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Report 279

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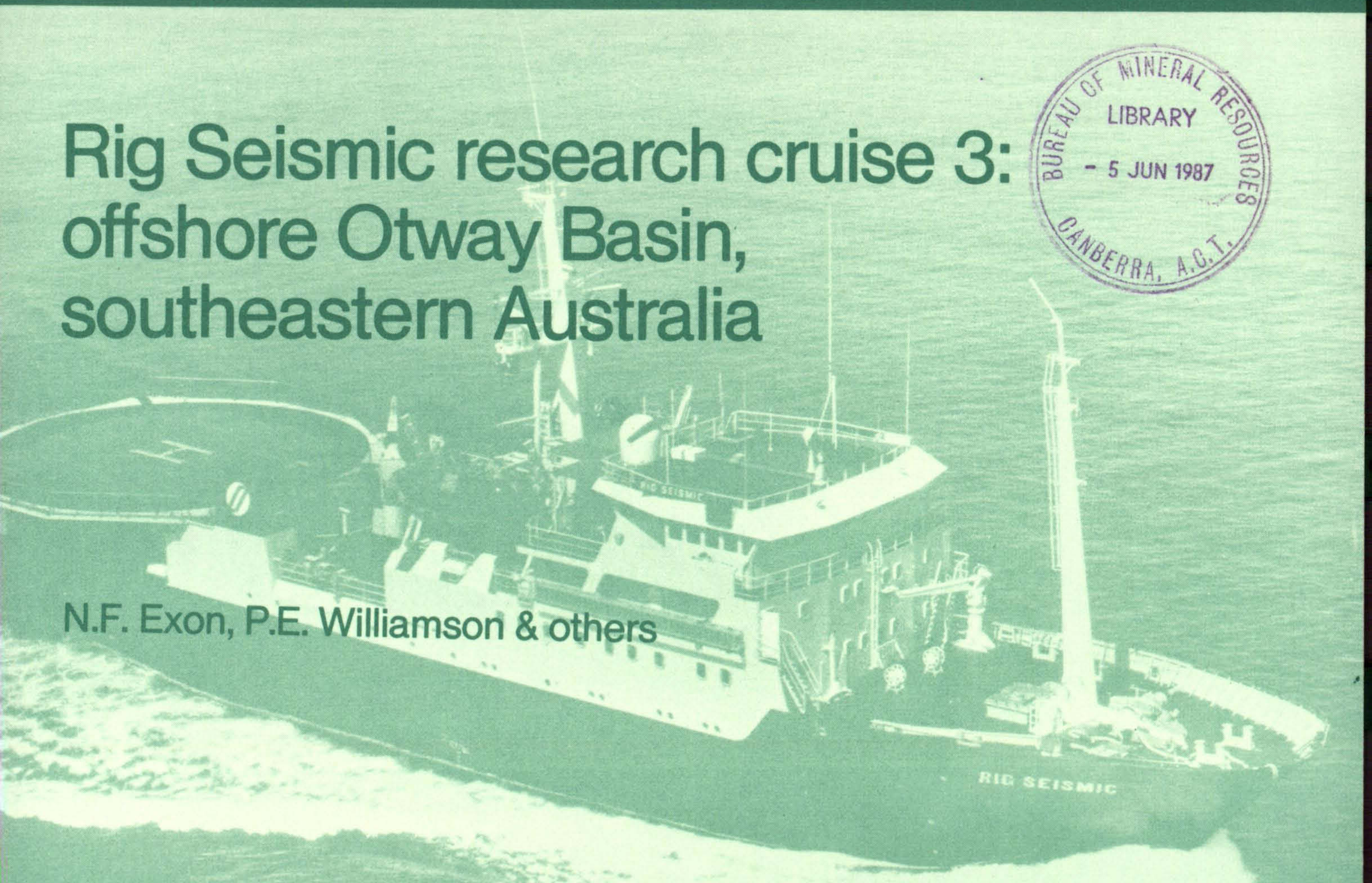

