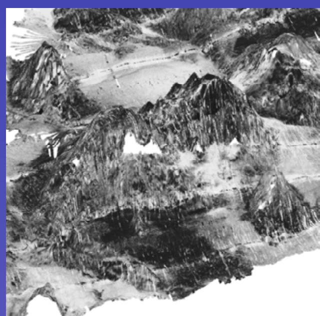

Fig. 6. Easterly perspective view of multibeam backscatter draped on bathymetry. See Fig. 7 for location.

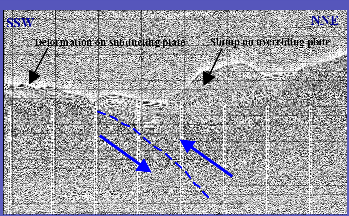

Fig. 5. Field monitor section - see Fig. 1 for location.

Tectonic Implications

The entire Macquarie Ridge Complex (MRC) defines the boundary between the Indo-Australian and Pacific plates, from the Alpine fault of New Zealand's South Island to a segmented ridge-transform system to the east of the Macquarie Triple Junction (MTJ), that involves the Antarctic Plate (Figs 2 and 3). The new data over the southern MRC reveal a region of complex strain-partitioning along the length of the Hjort Trench. Salient features of a preliminary interpretation (Fig. 3) are:

- We extend identification of the Macquarie Fracture Zone[1] as an arcuate-shaped zone of anastomosing faults averaging 10 km-width. Seafloor morphology, backscatter and seismic data reveal a classic style of restraining/releasing bends supporting right-lateral transcurrent motion.
- Normal faulting along the western edge of the southern Hjort Trench may indicate shear strain relief on a steeply-plunging Indo-Australian Plate.
- Volcanism atop the Hjort Ridge and the alignment of several seamounts to its SE may be related to current/previous melting of a subducted Indo-Australian Plate/slab.
- The broad shape of the Hjort Ridge probably represents a flexural response to shortening and thickening of oceanic crust due to local counter-clockwise rotation of the Pacific Plate into the large restraining bend between the southern MRC and the segmented ridge-transform system at the MTJ.
- Evidence for strike-slip and subduction motion in the northern and southern halves of the Hjort Trench, respectively, suggests the presence of a hybrid plate boundary manifesting time-variable strain-partitioning.

Our initial findings indicate that the Hjort region is a plate boundary of transitional subduction to strike-slip tectonics. This hybrid characterisation was the focus of the 1999 Penrose Conference (*Subduction to Strike-slip Transitions on Plate Boundaries*).

[1] Massell et al., Journal of Geophysical Research, 2000 (in prep).

Figure 32. Macquarie Ridge seafloor characteristics and tectonic development poster as presented at the 15th Annual Australian Geological Convention in Sydney in July 2000.

