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GEOLOGICAL FRAMEWORK OF THE SOUTHERN LORD HOWE RISE/WEST NORFOLK RIDGE REGION

BY J. MARSHALL, D. FEARY & H. ZHU

RECORD 1994/65

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Marine Geoscience and Petroleum Geology Program

GEOLOGICAL FRAMEWORK OF THE SOUTHERN LORD HOWE RISE/WEST NORFOLK RIDGE REGION

Project 121.30

POST CRUISE REPORT

RECORD 1994/65

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EXECUTIVE SUMMARY

Project 121.30 - "Lord Howe Rise and Norfolk Ridge 'Law of Sea' Study" -was initiated to improve our understanding of the geological framework of the southern part of the Lord Howe Rise region, in the vicinity of the Australia/New Zealand seabed boundary zone.

The major objectives of the project are:

To investigate the structure, stratigraphy and basin development of the southern Lord Howe Rise, southern New Caledonia Basin and the West Norfolk Ridge.

To assess the resource potential of the major structural features within the region.

To determine the tectonic framework, crustal characteristics and evolution of the region, and attempt to understand the processes that have produced narrow strips of thinned and extended continental lithosphere ("ribbon continents") separated by narrow ocean basins.

To acquire data to assist with the definition of Australia's 'legal' Continental Shelf on the southwestern margin of the Lord Howe Rise.

Because of the presence of Lord Howe Island and Norfolk Island, Australia has laid claim to a large part of the seabed in the region, enveloped by a 200 nautical mile Exclusive Economic Zone (EEZ) around each island, plus areas of 'legal' Continental Shelf beyond the EEZ. The total area of Australia's 'legal' Continental Shelf in the Lord Howe Rise region would be about 1.65 million km^2. While the seabed boundary in the northern part of the region has been negotiated between Australia and France, there is not, as yet, a negotiated boundary between Australia and New Zealand in the southern Lord Howe Rise/West Norfolk Ridge region.

The proposal for Survey 114 was to acquire approximately 3250 km of multichannel seismic and associated geophysical data. The data was acquired mainly on long regional lines, two of which extended from the Tasman Basin to the Norfolk Basin,

using a 3000 m streamer (120 x 25 m groups), 49 litre sleeve gun arrays, 16 second records, and 30-fold coverage.

The ship departed Sydney at 2000 hrs on Friday, 6 November 1992, and, after transiting through rough seas, arrived in the study area on the evening of 9 November. The cable was deployed and balanced by midnight, 10 November. The next twenty one days was spent shooting deep crustal (16 sec.) seismic . During this period a total of 3191 km of seismic was shot, over 70% with two gun arrays operating. This was achieved in spite of 3.5 days loss as a result of bad weather and 20 hours loss for cable repairs as a result of fish bites. Seismic acquisition ceased on the afternoon of 1 December. The ship returned to Sydney at 1730 hrs on Thursday, 3 December.

Overall, the quality of the seismic data was very good. When shooting the two very long lines, the weather remained reasonably calm, and so noise levels were within specifications.

INTRODUCTION

The Lord Howe Rise (LHR) region is an enormous area of complex seabed lying 500-1500 km east of Australia, and extending over 20° of latitude (approximately 2200 km). It includes relatively shallow water elongate plateaus and ridges such as the Lord Howe Rise, and the Norfolk, West Norfolk and Dampier Ridges, and intervening deeper water basins such as the Lord Howe, Middleton and New Caledonia Basins (Fig. 1). The region is bounded in the west by the Tasman Basin and in the east by the North and South Norfolk Basins. Under the terms of the United Nations Law of the Sea Convention, Australia has a large seabed claim in this region because of its territorial ownership of Lord Howe Island, on the western Lord Howe Rise, and Norfolk and Philip Islands, on the Norfolk Ridge. Each of these islands would generate a 200 nautical mile Exclusive Economic Zone and related 'legal' Continental Shelf (LCS). There is a negotiated seabed boundary in the northern part of the region separating French and Australian territory, but as yet there is no negotiated seabed boundary separating New Zealand and Australian territory in the south. Article 76 of the 1982 United Nations Convention on the Law of the Sea provides a series of rules to determine a 'legal' outer limit for the LCS. Full application of these rules requires location of the foot-of-continental-slope, knowledge of sediment thickness to a least the edge of the continental rise, and good bathymetric information defining the 2500 isobath. The outer limit of the LCS must be defined at least every 60 nautical miles around parts of the margin extending beyond the EEZ. Seismic and bathymetric information are required over the southwestern Lord Howe Rise to ensure optimum definition of an Australian LCS. The total area of Australia's 'legal' Continental Shelf in the Lord Howe Rise region could be about 1.65 million km^2 - about 20% of the area of the Australian land mass. Therefore, a better knowledge of the geological framework and resource potential of the southern Lord Howe Rise and West Norfolk Ridge is required for any future seabed boundary negotiations between Australia and New Zealand in this region.

Although many line kilometres of seismic data have been collected throughout the Lord Howe Rise region, because of its vast size, coverage of most features remains sparse. Much of the seismic data was shot in the 1970's and is only of poor to fair quality. A summary of pre-1985 surveys in the region is given in Appendix 1. The most recent data sets were recorded in 1985 and 1989. In 1985 AGSO's R V *Rig Seismic* acquired

1250 km of 24 fold multichannel seismic data over the western Lord Howe Rise to the south of Lord Howe Island (Whitworth, Willcox and others, 1985). These data were recorded using a 2400 m streamer with 48 channels and two 500 cubic inch airguns. In 1985 the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in co-operation with AGSO used the R V *Sonne* to undertake a survey of the western Lord Howe Rise to the northeast of Lord Howe Island (Roeser and Shipboard Party, 1985). This survey collected 3600 km of 24 fold multichannel seismic data using a 2400 m streamer with 48 channels, and a 25.6 litre airgun array. In 1989 the Geophysics Division, Department of Scientific and Industrial Research, New Zealand, shot a grid of 1700 km of single-channel, digitally recorded seismic data over the southernmost part of the New Caledonia Basin (Uruski and Wood, 1991).

Analysis of these data has defined several areas that may have long-term petroleum potential. The most significant areas are the rift system beneath the western Lord Howe Rise, the New Caledonia basin and the Taranui Sea Valley area of the southern Norfolk Ridge. The eastern flank of Lord Howe Rise and the western flank of the West Norfolk Ridge are also considered to have some petroleum potential.

ACKNOWLEDGEMENTS

The cruise was developed in consultation with the Sea Law and Ocean Policy Group of the Department of Foreign Affairs and Trade, the Petroleum Division and Offshore Minerals and Policy Co-ordination Group of the Department of Primary Industries and Energy, the New Zealand Department of Foreign Affairs, and the New Zealand Institute of Geological and Nuclear Sciences Limited. A geophysicist, Dr H. Zhu, from the latter organisation took part on the cruise. Much of the planning for the cruise was developed by Phil Symonds and Jim Colwell, and they were responsible for siting the seismic lines and preparing the Cruise Proposal (Symonds and Colwell, 1992). We thank them for allowing us to use this document as a basis for this report.

STUDY TRANSECTS

The proposal for cruise 114 was to acquire approximately 3250 km of multichannel seismic and associated geophysical data along the cruise track outlined in Figure 2. The majority of the data was to be acquired mainly on two long regional lines, which extend from the Tasman Basin to the Norfolk Basin, using a 3000 m streamer (120 x 25 m groups), 49 litre sleeve gun arrays, 16 second records, and 30-fold coverage. The transects were designed to provide additional or new data on the following:

1. **Western LHR rift system:** Four dip line segments and one strike line over a complex zone of fault blocks and grabens/half grabens beneath the western LHR.
2. **LHR/West Norfolk Ridge transect:** Two very long (about 1000 and 800 km) lines across the whole province, from the Tasman Basin to the South Norfolk Basin. These lines are intended to link all the main structural elements in the region.
3. **Southwest margin of LHR:** Two segments of line cross the southwest flank of LHR to acquire data necessary for definition of a 'legal' Continental Shelf. These lines fill a data gap, and allow foot-of-continental-slope points to be determined at least 60 nautical miles as required by the continental shelf definition contained within Article 76 of the 1982 United Nations Convention on the Law of the Sea.

REGIONAL GEOLOGY

Much of the following discussion on the geological background of the region is taken from Willcox and others (1980), Symonds and Willcox (1989) and Symonds and Colwell (1992).

REGIONAL PHYSIOGRAPHY

The major submarine feature in the region, the Lord Howe Rise (Fig.1), extends north-northwest from the south island of New Zealand to Lord Howe Island and then north to the Chesterfield Island group at about 20°S. Lord Howe Rise is a plateau-like feature, which is most clearly defined by the 2000 m isobath - the crest of the rise is generally 750 to 1200 m below sea level. The small Middleton and Lord Howe Basins separate the northern Lord Howe Rise from the Dampier Ridge to the west. Beyond this, the 4500 m deep Tasman Basin extends to the narrow continental margin of eastern Australia. Lord Howe Rise is separated from the Norfolk Ridge to the east by the 3000-3500 m deep New Caledonia Basin. Eade (1988) divides the New Caledonia Basin into two parts - the New Caledonia Trough in the northeast and the Fairway Trough in the southwest (Fig. 1). These troughs are separated by a north-northwest-trending ridge system consisting of the Fairway Ridge in the north and an extension of the West Norfolk Ridge in the south.

The Norfolk Ridge system is a complex feature, which extends from the northern tip of New Zealand to New Caledonia (Fig. 1). The northern segment, which is north-trending, steep-sided and about 90 km wide, it is called the Norfolk Ridge. The southern, northwest-trending segment is offset to the west and forms a complex triple-ridge system about 200 km wide. The western part of the ridge complex is generally referred to as the West Norfolk Ridge, the central part as the Wanganella Ridge (Eade, 1988), and the eastern part as the Norfolk-Reinga-South Maria Ridge system (Eade, 1988). The crestal relief of the Norfolk/West Norfolk Ridge is more rugged than that of the Lord Howe Rise, and the crestal depth ranges generally from about 500 to 1500 m. The West Norfolk and Wanganella Ridges are separated by a narrow, 1500 m deep bathymetric trough, the Wanganella Trough. The Wanganella and Norfolk-Reinga-South Maria Ridges are separated by the poorly known Taranui Gap (Sea Valley), which lies on the eastern flank of the ridge system, near its point of offset, and the Reinga Basin (Eade, 1988). The 3500 m deep North Norfolk, or Kingston Basin, lies to the east of Norfolk Ridge to the northeast of Norfolk Island, and by the South Norfolk, or Norfolk Basin, to the east of the Norfolk-Reinga Ridge system.

CRUSTAL STRUCTURE AND TECTONIC EVOLUTION

Seismic refraction and gravity anomaly measurements (Officer, 1955; Dooley, 1963; Shor and others, 1971; Woodward and Hunt, 1971), and seafloor spreading magnetic anomalies (Ringis, 1972; Weissel and Hayes, 1977; Shaw, 1978), indicate that The Tasman Basin is a normal oceanic basin. The crust beneath the New Caledonia, Middleton and Lord Howe Basins is commonly considered to be oceanic, though it is slightly thicker than typical oceanic crust.

Seismic refraction surveys and gravity modelling over Lord Howe Rise (Shor and others, 1971) indicate that the crust is 26 km thick and of continental origin. The rise is largely composed of crust with a P-wave velocity of 6.0 km/s, which is similar to values found for the Australian continent (Shor and others, 1971). A recent study of marine magnetic anomalies in the Lord Howe Rise region (Schreckenberger and others, 1992) provides further evidence for the continental origin of both the LHR and

Dampier Ridge, and indicates strong magnetisation of the lower crust. Thus the Lord Howe Rise is a fragment of continental crust, with a velocity structure that is indistinguishable from the Australian continent. The complex nature of basement rocks beneath Lord Howe Rise, as shown by their seismic character and magnetic response, indicates that these rocks may once have formed part of the similarly complex Tasman Fold Belt of eastern Australia.

The Dampier Ridge is thought to be a continental fragment altered by rifting and igneous intrusions, and this theory seems to be confirmed by dredging carried out by R/V *Sonne* (Roeser and others, 1985), which recovered granite, microdiorite and felspathic sandstone (Symonds and others, 1988). The Lord Howe Rise and Dampier Ridge were detached from Australia during seafloor spreading, which commenced some 80 Ma ago and formed the Tasman Basin, and possibly the Middleton and Lord Howe Basins.