N.F. Exon, P.E. Williamson & others

Bureau of Mineral Resources, Geology & Geophysics

Department of Resources & Energy
BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

REPORT 279

RIG SEISMIC RESEARCH CRUISE 3:

OFFSHORE OTWAY BASIN, SOUTHEASTERN AUSTRALIA

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ABSTRACT

During a research cruise by the R/V *Rig Seismic* in the Otway Basin of southeastern Australia in mid 1985, some 3700 km of high-quality multichannel seismic, magnetic, and gravity data were collected. Data from 14 sonobuoys were recorded, and six dredge hauls were made. About half the geophysical data were gathered on the continental shelf; the remainder consisted of deepwater lines extending to the abyssal plain 200 km offshore.

The Cretaceous and younger sedimentary sequences of the extensional Otway Basin are up to 10 km thick beneath the shelf, but they thin oceanward, pinching out altogether at the edge of the abyssal plain. The offshore basin is dominated by west-northwest-trending normal faults, mostly downthrown to the west. Sedimentary facies do not appear to change greatly oceanward, and the four major sequences known beneath the shelf are probably present on the continental slope: Lower Cretaceous non-marine detrital, Upper Cretaceous transgressive-regressive detrital, Paleocene-Eocene transgressive-regressive detrital, and Oligocene-Miocene shelfal carbonate.

In general, older sequences crop out further down the slope. Palaeozoic metasediments were dredged from the edge of the abyssal plain, indicating post-depositional subsidence of as much as 3500 m since the middle Eocene.

INTRODUCTION

The Otway Basin study (BMR survey 48) is the third in a series of research cruises using the R/V *Rig Seismic* to be undertaken by the Bureau of Mineral Resources under its new initiative in marine geoscience. The aim of the cruise was to define the structural and stratigraphic framework of the offshore Otway Basin and to investigate its petroleum potential.

The Otway Basin trends west-northwest straddling the Victorian and South Australian coastlines for 500 km. It is one of three sedimentary basins in the the Bass Strait region and occurs west of the Bass and Gippsland basins (Fig. 1). Although the Otway Basin has stratigraphic similarities to these basins, exploration has to date met with only limited success whereas the Gippsland basin is a prolific hydrocarbon producer. Consequently, this study focuses on the structural and stratigraphic factors that could have implications leading to a different exploration strategy in the Otway Basin.

Since the early 1960s, about 50 petroleum exploration wells have been drilled onshore and 19 offshore (Fig. 1), although the only viable hydrocarbon discoveries to date have been those of gas in the Port Campbell area. Oil, gas and condensate shows are widespread both in the onshore and offshore Otway Basin, having been found in Cretaceous and Tertiary sequences in about 20 wells. Drilling, especially in recent years, has concentrated on structural traps at Upper Cretaceous and Tertiary levels. Only one offshore exploration permit in the western Otway Basin is current. Permit coverage onshore is extensive.

During this survey, 3700 km of multichannel seismic data were collected, covering both the shallow-water continental shelf and the deeper areas of the continental slope and rise, and reaching the abyssal plain (Fig. 2). Fourteen sonobuoys were recorded to give additional velocity information for seismic interpretation and data processing. Six rock and mud samples were collected with a newly commissioned coring winch, which is capable of deploying 10 km of wire cable with a breaking strain of 20 tonnes. Preliminary interpretations indicate well-developed Cretaceous rift structures with possible petroleum-trapping potential.

Acknowledgements

The enthusiasm, skill, and cooperation of the master and crew of the *Rig Seismic* are gratefully acknowledged. They made a major contribution to the success of the cruise.

The contributions of J.B. Willcox in preparing the precruise report and S. Kravis, K.L. Lockwood and J. Lock for scientific input before and during the cruise are gratefully acknowledged.