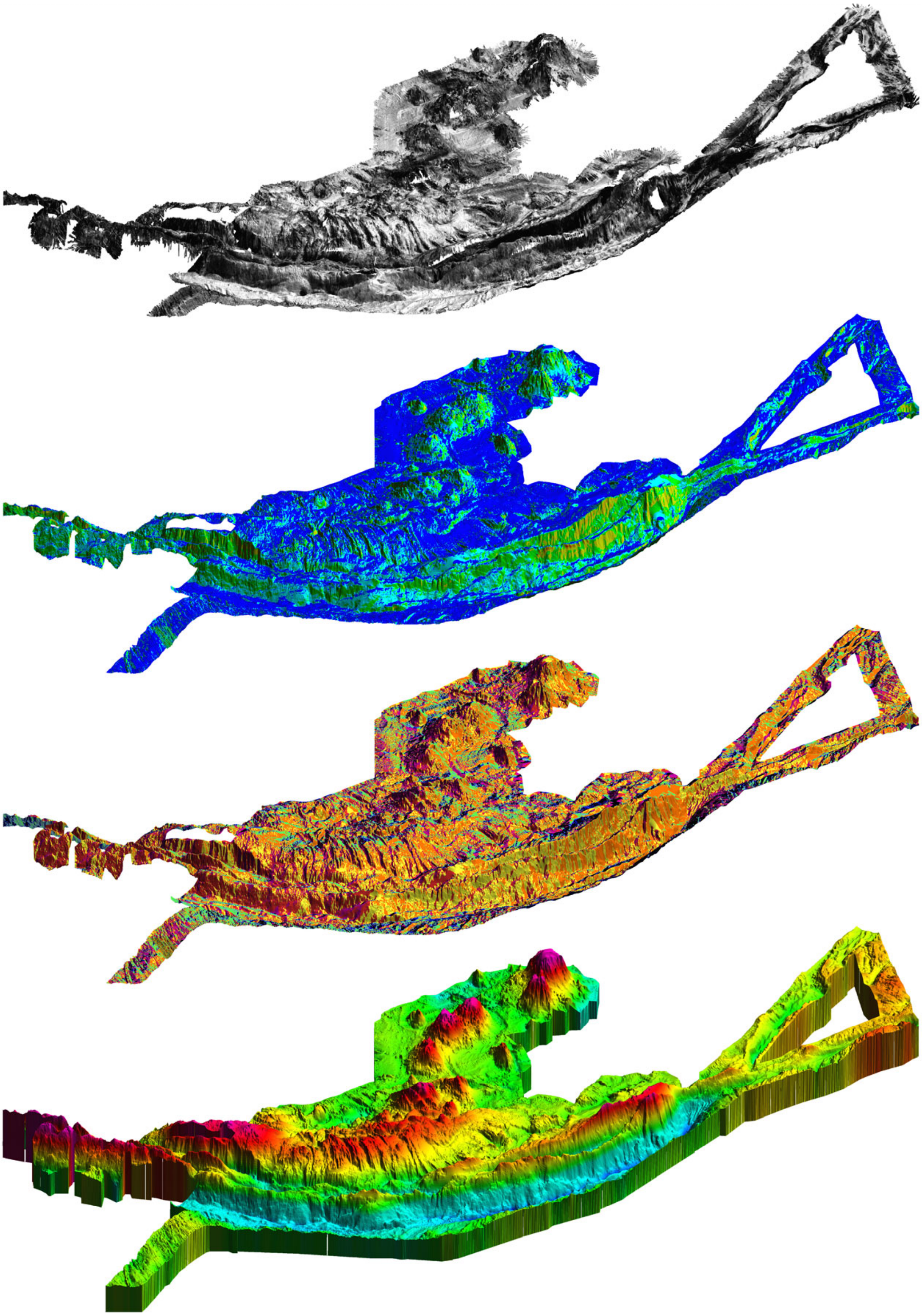

Figure 33. 3D perspective view from the west of seafloor bathymetry in the Hjort region of the southern Macquarie Ridge overlain by, from bottom to top: colour-coded bathymetry, terrain aspect, terrain slope and seafloor backscatter. Colour calibrations as in Figures 12, 16, 15 and 13, respectively.