There is general agreement that at least part of the Norfolk Ridge system was rifted and separated from Gondwanaland, probably during the Late Cretaceous (Willcox and others, 1980; Kroenke, 1984). However, several hypotheses have been advanced to explain the Tertiary development of New Caledonia and its marine continuation southward, the Norfolk Ridge, and the adjacent New Caledonia Basin. These include the evolution of a complex arc system (Dubois and others, 1974; Kroenke, 1984), and arc migration and marginal basin development (Karig, 1971; Packham and Falvey, 1971). The pre-Permian metamorphic and sedimentary rocks forming the core of New Caledonia were once part of the ancient Australian (Gondwanaland) continent, so it is most probable that the core of the Norfolk Ridge is also continental. Kroenke (1984) proposed that by middle Eocene time north-south convergence had developed between the Australia and Pacific Plates resulting in subduction of the Australia Plate beneath the northwest-trending parts of the Norfolk Ridge system adjacent to New Caledonia and the West Norfolk Ridge. Eade (1988) argued that the convergence in the southern part of the region resulted in buckling of the oceanic, proto-New Caledonia Basin forming the Fairway, West Norfolk and Wanganella Ridges. This model infers that basement beneath the southern sector of the Norfolk Ridge system is oceanic.

The plate tectonic model for the evolution of this part of the southwest Pacific appears to have been one of progressive rifting of the eastern margin of the Australia-Antarctic supercontinent (Gondwana), followed by continental break-up and seafloor spreading, island arc development and the creation of new ocean basins by further seafloor spreading. The fragments of continental crust that were rifted, thinned and left stranded between the Tasman Basin and the New Caledonia Basin during this process subsided to form a complex zone of troughs and plateaus, extending from New Zealand in the south, through Lord Howe Rise, to the Queensland Plateau in the north. Recently, the region has been interpreted in terms of a detachment model (Etheridge and others, 1989; Lister and others, 1991) in which southeastern Australia is an underplated upper plate margin, with the Lord Howe Rise/Norfolk Ridge region being its complementary lower plate margin. This implies that a detachment system underlies the whole region, and that the Lord Howe Rise and Norfolk Ridge are composed of areas of extended upper continental crust, bounded by detachment branches, and underpinned by extended lower crust and upper mantle. The small intervening ocean basins may be floored by highly thinned lower continental crust and upper mantle. Some support for this idea is provided by the study of Uruski and Wood (1991), which correlated seismic sequences and structures of the southernmost part of the New Caledonia Basin with those of the adjacent Taranaki Basin, and concluded that this part of the New Caledonia Basin is a continental rift, that was active during the Cretaceous and may have been initiated in the Jurassic. They suggest that the rifting may have been initially related to back-arc tectonism associated with Mesozoic subduction (Bradshaw and others, 1981; Korsh and Wellman, 1988), and later to extension preceding breakup, seafloor spreading and continental margin formation.

SEAFLOOR SPREADING HISTORY

Seafloor spreading in the Tasman Basin resulted in the separation of Lord Howe Rise from Australia, and the development of the east Australian and Lord Howe Rise conjugate margins (Fig. 3). In the central Tasman Basin, breakup commenced about 80 Ma (Hayes and Ringis, 1973; Weissel and Hayes, 1977; Shaw, 1978, 1979), although Johnson and Veevers (1984) suggest that it may have occurred as early as 95 Ma, with the 95-80 Ma oceanic lithosphere remaining attached to Lord Howe Rise as a result of a ridge jump to Australia. Off the New South Wales margin, early seafloor spreading probably lay to the east of the Dampier Ridge, which has now been confirmed as a continental fragment (Symonds and others, 1988). A ridge jump to the west at about 69 Ma started seafloor spreading in the northern Tasman Basin, with some margin segments initially having a significant strike-slip component of separation (Shaw, 1978, 1979). Seafloor spreading adjacent to the Capricorn Basin did not commence until around 63 Ma, about the same time as in the Coral Sea Basin. The Coral/Tasman spreading ridges were presumably connected by a series of transform/ridge segments (Weissel and Watts, 1979; Shaw, 1979) through the Cato Trough (Fig. 3), although the spreading pattern has not yet been defined in this area. This single spreading system continued until 56 Ma, when the entire ridge system ceased activity.

A seafloor spreading, magnetic anomaly pattern has not been recognised in the New Caledonia Basin; however, Willcox and others (1980) suggested that it is somewhat older than the Tasman Basin, whereas Kroenke (1984) suggested that it began to open at about the same time but finished somewhat earlier - in the early Paleocene, rather than the early Eocene as in the Tasman Basin. The age of the North and South Norfolk Basins, to the east of the Norfolk Ridge, is also a matter of speculation. Launay and others (1982) defined magnetic anomalies 34 and 33 in the limited data set over these basins, giving them a Late Cretaceous (Campanian) age like the Tasman Basin. Eade (1988) recognised that the depth to basement in the North and South Norfolk Basins supported a Late Cretaceous age of breakup. Kroenke (1984), however, speculated that these basins formed during the late Eocene.

As mentioned above, part of this region has recently been interpreted in terms of a continental margin detachment model (Etheridge and others, 1989; Lister and others, 1991). This model implies that a detachment system underlies the whole region, and that the Lord Howe Rise and Norfolk Ridge are mainly composed of variously extended upper continental crust and thinned lower crust/upper mantle, whereas small intervening basins such as the New Caledonia Basin, those separating Lord Howe Rise and the Dampier Ridge, and perhaps the Cato Trough, may be floored only by highly thinned lower continental crust. This model tends to simplify the breakup history of the region by removing the need for small isolated areas of spreading and associated spreading ridge jumps.

REGIONAL STRATIGRAPHY

The only direct information on the nature of rocks on the Lord Howe Rise region comes from outcrop on Ball's Pyramid, and Lord Howe, Norfolk and Philip Islands; the Deep Sea Drilling Project (DSDP); dredging of a volcanic feature (Bentz, 1974) on the southeastern part of the Lord Howe Rise; and coring and dredging on the central Lord Howe Rise and southern Dampier Ridge during a 1985 BGR *Sonne* survey.

Lord Howe Island and Ball's Pyramid are volcanic features and form part of the Lord Howe Seamount Chain, which runs along the western margin of Lord Howe Rise. Game (1970) described at least three major eruptive periods on the islands, and considered that they began a early as the mid-Tertiary and ended with an eruptive episode that was isotopically dated as Late Miocene (7.7 Ma). Norfolk and Philip Islands, on the central Norfolk Ridge, were formed by Pliocene volcanic activity dated at 3.1-2.3 Ma (Jones and McDougall, 1973; Aziz-Ur Rahman and McDougall, 1973).

There are a number of DSDP holes in the region; three of which are directly relevant to this study - Sites 206 and 207 of Leg 21 (Burns, Andrews and others 1973), and Site 592 of Leg 90 (Kennett, von der Borch and others, 1986) (Figs 4 and 5). At Site 206 in the New Caledonia Basin a relatively uniform sequence of Early Palaeocene to ?Late Pleistocene calcareous ooze was intersected. Bathyal conditions prevailed throughout the deposition of the sampled units. At Site 207 on the southern Lord Howe Rise, the basal unit consisted of Upper Cretaceous rhyolitic lapilli tuffs and vitrophyric rhyolite flows; van der Lingen (1973) suggested that at least some of the flows were of subaerial or very shallow marine origin. The rhyolites, which have a mean potassium-argon age of 94 Ma (McDougall and van der Lingen, 1974), are overlain by a sandy sequence containing reworked rhyolitic material, and then by a Maastrichtian glauconitic silty claystone. The rarity of planktonic fossils in this claystone led Burns, Andrews and others (1973) to suggest that it was probably deposited in a shallow marine environment with restricted (non-oceanic) circulation. The remaining rocks at this site are mostly carbonate oozes of Palaeocene to Pleistocene age which were deposited well above the carbonate compensation depth. Palaeontological evidence at this site indicates that there was a rapid increase in the depth of sedimentation from relatively shallow water in the Maastrichtian to depths similar to present day (1400 m) by the Early Eocene. The major regional Eocene-Oligocene hiatus is present at both Sites 206 and 207, but is somewhat ill-defined at Site 207 because of mixing or slumping.

Site 592 is also on the southern Lord Howe Rise about 50 km north of Site 207. The bottom of the hole consists of Late Eocene to Early Oligocene ooze and chalk, overlain by middle Lower Miocene to Quaternary nannofossil ooze. The regional Eocene-Oligocene hiatus is well represented and corresponds with a significant angular unconformity on seismic data over the site.

Further direct evidence of the rocks forming Lord Howe Rise comes from dredges on the flank of a volcanic feature described by Bentz (1974) on the southwestern margin of the Rise (Launay and others, 1977). Olivine basalts, gabbros, and a mixture of hyaloclastic breccias and biomicrites were obtained; the biomicrites contained planktonic foraminifera of mid-Miocene or younger age.

In 1985 a co-operative BGR/BMR sampling and geochemical cruise using R V *Sonne* conducted dredging and coring operations over the central Lord Howe Rise and the southern Dampier Ridge (Roeser and Shipboard Party, 1985). The dredging on Lord Howe Rise occurred on a major northwest-southeast structural lineament about 250 km northeast of Lord Howe Island and yielded Mn/Fe nodules containing pebbles of sandstone, quartzite, coralline and ?algal limestone, phyllite and granite. A large block of shallow water calcarenite/calcirudite, thickly encrusted by Mn/Fe, was also obtained. The presence of intercalated mineralised layers within a complex stratigraphy of dark and dense Mn/Fe crusts may indicate that hydrothermal activity was associated with the structural zone (Roeser and Shipboard Party, 1985). Dredging on the eastern margin of the southern Dampier Ridge obtained fragments of slightly metamorphosed granite and ?microdiorite or andesite, together with felspathic sandstone, and confirmed for the first time that this feature is, at least in part, an elongate piece of continental crust. U-Pb, K-Ar and Rb-Sr dating of the igneous samples gave precise ages mainly in the range 250 to 270 Ma - mid Permian (McDougall and others, in press).

Willcox and others (1980) developed a seismic stratigraphic framework which allowed them to carry the direct site-related information described above throughout the central Lord Howe Rise region. Uruski and Wood (1991) developed a seismic stratigraphic framework for the southern New Caledonia Basin based on seismic ties to the exploration wells in the Taranaki Basin off northwest New Zealand.

PETROLEUM POTENTIAL

WESTERN LORD HOWE RISE

The general absence of Cretaceous rift basins along the eastern seaboard of Australia has led to speculation that the basins may have separated from Australia during breakup and seafloor spreading in the Tasman Basin, and may now be located beneath the western flank of Lord Howe Rise (Jongsma and Mutter, 1978). A zone of horst and graben structures of probable Cretaceous age, and some 200 km wide, exists on the western Lord Howe Rise in water depths of 1000-2000 m (Willcox and others, 1980). Elsewhere, particularly beneath the eastern third of the Lord Howe Rise, mainly thin sediments overlie basement, which is commonly planated. The grabens are up to 50 km wide, several tens of kilometres long, and are best developed north of Lord Howe Island, where sediment fill is up to 4500 m in places (Roeser and others, 1985). Diapiric structures, which suggest the movement of shale or possibly salt, have been recognised in several of the grabens (Roeser and others, op. cit.). South of Lord Howe Island, the extensional basins appear to be less complex. Work by *Rig Seismic* in this area (Whitworth, Willcox and others, 1985) indicates that some of the horst blocks southeast of Lord Howe Island may contain dipping strata of Mesozoic age, possibly comparable to the Strzelecki Group of the Gippsland Basin (Symonds and Willcox, 1989).

The nature of the sediments filling the basins on the Lord Howe Rise is a matter of conjecture. The sediments are generally assumed to be of late Mesozoic age, but correlation with the older sedimentary basins of eastern Australia cannot be completely ruled out (Symonds and Willcox, 1989). If the basins developed along the lines of classical models for rifted ('Atlantic-type' passive) margins, much of the earliest sediment fill would have been of fluvial-lacustrine origin, and may have contained a high proportion of organic material. However, at least the upper part of the Lord Howe Rise rift-fill section may depart from classical models. Evidence of wave-base erosion of several of the horst blocks, during the Late Cretaceous, implies that a shallow sea may have occupied the intervening grabens, and that anaerobic conditions favouring the deposition of petroleum source rocks may have prevailed due to restricted circulation (Willcox and others, 1980). Results from the DSDP Site 207 on the southern Lord Howe Rise confirm the presence of restricted shallow-marine silts and clays of Maastrichtian age overlying horst blocks (Burns and others, 1973). These sediments are similar in age and type to rocks dredged from the lower continental slope off southern

New South Wales, but are younger than similar marine sediments dredged from the eastern part of the Gippsland Basin (Marshall, 1988, 1990).