Crew of R/V *Rig Seismic*

Master	H. Forman
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2nd Officer	W. McKay
Chief Engineer	C. de Souza
2nd Engineer	T. Ireland
Electrical Officer	P. Jiear

ERA/AB	K. Halliday
Chief Steward	R. Plenty
Cook	G. Conley
Steward	J. Caminitti
2nd Steward	S. O'Rourke
AB	L. Luscombe
AB	B. Marsh
AB	P. Hallsworth

OBJECTIVES

The objectives of the Otway Basin offshore study are:

1. To obtain structural and stratigraphic data and, in particular, to determine the configuration of structural highs and areas of major sedimentary sub-basins and their structural and stratigraphic relationships.

2. To determine areas that could constitute leads for petroleum exploration owing to their structural or stratigraphic cabability for petroleum trapping, and areas where sequences with favourable source rocks, age, and depth of burial would suggest potential petroleum sources.

3. To determine the structure and stratigraphy of the relatively unstudied southwestern margin of the Otway Basin and to incorporate them into an overview of the whole basin.

4. To examine the geological history of the basin in relation to the rifting and separation of Australia and Antarctica, and subsequent seafloor spreading at the Indian-Antarctic spreading ridge.

CRUISE PLAN

The cruise plan had five components

1. Shallow-water 48-channel seismic traverses (1500 km) were devised to give a framework coverage of approximately 40 km square over the northern offshore Otway Basin, which, having a water depth of less than 200 m, is most suitable for present-day petroleum exploration. This coverage consists of a number of short lines angled to existing data to obtain additional structural information, and tied with two long strike lines, which also tie data sets from different basinal areas.

2. Deep water seismic dip lines (1600 km) were devised to give information on the western, central, and southern offshore Otway Basin. These lines were located to infill and extend existing sparse, good-quality, deep-water data recorded by Shell in 1972 and BMR in its 1982 survey 40. They were also designed to tie shallow-water seismic data and wells to subcropping strata on the continental slope and so to give a structural and stratigraphic overview of the basin. A deep-water tie line (350 km) was added at the end of the cruise.