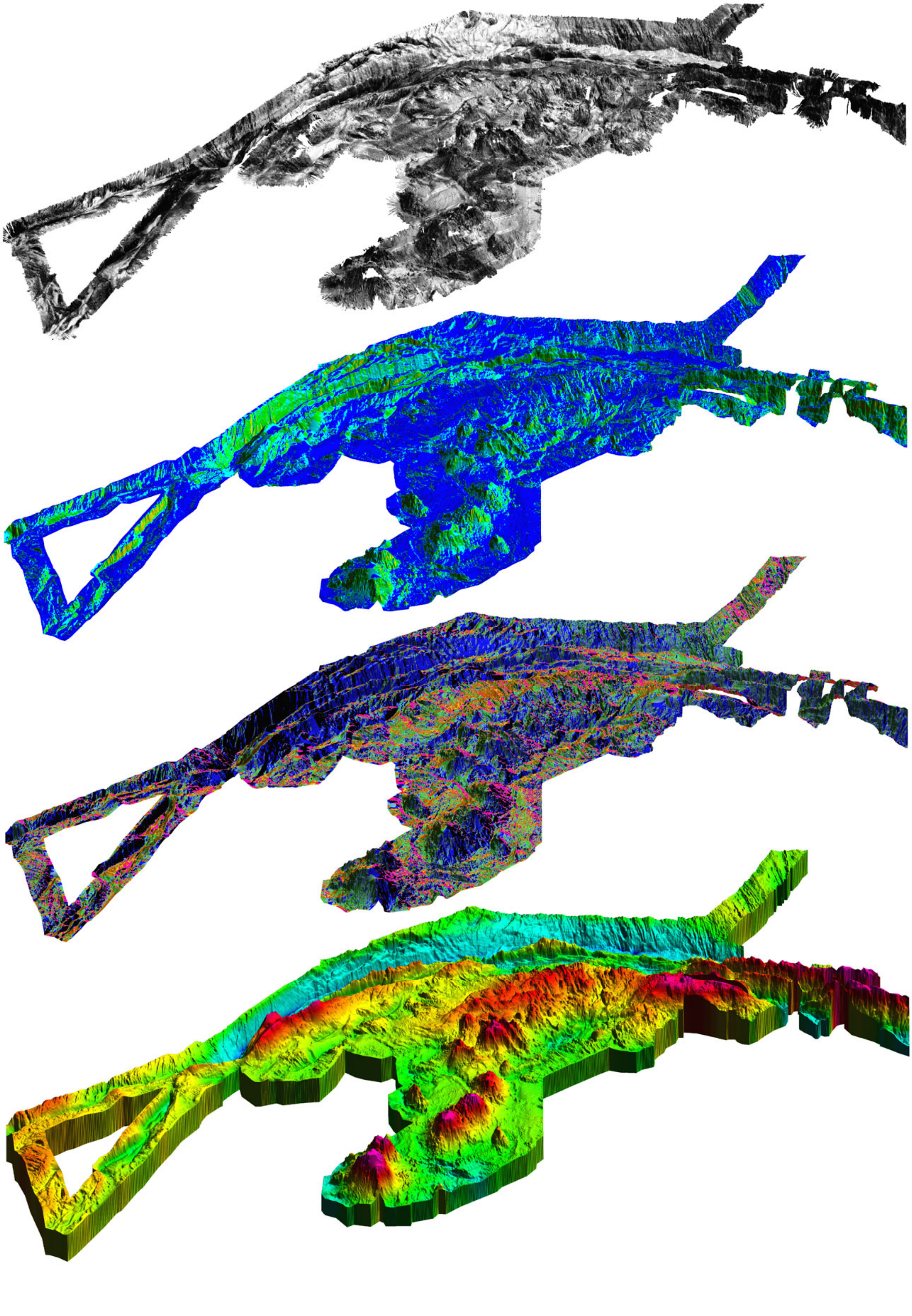

Figure 34. 3D perspective view from the east of seafloor bathymetry in the Hjort region of the southern Macquarie Ridge overlain by, from bottom to top: colour-coded bathymetry, terrain aspect, terrain slope and seafloor backscatter. Colour calibrations as in Figures 12, 16, 15 and 13, respectively.

Instructions for the CD-ROM

Seafloor mapping of the South-east Region and adjacent waters – AUSTREA final report: southern Macquarie Ridge

This CD-ROM contains the above-titled document as GeoscienceAustraliaRecord2001_46.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_46.pdf to launch the document.

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

Directories on this CD

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

Plot files directory:
With sub-directories containing A4, A2 and A0 plot files (.PRN) and Raster Transfer Language (.RTL) plot files of the A0 and A2 figures used in this Record. All A0, A2 sizes are suitable for plotting to large format plotters.

Record directory:
GeoscienceAustraliaRecord2001_46.pdf