Up to 3000 m of sediment containing potential source rocks may occur in the basins of the western Lord Howe Rise. In general, the Maastrichtian shallow marine sequence has less than 1000 m of overburden, probably insufficient for petroleum formation. However, petroleum generation may have taken place in older sediments at depth within the grabens, or at shallower levels if, as suggested by the only heatflow measurement on the rise (Grim, 1969), heatflow was anomalously high. Despite the sparse knowledge of the area, three potential petroleum plays can be identified on the western Lord Howe Rise (Symonds and others, in prep.). Fault structural/ stratigraphic traps within the fluvial to shallow-marine, rift-fill sediments (Symonds and Willcox, 1989) are the most widespread potential play identified to date. Sub-unconformity traps created by dipping reflectors within the horst blocks, potentially sealed by the rift and post-breakup section, would be dependent on a source within the pre-rift 'Strzelecki equivalents' or older section. Potential plays are associated with diapir-like structures , which occur northeast of Lord Howe Island, in water depths of 1500 m. Because of the age of movement of the 'diapirs', this play is only valid if there has been late (?post-Oligocene) maturation and migration.

The eastern flank of the Gippsland Basin reconstructs against the western margin of the Lord Howe Rise south of Lord Howe Island prior to seafloor spreading in the Tasman Sea (Shaw, 1978). It has been suggested that the Gippsland Basin formed within the failed-arm of a three-branched rift system (Burke and Dewey, 1973), and this implies that dissected remnants of the other arms should occur beneath western Lord Howe Rise. Etheridge and others (1985, 1987) suggested that the Gippsland Basin was the product of NNE-SSW oriented extension in the Early Cretaceous. If such a phase of basin development affected Lord Howe Rise then today, following seafloor spreading in the Tasman Basin, the normal extensional faults would trend approximately northeast and any transfer faults or accommodation zones would trend northwest. These proposed trends are nearly perpendicular to those that have been mapped to the northeast of Lord Howe Island (Symonds and others, in prep). More recently, Willcox and others (1992) proposed that the Gippsland Basin formed as a transtensional basin during the Late Jurassic and Early Cretaceous, by NW-SE transport sub-parallel to the basin's axis. This implies that any Lord Howe Rise basins formed by a similar process would be bounded today by ENE-WSW trending major strike-slip fault systems. This is not a trend that has been recognised to date beneath western Lord Howe Rise. Willcox and others

(1992) also suggested that a Late Cretaceous phase of movement, along major ENE to NE-trending strike-slip faults associated with rifting along the future locus of Tasman Basin breakup, resulted in extension in Bass Strait, forming the Boobyalla Sub-basin, and compression and wrenching in the Gippsland Basin. This phase of tectonism could produce the NE-SW-trending transfer or strike-slip faults and NNW-SSE normal faults as mapped to the northeast of Lord Howe Island.

EASTERN FLANK OF LORD HOWE RISE

It has been suggested that the eastern flank of Lord Howe Rise might have formed an ancient seaboard of the Australian-Antarctic supercontinent (Willcox and others, 1980). A considerable thickness (about 2000 m) of clastic sediment was deposited across this margin during or before the Late Cretaceous . Most of this sediment was probably derived from the now planated basement blocks to the west. The sedimentary (?pelagic) overburden ranges from about 1000 m on the eastern edge of the Lord Howe Rise to more than 2000 m in the New Caledonia Basin.

Depositional environments favourable for both the production and preservation of marine petroleum source rocks may have occurred on this continental slope, as is thought to be the case on many other continental slopes around the world (Dow, 1979). Faulting, and folding of the ?Late Cretaceous sediment wedge, could provide structural traps for petroleum. The progradation observed on some profiles may give rise to stratigraphic traps . Petroleum migrating up dip could be trapped against the basement surface and at unconformities, and sealed by the overlying pelagic oozes.

NEW CALEDONIA BASIN

The New Caledonia Basin may contain at least 4000 m of sediment (3 seconds of reflection time) in places and, near its margins, the basal 2000 m of this section probably consists of Cretaceous marginal and shallow marine terrigenous sediments. This sequence was gently folded throughout the basin during the Late Cretaceous and early Tertiary, perhaps in response to convergent tectonics to the east. The basal sequence is overlain by deep-sea biogenic ooze.

The prospectivity of the New Caledonia Basin is difficult to assess, as both its origin and the depositional environment of the deeper sediment are uncertain. In theory, small enclosed ocean basins are among the most promising areas for petroleum accumulation (Hedberg and others, 1979). Proximity to land ensures deposition of thick sedimentary sections, where both terrestrial and marine organic matter accumulate, even in the centre of the basins. The restricted nature of the basins limits circulation and favours the preservation of organic matter, and favourable reservoirs are to be expected in deltaic and submarine fan sediments.

WEST NORFOLK RIDGE SYSTEM

The western part of the West Norfolk Ridge is underlain by relatively planar basement, which has been downfaulted to form flanking grabens which, in places, contain up to 3000 m of sediment. The sediments in the grabens are probably very similar to those already described within the rift basins beneath the Lord Howe Rise; however, on the West Norfolk Ridge, the rift-fill sediments have been folded, resulting in a larger variety of structural petroleum plays than on the Lord Howe Rise. The northern end of the Wanganella Trough, to the east of West Norfolk Ridge, is underlain by at least 1500 m of sediment containing mounded and progradative facies. This might be a deltaic sequence deposited along the trough during subaerial erosion and planation of the northern West Norfolk ridge. This sediment undoubtedly thickens to the south beyond Australia's putative Legal Continental Shelf. The Wanganella Ridge appears to be an area of shallow basement, and is flanked to the east by a narrow trough and ridge, which could be a volcanic feature.

TARANUI GAP (SEA VALLEY)

Up to 4000 m of faulted and folded sedimentary rocks occur in a complex graben-like feature beneath the head of the Taranui Gap, in less than 2000 m of water. Several prominent angular unconformities occur throughout the sedimentary section, but both the nature and depositional environment of the sediments, and the nature of the underlying basement are unknown. The structural style of the basin suggests wrench tectonics, and could indicate that the sediments were deposited in a dextral strike-slip zone which was responsible for the offset of the Norfolk Ridge.

NORFOLK-REINGA-SOUTH MARIA RIDGE SYSTEM

Small pockets of sediment cover basement on the Reinga Ridge (Davey, 1977). Dredging on the South Maria Ridge has recovered fine-grained volcanics of the Cretaceous Whangakea Volcanic Series, indurated greywacke of probable pre-Cretaceous age, and Tertiary sandstone and siltstone (Summerhayes, 1969). Eade (1988) suggested that the whole Norfolk-Reinga-South Maria Ridge system is a continental sliver which connects New Zealand to New Caledonia along the Norfolk Ridge.

SOUTH NORFOLK BASIN

The South Norfolk or Norfolk Basin is thought to be an oceanic basin formed by Late Cretaceous seafloor spreading (Eade, 1988). A Cretaceous age is supported by the existence of obducted oceanic crust and deep-sea sediments as old as 102 Ma in Northland, New Zealand (Brothers and Delaloye, 1982), which were emplaced from the northeast and presumably represents a southeastern extension of the South Norfolk Basin (Eade, 1988).

PETROLEUM POTENTIAL OF THE REGION

Symonds and Willcox (1989) used a volumetric/analogue approach to assess the petroleum potential of various features within the region, and concluded that the western Lord Howe Rise, the New Caledonia Basin and the Taranui Sea Valley areas are the most interesting from the view of long-term potential. They considered the western Lord Howe Rise basins, although promising in terms of total potential recovery, individually less attractive, because they appear to be mainly small and consequently may only contain relatively small quantities of source rock. The few larger grabens and basins so far identified might be the most promising areas: both the diapiric structures in the basin northeast of Lord Howe Island (Gower Basin; Roeser and others, 1985), and possible Mesozoic pre-rift sequences in fault blocks southeast of Lord Howe Island (Whitworth, Willcox and others, 1985) warrant further investigation. Symonds and Willcox (1989) rated the western Lord Howe Rise basins as having fair potential.

From the point of view of sediment volume, the New Caledonia Basin may have significant deep water potential. However, the exploration possibilities associated with this feature, which lies in relatively deep water, perhaps partially on oceanic lithosphere, are totally unknown. The northern Taranui Gap (Sea Valley) with its relatively thick (4000 m) sediment, and apparent structural complexity in moderate water depth (about 1600 m), has been rated as having fair potential (Symonds and Willcox, 1989).

CRUISE RESULTS

CRUISE NARRATIVE

The ship departed Sydney at 2000 hrs on Friday 6 November, 1992 and headed east towards the study area of the southern Lord Howe Rise. The first waypoint was reached on Monday, 9 November at 2115 hrs, and deployment of the seismic cable commenced. The streamer was fully deployed and balanced, and seismic acquisition commenced at 0100 hrs on Wednesday, 11 November (Line 114/01). The streamer had to be retrieved on 12 November because of damage to one section from fish bites. At 1500 hrs on November 13, acquisition was suspended because of an increasingly worsening sea state. Bad weather curtailed operations until 0640 hrs on Monday, 16 November when Line 114/02 was started. This line was shot across the Lord Howe Rise and New Caledonia Basin without incident, but on November 19 the ship had to come off line to repair several fish bites and replace a damaged section. Line 114/02 continued over the West Norfolk Ridge, Wanganella Trough, Norfolk Ridge and Taranui Sea Valley, before finishing on 21 November in the South Norfolk Basin.

Line 114/03, a short line to tie to the next long line, was commenced on 21 November, but had to be abandoned after only covering 15 km because of a deterioration of the sea state. The ship made its way slowly to the next waypoint. Line 114/04 was started at

0100 hrs on 22 November, but the ship came off line at 0530 hrs because of bad weather and increasing noise levels.

Line 114/04 was restarted at 1513 as seas began to abate. The line crossed the Reinga Ridge and then the Norfolk Ridge, West Norfolk Ridge, New Caledonia Basin and Lord Howe Rise. The line finished on the western flank of LHR at 2100 hrs on 25 November after covering 764 km.

Line 114/05 was commenced at 0223 hrs on 26 November along the southwestern flank of LHR. On NZOI bathymetric maps, the ship was supposed to cross the Monawai Sea Valley, but the sea floor remained flat. The line then rose up to the crest of the Dolphin Spur. The line finished at 2310 hrs.

Line 114/06, which was run up the spur to DSDP Site 207, started at 0036 hrs on 27 November. Site 207 was reached by 1400 hrs and the ship then did a butterfly turn to tie the hole into Line 114/07, which was started at 1615 hrs. This line ran north to tie to DSDP Site 592, which was reached at 2320 hrs. The tie to Site 592 was carried through at the start of Line 114/08. This line extends from Site 592 to the major tie line for the cruise. Line 114/09, the tie line, was started at 1309 hrs on 28 November. Seismic acquisition ceased on the afternoon of 1 December. The ship docked at Pymont, Sydney at 1730 hrs on Thursday, 3 December.

SEISMIC INTERPRETATION

The following section is a preliminary description and interpretation of the monitor records on board ship. While the record length during the survey was 12 seconds (for Line 114/01) and 16 seconds, this interpretation is confined to the shallow layers that could usually be observed above the first multiple. A more detailed analysis awaits processing of the data.

Western Lord Howe Rise

The general absence of Cretaceous extensional basins on the continental margin of southeastern Australia has led to speculation that the basins may have become detached, and are now located beneath the western flank of LHR (Jongsma and Mutter, 1978). A zone of horst and graben structures, possibly of this age and some 200 km wide, has been described by Willcox and others (1980). These grabens, which are up to 50 km wide and several tens of kilometres long, trend in a north northwesterly direction. North of Lord Howe Island, the grabens contain up to 4500 m of sediment. Results from DSDP Site 207 (Burns and others, 1973) show that restricted shallow marine silts and clays of Maastrichtian age overlie horst blocks of southern LHR.

Several graben or half-graben features were encountered on the western LHR during Cruise 114. These were located mainly on Line 114/01 and the western end of Lines 114/02 and 114/04. These grabens range from 5-23 km in width and are filled by 1.0-1.8 sec. (TWT) of sediment whose reflection characteristics indicate a range from poorly to well bedded (Fig. 6). The graben fill is overlain by 0.6-0.7 sec. (TWT) of well bedded sediment. These two sequences are divided by a fairly prominent unconformity. Following Willcox and others (1980) analysis of the sequence stratigraphy of the Lord Howe Rise, we would equate this with the Maastrichtian breakup unconformity.