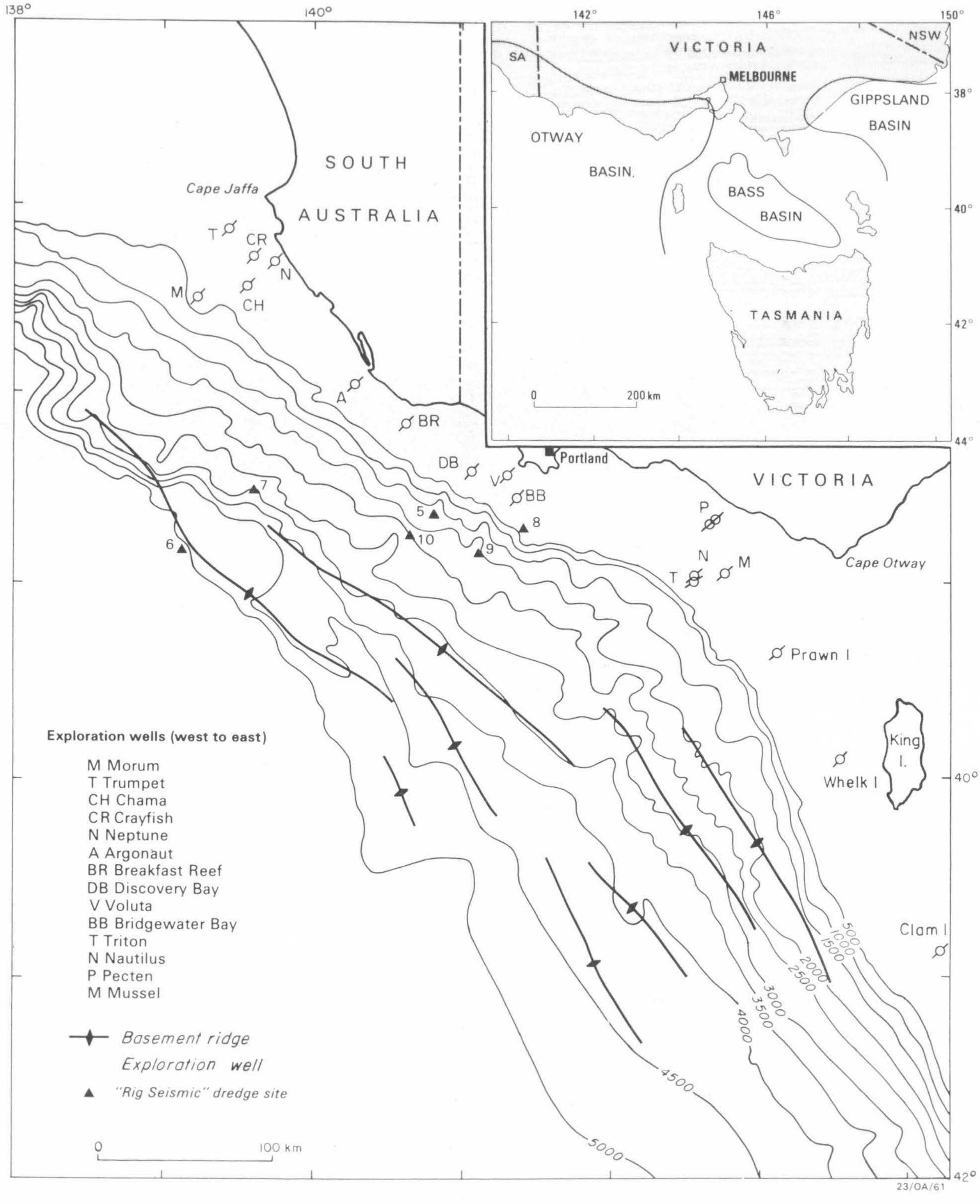


Figure 1. Regional bathymetry, offshore petroleum exploration wells, and deepwater basement ridges