There has been some debate about the nature of these grabens, particularly as to whether or not they are true half-grabens that have been formed by rotational faults. That they are half-grabens is crucial to Jongsma and Mutter's (1978) interpretation of the western half of the LHR as the pre-Tasman rift basin. This has been questioned by Willcox and others (1980).

Most of the grabens encountered on this cruise tend to form a symmetrical V-shaped depression, although several do exhibit a typical half-graben profile. In many of the grabens, the sediments are poorly reflective and it is difficult to distinguish whether the bedding characteristics are typical of syn-rift fill. However, in those grabens that do show reasonably good reflection character, it is apparent that sequences are thick on one side and thin toward the other (Fig. 6). This is particularly obvious in the more asymmetric grabens. At this stage, the question of whether these are true half-grabens awaits clarification, hopefully after processing. If they are half-grabens, their western sides would represent the hanging wall; i.e. the fault planes dip to the east.

Crestal Zone of the Lord Howe Rise

Seismic basement is very shallow beneath the crest of the Lord Howe Rise; of the order of 40-400 m sec (TWT). The basement surface is reasonably planated, with low amplitude highs and lows of the order of 100 metres wide. The overlying sediments are aggradational and highly reflective. The sediment wedge begins to thicken both on the eastern and western edges of the crest.

A series of small half grabens occur on the crest of the Rise. On line 114/01 there is a small graben, about 5 km wide. There is about 700 m sec of horizontally bedded, highly reflective sediment fill at the top of the sequence which is post rift. Beneath that is a 1.6 sec thick sequence of poorly reflective rift fill sediments. On line 114/04 there is a 18.5 km wide half-graben structure, just over the crest of the Rise, with up to 1.5 sec of syn-rift sediment within it.. The syn-rift sediment is well layered and forms a prominent rollover. The top of the syn-rift section has been truncated by a prominent unconformity, which shows both negative and positive relief. Following Willcox and others (1980) we would equate it with the Maastrichtian breakup unconformity. Another mild disconformity in the overlying sedimentary sequence could possibly be equated with Willcox and others (1980) B/C boundary of Eocene age

In places near the crest of the Rise, the seismic records become complicated due to the frequent occurrence of volcanic intrusions. For a distance of some 55 km on line 114/01 intrusions are prominent. Most occur in the subsurface, with only two emerging as relief above the general level of the seafloor, with relief up to 300 m. Several grabens could be present along this part of the rise, but on the monitors they tend to be masked somewhat by the intrusives.

Eastern Lord Howe Rise

The sedimentary sequence thickens markedly down the eastern flank of the Lord Howe Rise. Towards the foot of the slope, basement appears to be faulted, dropping from 4.0 to 6.0 sec in less than 4 km (Fig. 7). A similar fault? can be observed in line SO-7-001A in the same vicinity as line 114/02 (Fig. 8). Above this basement escarpment is a thick lens of almost seismically transparent sediment. What bedding can be discerned is concave upwards rather than progradative, and this makes the environment of deposition of the sediment lens somewhat conjectural, particularly if it was a shelf margin, as suggested by Willcox and others (1980). One would expect progradational outbuilding of a planar-convex nature if it were the latter. The upper boundary of this transparent sequence is unconformable and extends down beneath the New Caledonia Basin. According to Willcox and others (1980) sequence stratigraphic interpretation, the unconformity could represent their D/E boundary. They suggest that the D/E boundary or disconformity is widespread throughout the region and is representative of the Maastrichtian breakup unconformity of the Tasman Basin.

New Caledonia Basin

In the area of the survey, the New Caledonia Basin forms a fairly narrow, elongate basin, of the order of 100-150 km in width. The floor of the basin is extremely flat at around 3000-3200 m water depth. The monitor records show up to 3 seconds of penetration beneath the basin floor, with several well developed sequences displayed (Fig. 9). It is possible to divide the section into six sequences similar to those defined by Willcox and others (1980). The upper sequence of well bedded sediments appears to be equivalent their A to C sequences (Fig. 8), which they indicate consist of Tertiary pelagic carbonates. The B/C boundary in Figure 9 is a reasonably continuous reflection across the basin, and can be equated with the Eocene/Oligocene unconformity that is widespread in the region (Kennett and others, 1972). The fourth sequence consists of fairly well bedded sediments with a disconformable base. This can be related to sequence D of Willcox and others (1980), suggesting that it is the equivalent of the sequence of shallow marine silts and clays of Paleocene to Maastrichtian age encountered at the base of DSDP site 207. Willcox and others (1980) suggest that sediments above basement (their sequence E) would be of continental or shallow marine origin. The sequence stratigraphy of the New Caledonia Basin appears to be very uniform across the basin.

Along the western margin of the New caledonia Basin, a 1.6 sec section of well bedded horizontal sediments onlap and thin against the C/D boundary (Fig. 7), which here forms the surface of the Lord Howe Rise. On the eastern side of the basin, basement descends steeply from the Western Norfolk Ridge down beneath the New Caledonia Basin. The D/E boundary parallels it to some extent, and in between is a 1.4 sec thick section of sediment of likely Cretaceous age. Beneath the toe of the slope, the C/D boundary appears to form the top of a prominent slump structure, although bedding is distinguishable within it. Reflectors within the higher sequences onlap the C/D boundary at this particular point.

West Norfolk Ridge System

Basement rises along the eastern margin of the New Caledonia Basin and then continues up to the West Norfolk Ridge. While there can be up to 1 sec of sediment above basement on the ridge, basement does tend to be very shallow or even crop out on its flank. At the summit, the ridge sometimes forms a mesa-like feature in about 300 m of water, the flat top indicating planation by wave base at some stage in the past. This suggests that parts of the Ridge were emergent at times. Over most of the crest of the rise there is about 400 m of sediment over a basement that is planated on the western side, but becomes more rugged to the east.

Wanganella Trough

The Wanganella Trough shows a fairly similar half graben morphology on both crossings of this feature. On the eastern, side the basement surface is steeply dipping, and there is some suggestion of faulting, whereas beneath the western part of the trough, basement is gently dipping, and rises slowly to crop out on the foothills of the West Norfolk Ridge (Fig. 10). The sediment fill, of unknown age and origin, shows typical syn-rift thickening on the eastern side, and thinning and onlapping basement to the west. Maximum sedimentary thickness is about 2 sec.

Norfolk Ridge to Reinga Ridge

From the Wanganella Trough, basement rises steeply and crops out along the short slope of the Norfolk Ridge. The crest of the Ridge is planated and there appears to be very little sediment cover on top. The top of the ridge is in about 375 m of water. From the Norfolk Ridge the seafloor slopes down to an extensive gently sloping plain before rising onto the Reinga Ridge. From the top of the Ridge at about 1900 m, the seafloor descends to the floor of the South Norfolk Basin at a depth of 3900 m. In the subsurface there are number of sequences above basement. The lower sequence about 3.6 and 4.6 sec is unbedded and is a bit like Willcox and others (1980) sequence E (U. Cret.?). The upper boundary of this sequence forms an unconformity, while the lower boundary is basement. Above the unconformity the sediments are layered and probably represent Tertiary pelagic carbonates. The total sedimentary thickness is about 2.0 sec.

Closer to the Norfolk Ridge the sedimentary cover begins to thin over a "basement" high, but on the eastern side of this high the sedimentary sequence thickens dramatically. There is a major drop off in basement at this point. There appear to be at least two faults in basement, from a series of diffractions seen at depth, but the relationship between individual fault blocks is far from clear. Over the first fault basement appears to drop about 0.8 sec, but it then rises almost straight away to the sea floor. This latter high may be an intrusion that has come up the second fault. On the western side of the second fault, basement begins to drop away fairly rapidly and the sedimentary pile begins to thicken, immediately in front of the Norfolk Ridge. Similar to the Taranui Sea Valley there is a complex arrangement of sedimentary sequences with one sequence downlapping and onlapping onto an earlier sequence and then a third sequence onlapping the second. While this arrangement is similar to the sedimentary pile in the Taranui Sea Valley, there are several differences. In the Norfolk Ridge to Reinga Ridge sedimentary succession, the sediments are not folded, and there is a large offset in their respective positions to the Norfolk Ridge.

Taranui Gap (Sea Valley)

On line 114/02 the eastern flank of the Norfolk Ridge slopes down into the Taranui Sea Valley. For a distance of about 37 km there is a complex trough-like feature beneath the Taranui Sea Valley (Fig. 11). The basement horizon coming down from the Norfolk Ridge becomes very steep and is lost at about 5 sec on the seismic monitor section. Above basement the sediments form an anticlinal structure, whereas east of the anticline, the lower part of the sedimentary sequence begins to rise rapidly towards the seafloor (Fig. 11).

In the trough the sedimentary sequences show onlap onto both sides of the trough. Differences in the direction of onlap and downlap within the sedimentary section suggest uplift first on the eastern side, then a compressional event on the western side, resulting in the anticlinal structure, and then downlap onto it.

On the western side of the trough, the seafloor rises up to a ridge with a rugged topography. Beneath this ridge, the reflections become broken up and there are indications of imbrication. The ridge is highly faulted, with fault planes having the opposite dip on either side. This area appears to have undergone considerable crustal shortening at some stage, again suggesting a collisional event of some magnitude. The combination of an imbricated ridge and the trough formed by the Taranui Gap behind it could indicate some form of incipient foreland basin development in the past.

South Norfolk Basin

At the junction of the steeply sloping Reinga Ridge and the relatively flat sea floor of the South Norfolk Basin, basement crops out as a small ridge before descending beneath the floor of the South Norfolk Basin. This "basement" reflection can be traced for about 12 km beneath the abyssal plain and it is eventually lost at a depth of about 8 seconds (Fig. 12). However, another prominent surface, which elsewhere in the basin represents seismic basement, is present higher in the sequence. This higher "basement" surface is gently undulating and in places it breaks through the flat seafloor and forms abyssal hills. This basement does appear to be volcanic and is considered to be oceanic crust; in which case, the lower surface seen near the western margin of the basin, and which actually crops out there, may be either lower crust? or upper mantle.

CONCLUSIONS

Survey 114 achieved all of the major objectives of Project 121.30 Lord Howe Rise and Norfolk Ridge 'Law of the Sea' Study. The 3191 km of seismic reflection data was acquired mainly with two gun arrays under conditions that for the majority of time could only be described as ideal for this part of the world. Obviously, the success of the deep seismic profiling will have to await the outcome of processing, but it is anticipated that this deep crustal dataset will present new insights into the tectonic development and resource potential of the region.

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APPENDIX 1

SUMMARY OF PRE-1985 SURVEYS IN THE LORD HOWE RISE/WEST NORFOLK RIDGE REGION

Vessel	Cruise	Date	Seismic	Gravity	Magnetic	Other
BERGALL ISLAND (Deep Freeze)		1949	No	Pendulum	No	
CHALLENGER		1951	No	No	No	Refraction
TELEMACHUS		1956	No	Pendulum	No	
STRATEN ISLAND (Deep Freeze)		1960	No	No	Yes	
VEMA	V18	1962	Explosives	Yes	Yes	
CONRAD	C9	1964	Explosives	Yes	Yes	
ELTANIN	ELT 26	1966	Air gun	Yes	Yes	
TARANUI		1966	No	No	Yes	
TARANUI		1967	No	No	Yes	
ELTANIN	ELT 29	1967	Air gun	Yes	Yes	
ARGO	NOVA	1967	Air gun	Yes	Yes	Refraction
HORIZON	NOVA	1967	Sparker	Yes	Yes	Refraction
OCEANOGRAPHER		1967	No	yes	Yes	
ELTANIN	ELT 34	1968	Air gun	Yes	Yes	
ELTANIN	ELT 39	1969	Air gun	Yes	Yes	Sonobuoys
UNITED GEOPHYSICAL		1970	Yes	Yes	No	
CORIOLIS	C1	1971	Air gun	No	Yes	
CORIOLIS	C2	1971	Air gun	No	Yes	
ELTANIN	ELT 47	1971	Air gun	Yes	Yes	Sonobuoys
KANA KEOKI		1971	Air gun, sparker	Yes	Yes	
KIMBLA	K3	1971	Air gun	No	Yes	
KIMBLA	K4	1971	Air gun	No	Yes	
LADY CHRISTINE	BMR14/3	1971	Sparker	Yes	Yes	Sonobuoys
GLOMAR CHALLENGER	DSDP 21	1971/72	Air gun	No	No	Sonobuoy Drilling
CORIOLIS	Austradec 1	1972	Flexichoc	No	Yes	
FRED V H MOORE	Mobil	1972	HI/FES, air gun	Yes	Yes	Sonobuoys
CORIOLIS	Austradec 2	1973	Flexichoc	No	Yes	
GLOMAR CHALLENGER	DSDP 29	1973	Air gun	No	No	Sonobuoys Drilling
SONNE	SO-7A	1979	Air gun array	Yes	Yes	Sonobuoys

APPENDIX 2

SEISMIC DATA FOR LORD HOWE RISE 'LAW OF SEA' STUDY (SURVEY 114)

Seismic Waypoints

LINE	START TIME (DDD.HHMM)	START POSITION	END TIME (DDD.HHMM)	END POSITION
114/01	315.1546	33° 55.86'S 164° 02.38'E	318.0510	35° 32.59'S 159° 27.94'E
114/02 Part A	320.1909	36° 02.83'S 159° 37.58'E	322.1955	34° 38.08'S 164° 18.70'E
114/02 Part B	322.1955	34° 38.08'S 164° 18.70'E	325.2217	31° 46.04'S 169° 18.66'E
114/03	326.0314	31° 46.06'S 169° 16.28'E	326.0420	31° 50.39'S 169° 19.66'E
114/04	326.1222	32° 13.00'S 169° 42.63'E	330.1056	36° 30.25'S 163° 03.00'E
114/05	330.1423	36° 28.72'S 163° 04.66'E	331.1058	37° 42.46'S 164° 34.80'E
114/06	331.1257	37° 41.42'S 164° 32.47'E	332.0149	36° 55.63'S 165° 28.64'E
114/07	332.0436	36° 58.96'S 165° 26.05'E	332.1121	36° 25.45'S 165° 26.57"E
114/08	332.1427	36° 28.39'S 165° 31.49'E	332.2248	36.28.40'S 164° 40.06'E
114/09 Part A	333.0109	36° 29.34'S 164° 43.49'E	333.1435	35° 38.06'S 163° 50.56'E
114/09 Part B	333.1435	35° 38.06'S 163° 50.56'E	335.2251	33° 50.17'S 161° 10.24'E
114/09 Part C	335.2251	33° 50.17'S 161° 10.24'E	336.0432	33° 43.74'S 160° 39.36'E

Seismic Line Summary

Line	First good shot	Time (ddd.hhmm)	Last good shot	Time (ddd.hhmm)	Distance (nm)	Distance (km)
114/01	145	315.1546	9667	318.0510	245.4	454.5
114/02	184	320.1909	20779	325.2217	548.6	1016.1
114/03	164	326.0314	366	326.0420	5.2	9.6
114/04	166	326.1222	15799	330.1056	418.5	775.0
114/05	189	330.1423	4000	331.1058	103.0	190.7
114/06	164	331.1257	2535	332.0149	64.0	118.5
114/07	164	332.0436	1406	332.1121	33.5	62.1
114/08	168	332.1427	1700	332.2248	41.4	76.6
114/09	164	333.0109	10718	336.0432	263.5	487.9
				Total	1723.5	3191.0

APPENDIX 3

SEISMIC ACQUISITION PARAMETERS FOR SURVEY 114

Seismic streamer configuration:

Standard	length	3000 m
	group length	25 m
	number channels	120

Seismic source

sleeve gun capacity	50 litres (3000 cu in)
gun pressure	1800 psi (normal)
	1600 psi (minimum)
shot interval	19.4 sec @ 5 knots

Recording parameters

fold	3000%
record length	16 s
sample interval	2 ms

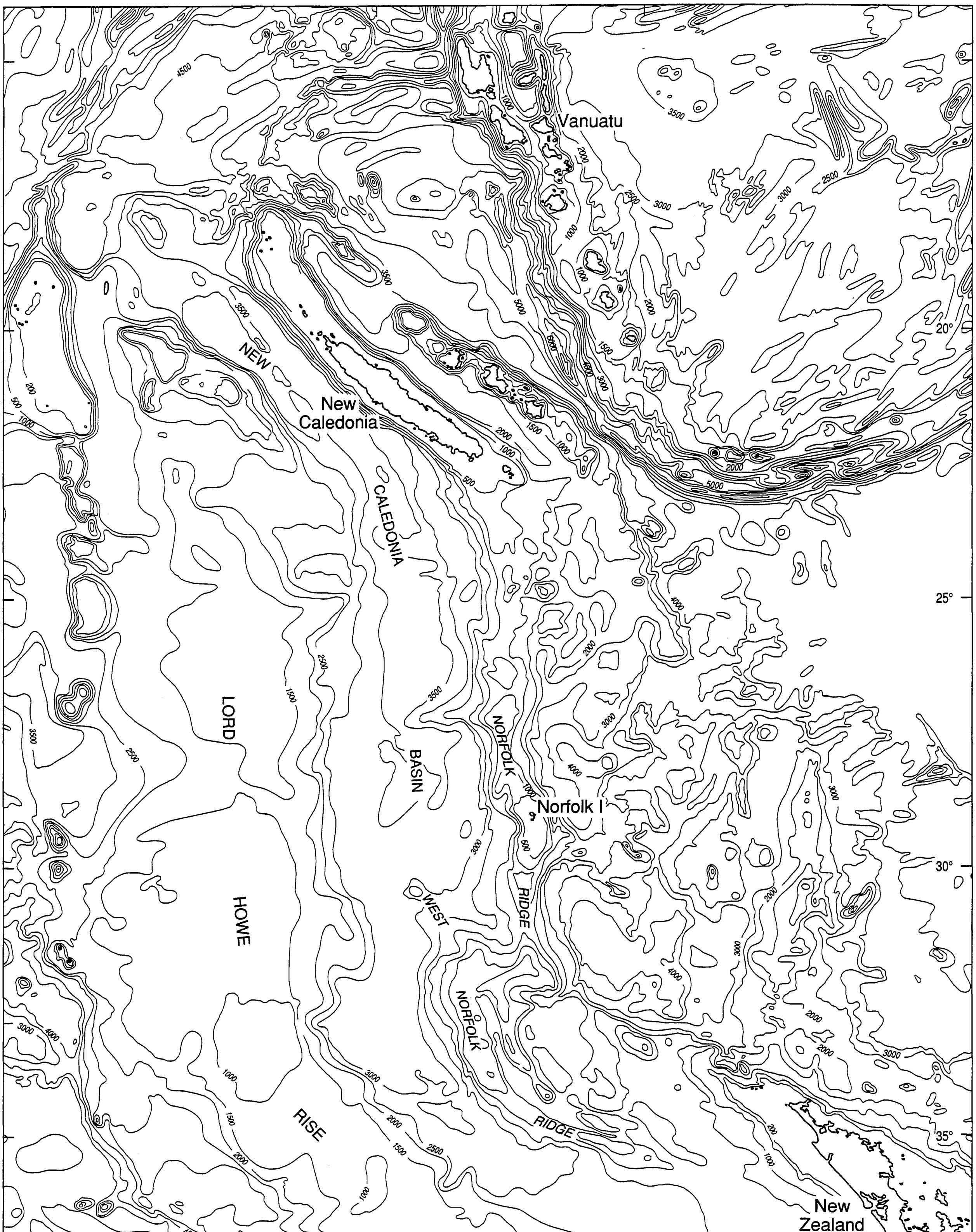

Figure 1. Bathymetry of the Lord Howe Rise/Norfolk Ridge region.

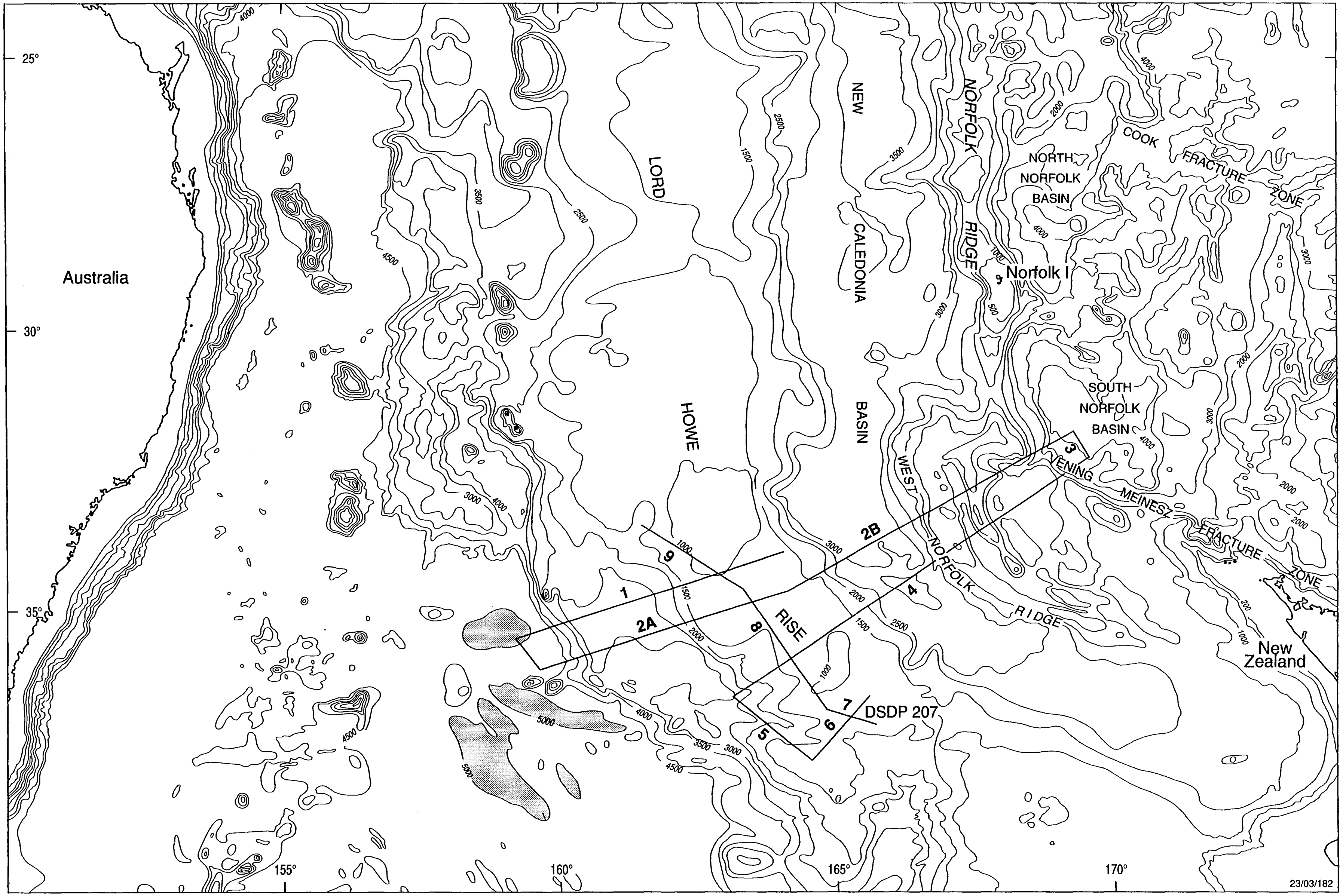

Figure 2. Map of the southern Lord Howe Rise region showing the location of Survey 114 seismic lines.

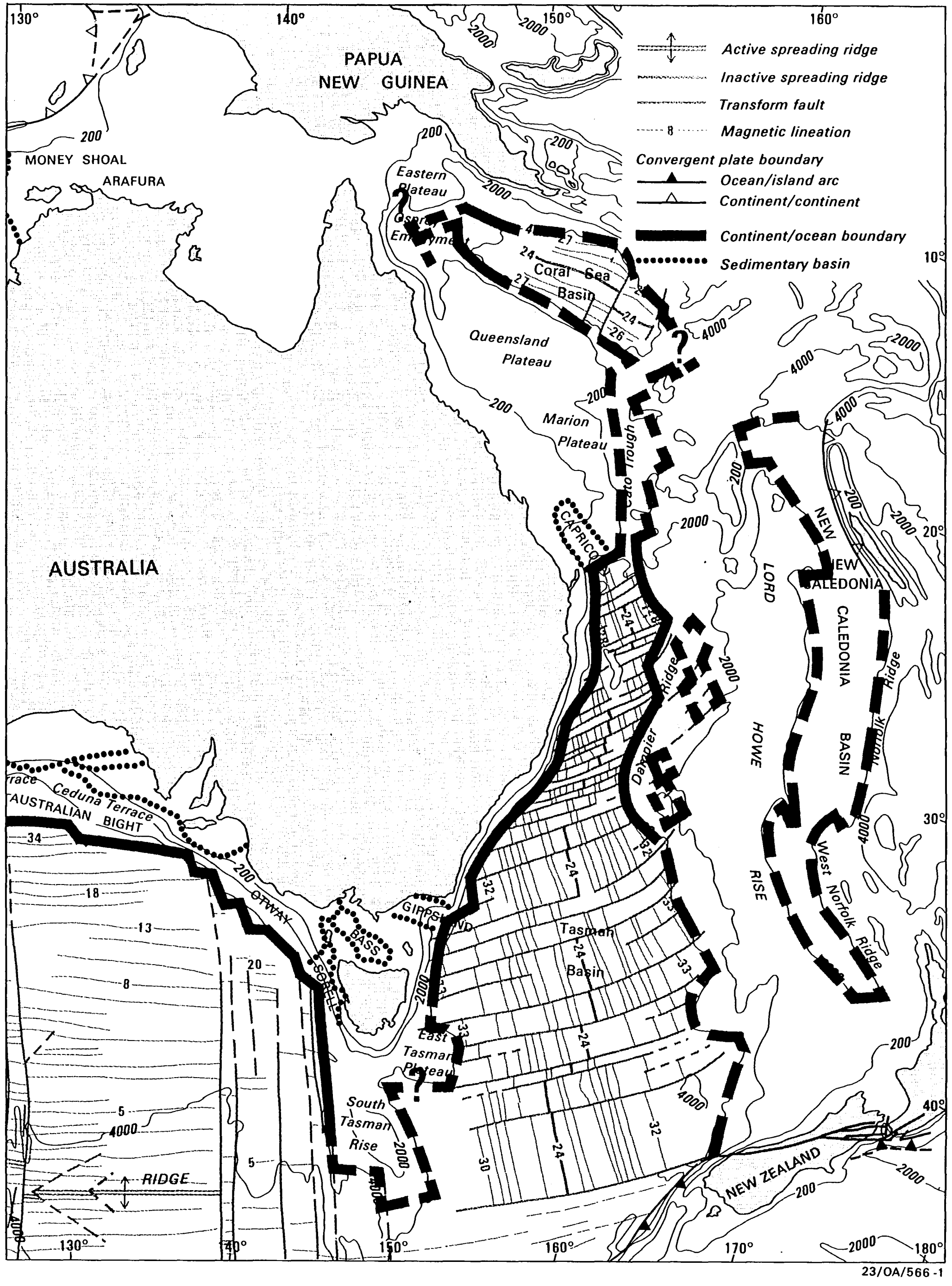

Figure 3. Seafloor spreading magnetic lineation pattern off eastern Australia.

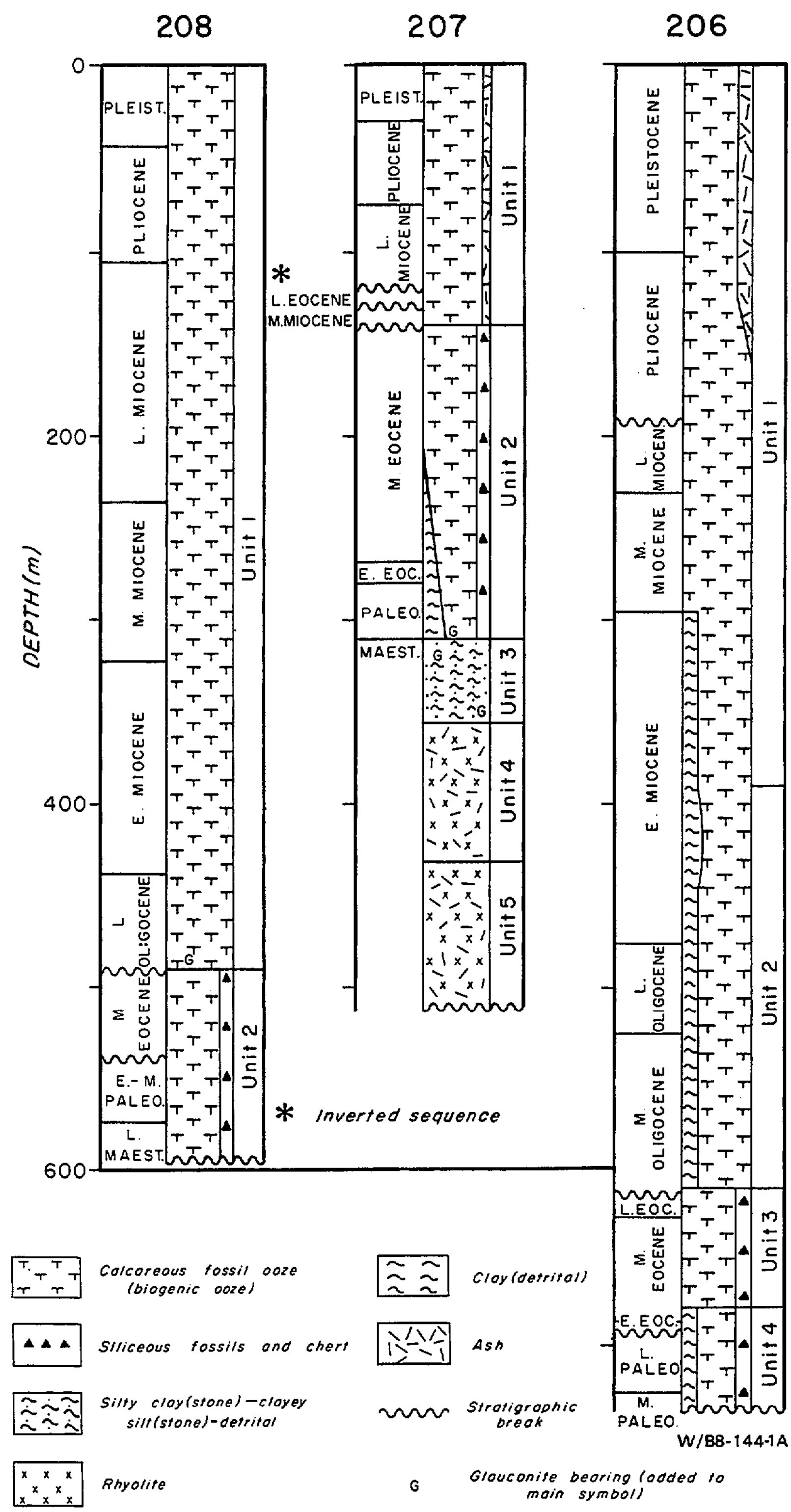

Figure 4. Summary logs of DSDP Leg 21 Sites 206, 207 and 208 drilling results.

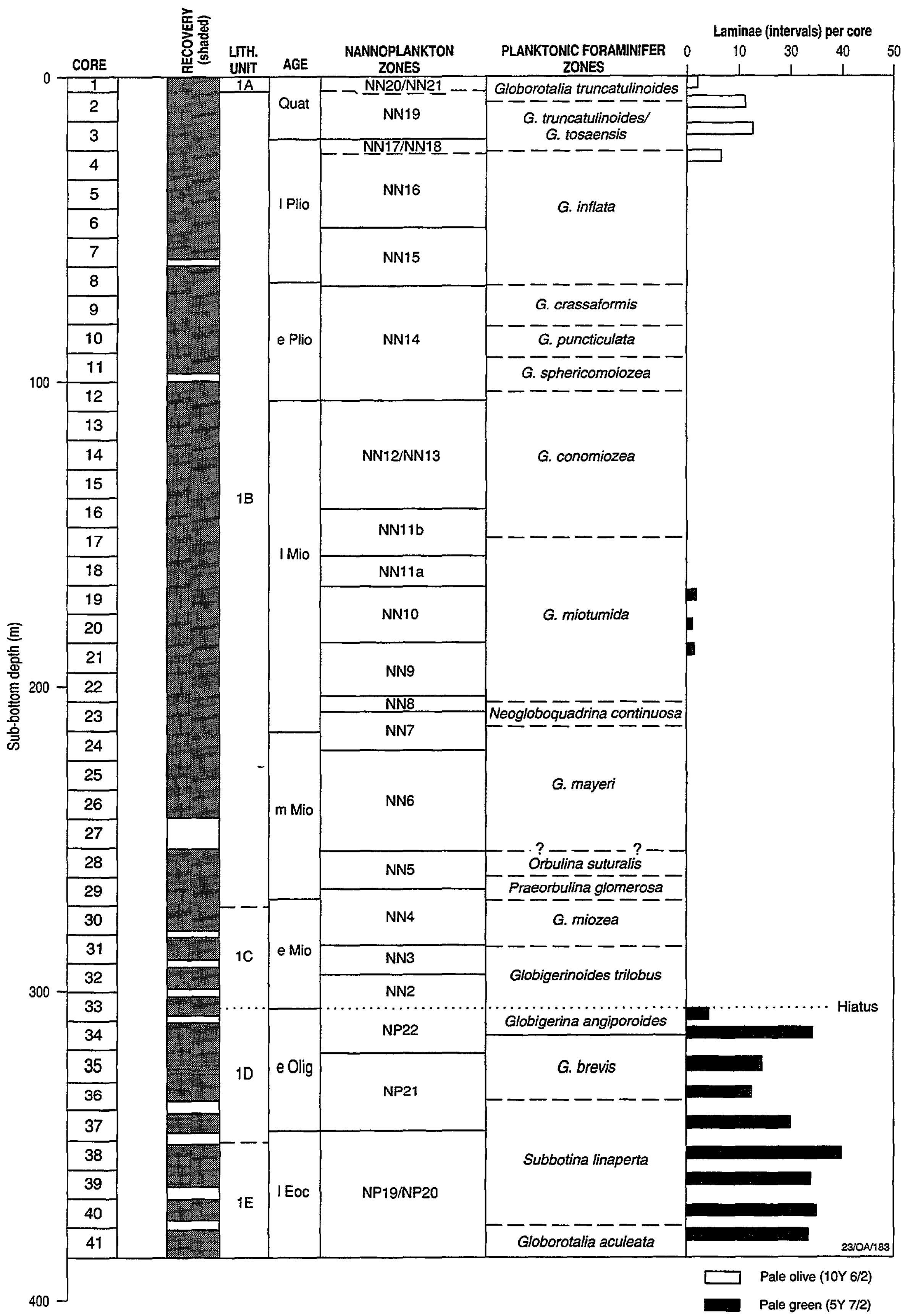

Figure 5. Summary of DSDP Leg 90 Site 592 drilling results.

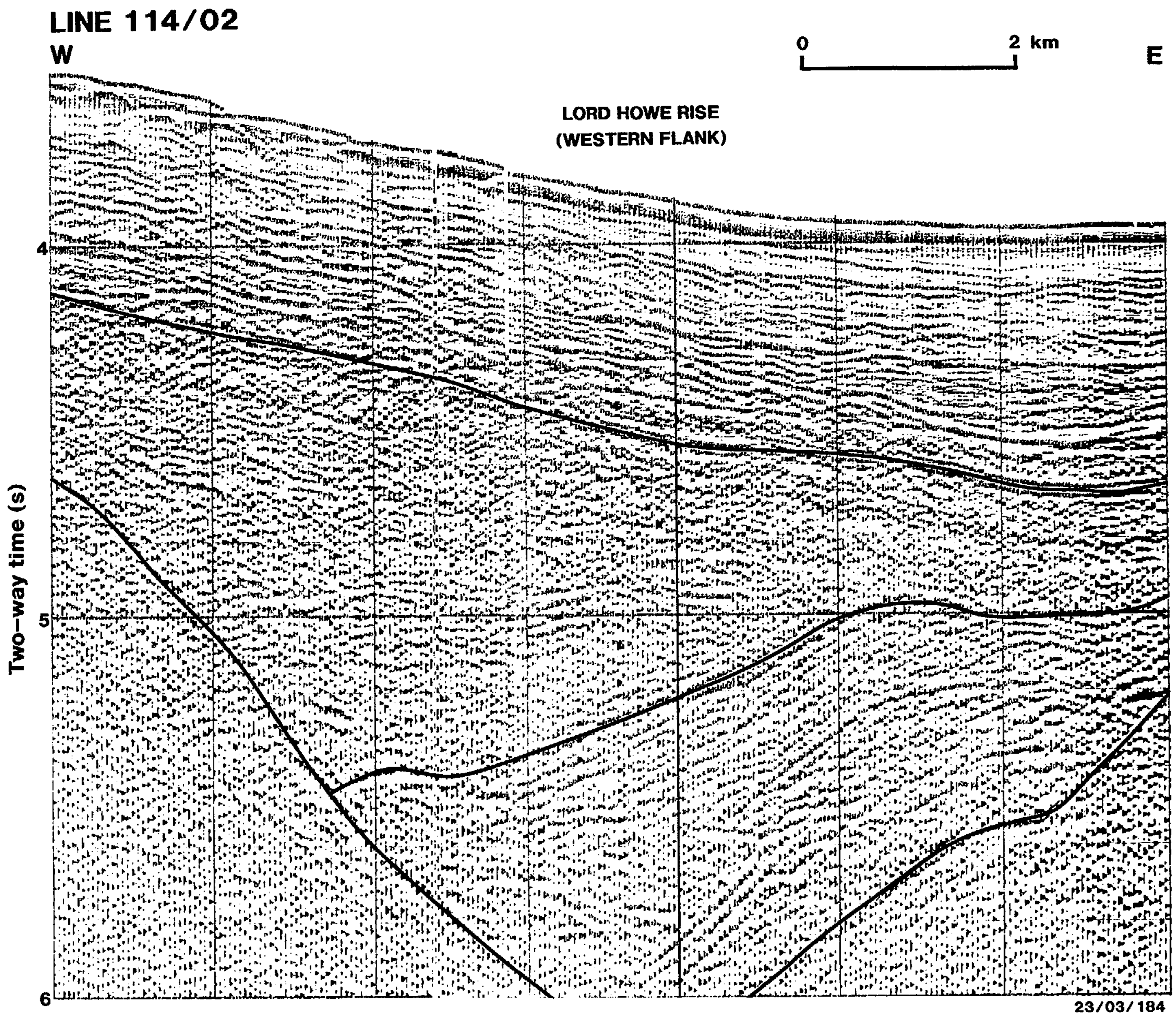

Figure 6. Shipboard seismic monitor display of an half-graben from the western flank of the Lord Howe Rise.

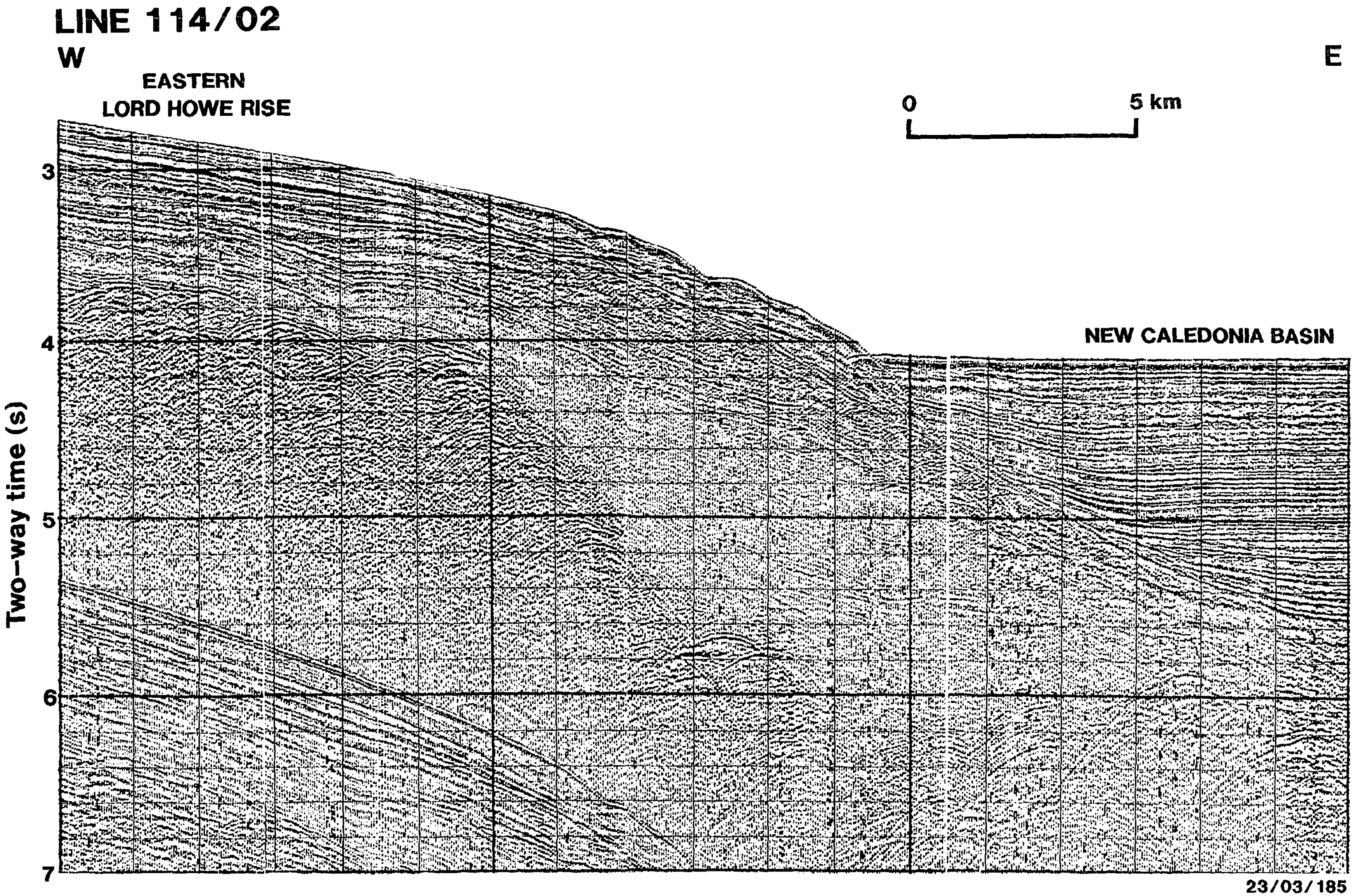

Figure 7. Shipboard monitor section of the eastern flank of the Lord Howe Rise

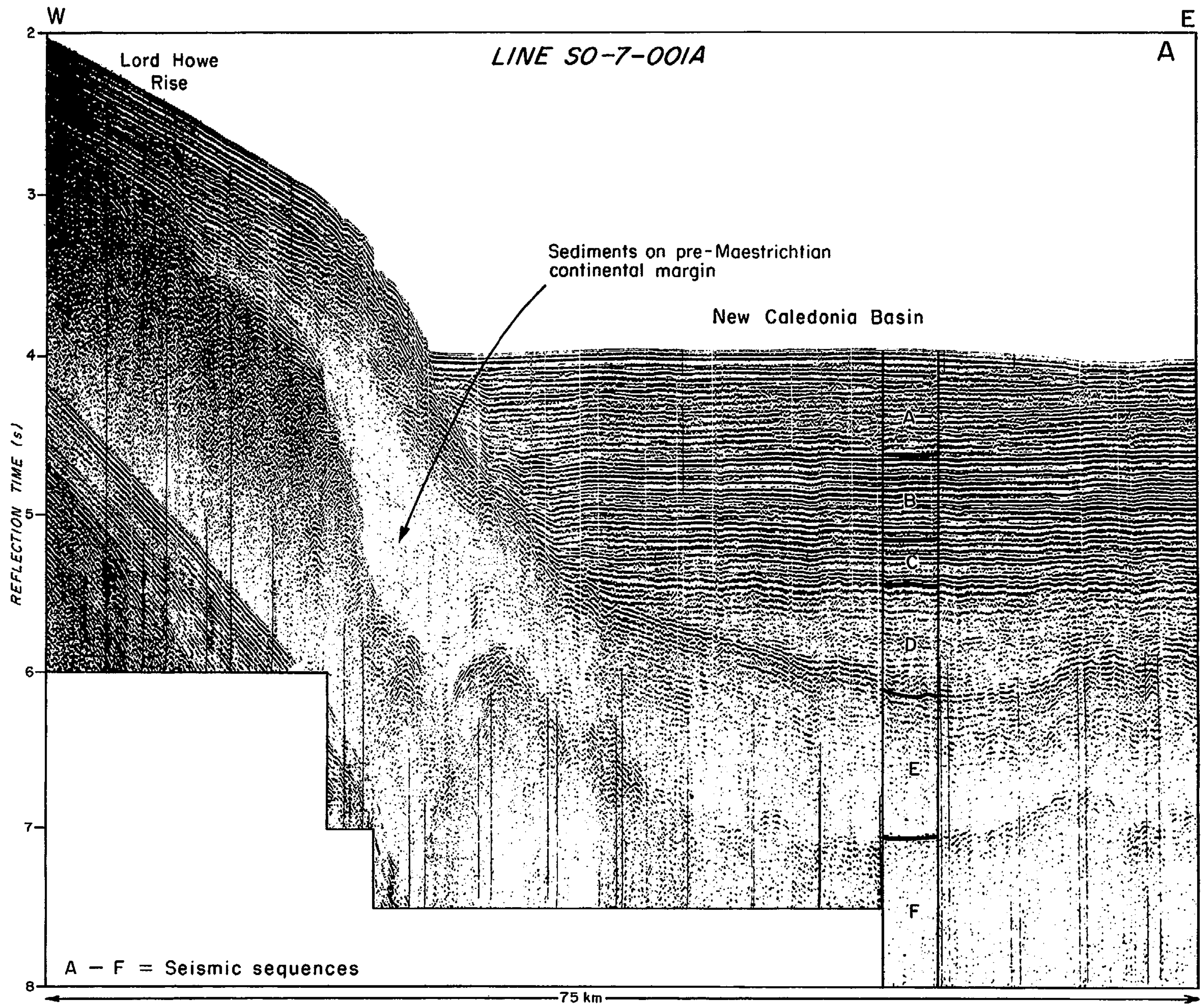

Figure 8. R.V.*Sonne* profile across the eastern Lord Howe Rise and the New Caledonia Basin (after Willcox and others, 1980).

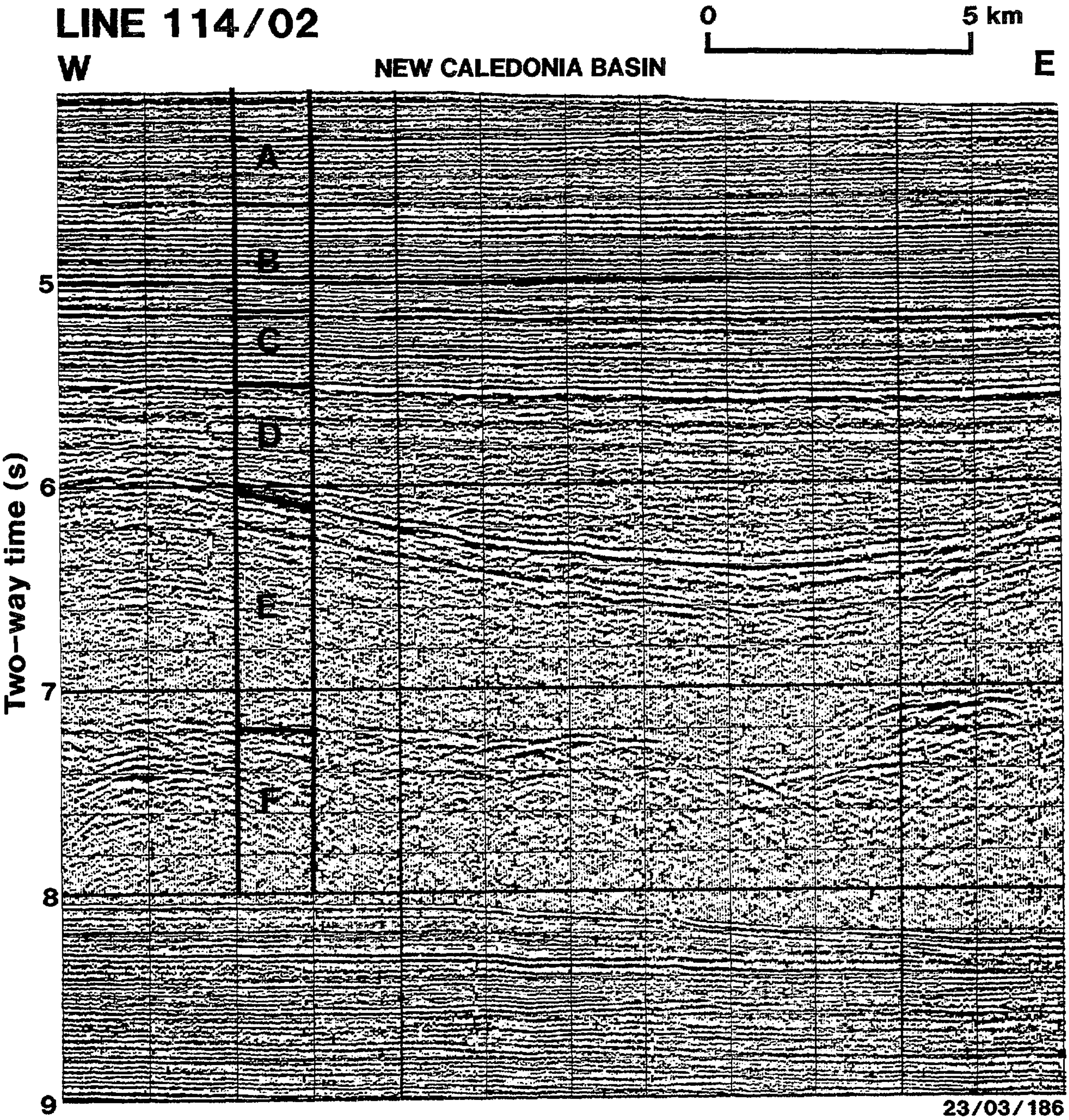

Figure 9. Interpreted statigraphic sequence beneath the New Caledonia Basin after Willcox and others (1980).

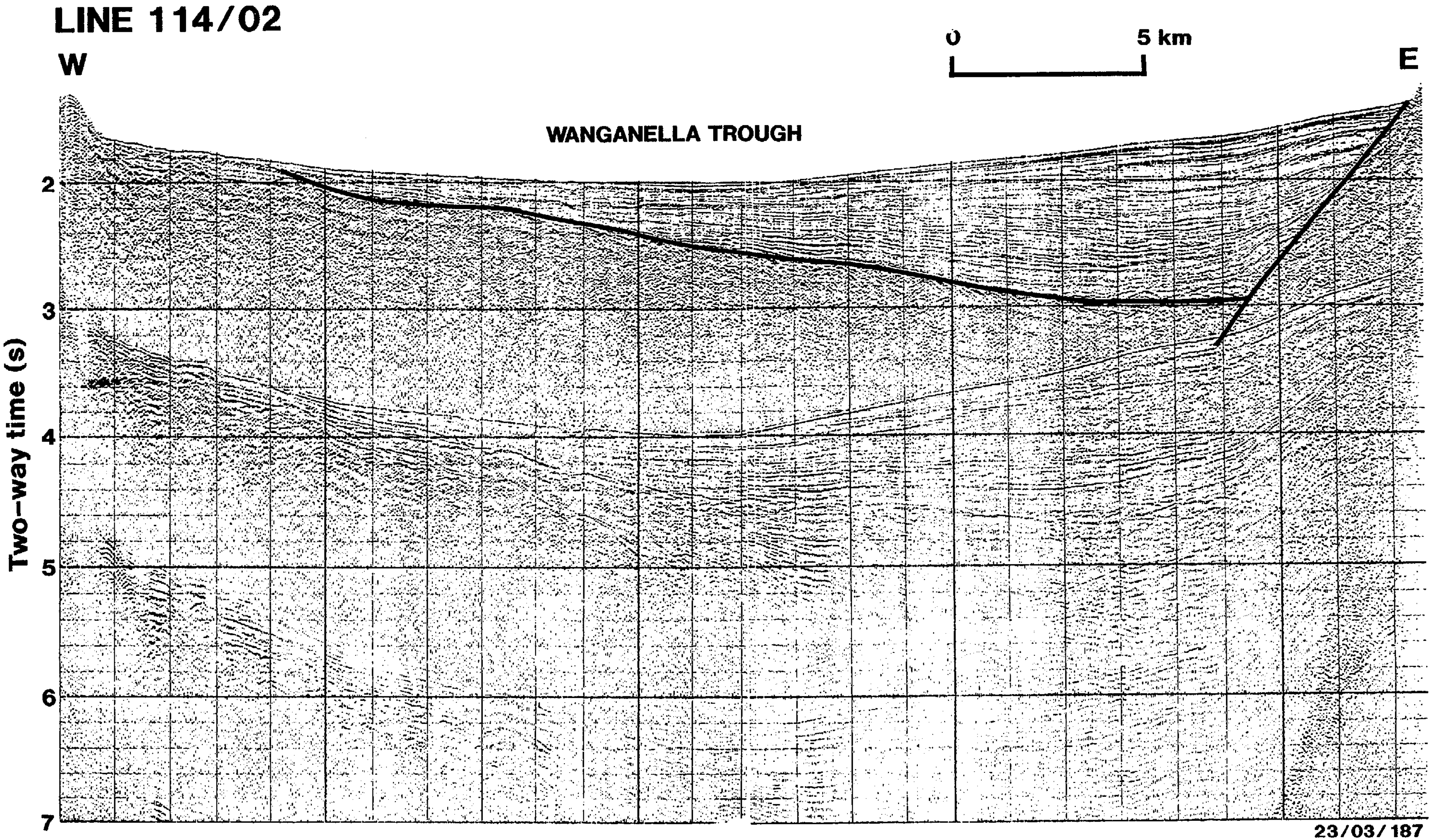

Figure 10. Shipboard monitor section showing the half-graben structure of the Wanganella Trough.

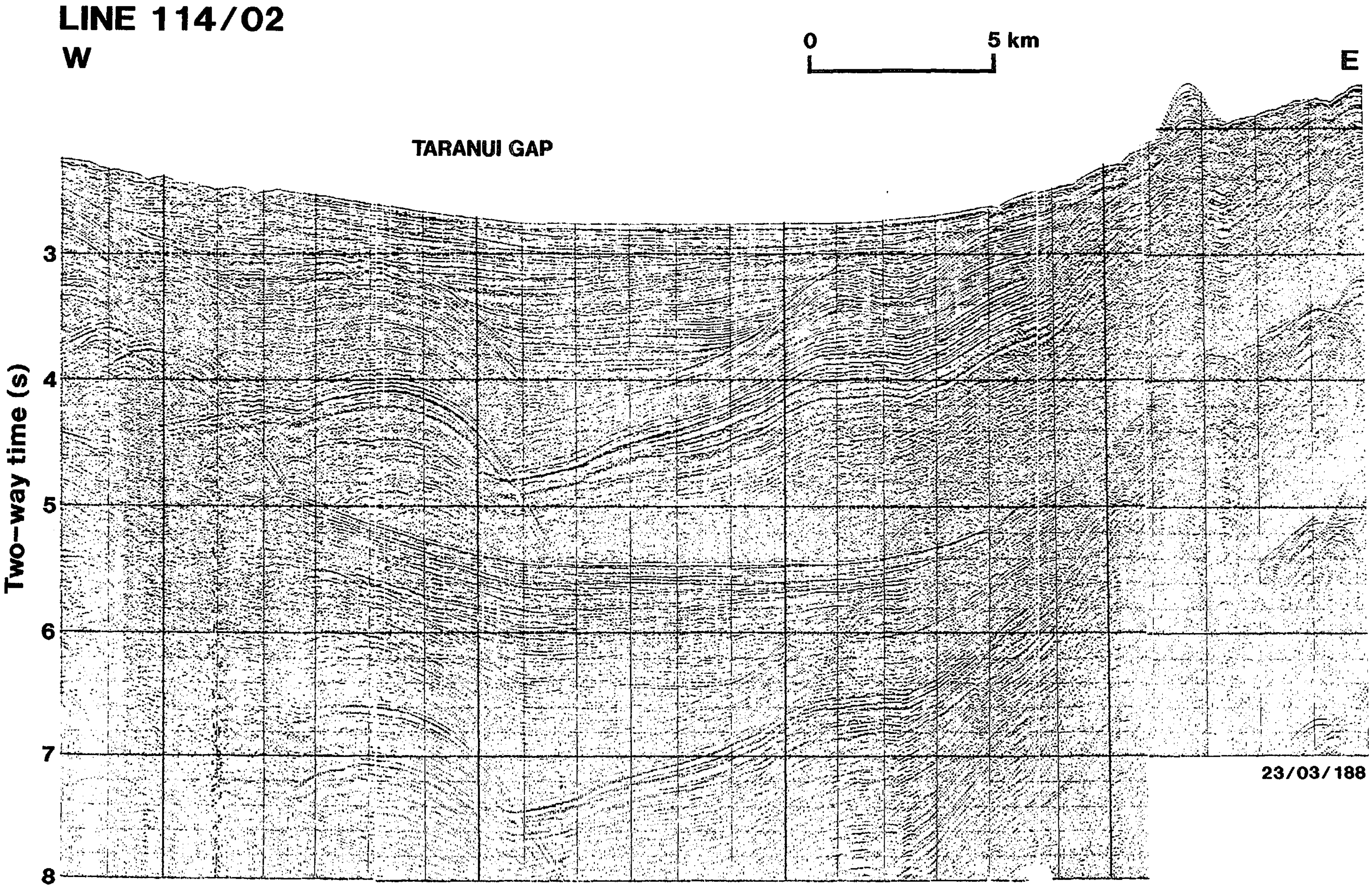

Figure 11. Shipboard monitor section across the Taranui Gap.

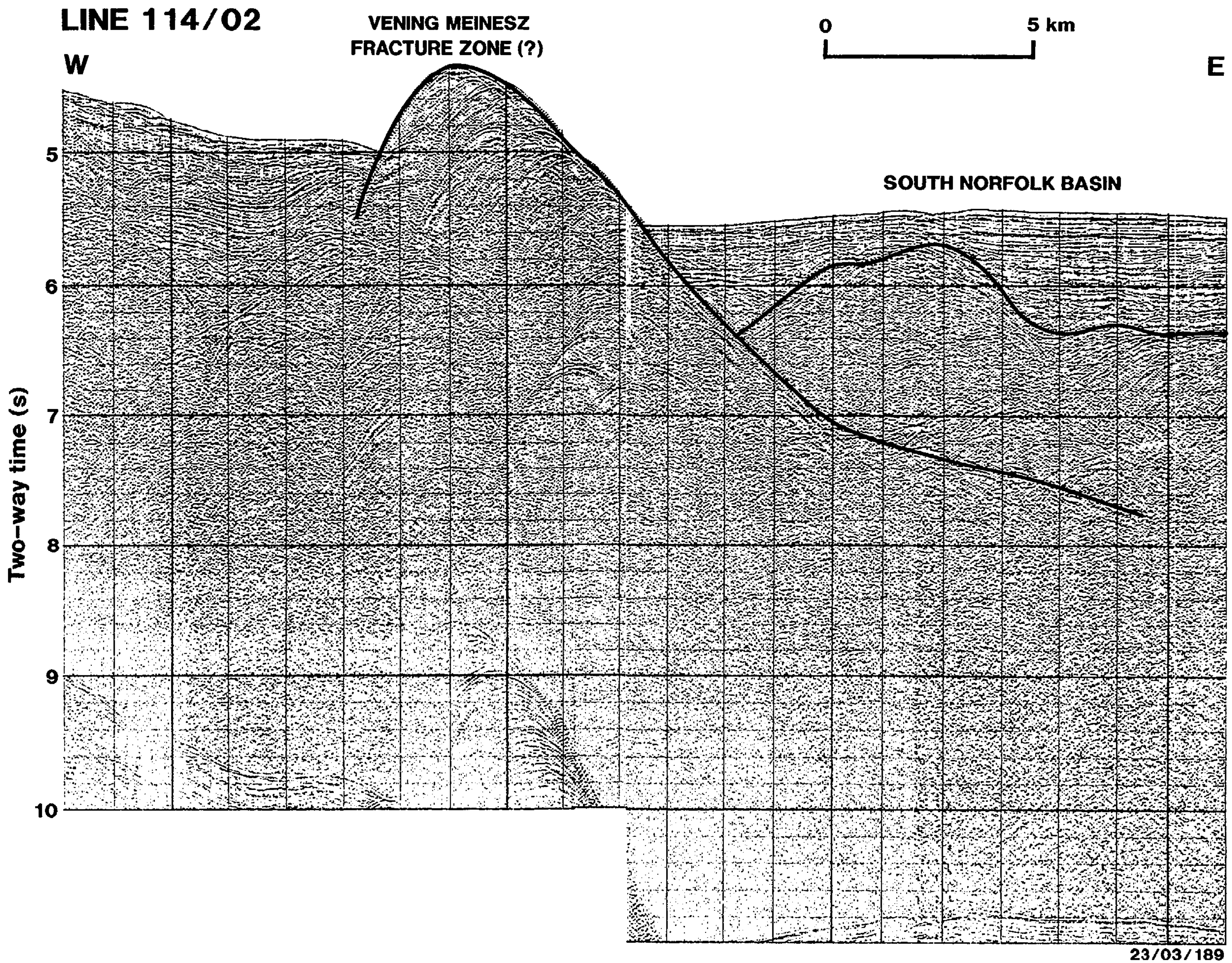

Figure 12. Shipboard monitor section from the western edge of the Norfolk Basin