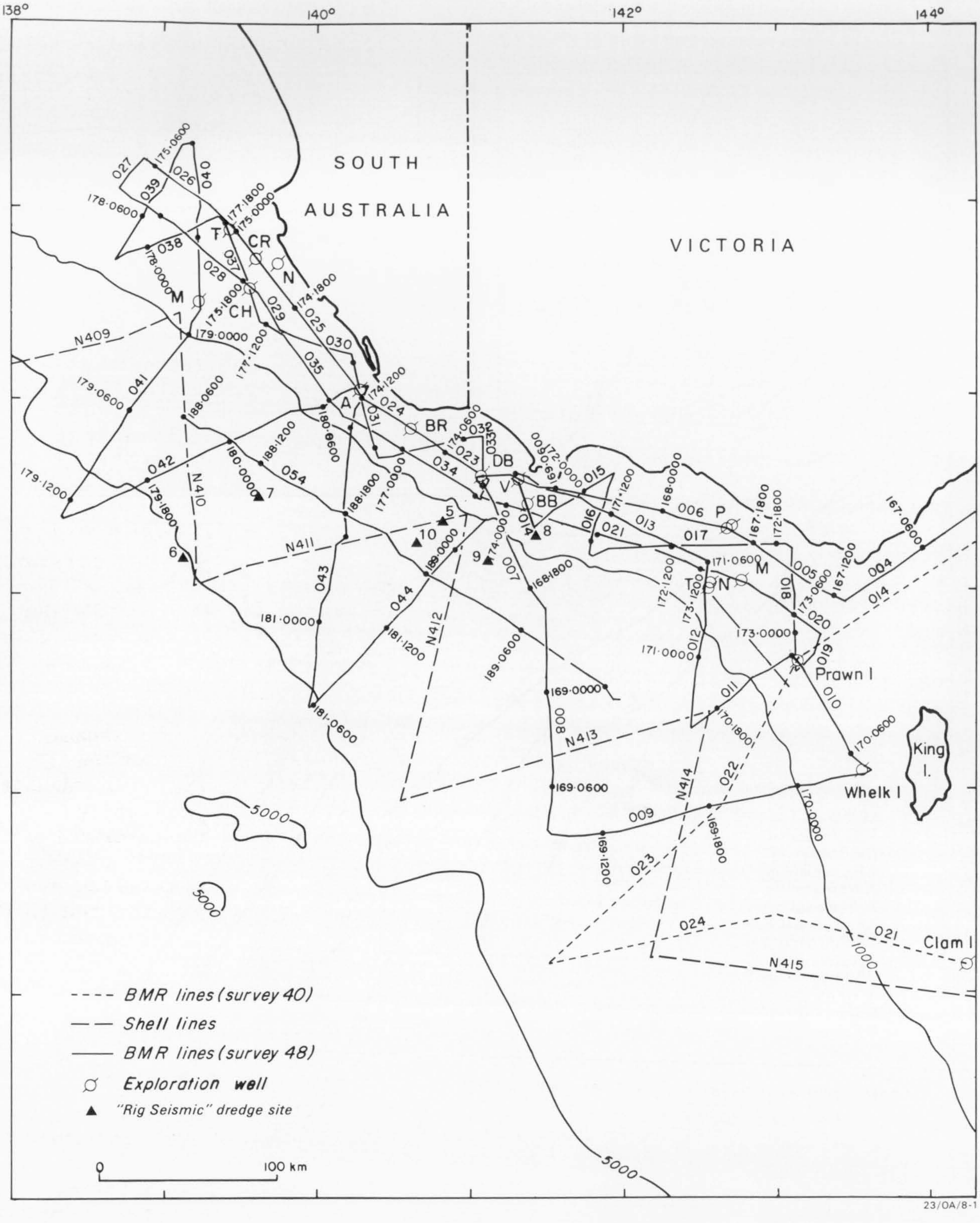


Figure 2. Track map of regional seismic coverage, including this survey (48).

3. Geological sampling was planned for a number of locations selected using seismic profiles from this and earlier cruises. Sites included targets believed to range in age from Early Cretacaeous to Early Tertiary.

4. Sonobuoys were to be deployed to give velocity information in both deep and shallow-water areas.

5. A number of line segments were assigned for testing and development of the seismic system.

GEOLOGICAL BACKGROUND

The considerable amount of existing well and seismic data ensures that the onshore and nearshore parts of the Otway Basin are fairly well known. We draw the following summary from papers such as those of Wopfner & Douglas (1971), Bouef & Doust (1975), Ellenor (1976), Benedek & Douglas (1976), Kenley (1976), Abele & others, (1976), Denham & Brown (1976), Robertson & others (1978), and Megallaa (in press).

The basin trends west-northwest, straddling the coastline for 500 km between the Mornington Peninsula in Victoria and Cape Jaffa in South Australia, and has an average width of 200 km. Its northeastern margin extends west-northwest from Port Phillip Bay through the Merino Ridge to the Padthaway Ridge; its southwestern margin is the base of the continental rise about 4500 m water depth. Most major structures (Figs. 3 & 4) formed in the Cretaceous, and trend either north-northeast or west-northwest.

Palaeozoic metasediments crop out north of the basin and form economic basement beneath it. The maximum sedimentary thickness is 10 km,and the sediments consist of four major sequences: Lower Cretaceous non-marine detrital sediments of the Otway Group; Upper Cretaceous transgressive-regressive detrital sediments of the Sherbrook Group; Paleocene-Eocene transgressive-regressive,largely detrital sediments of the Wangerrip and Nirranda Groups; and Oligocene-Miocene shelf carbonates of the Heytesbury Group. Deposition was most widespread in the Early Cretaceous and Tertiary,and most restricted in the Late Cretaceous.

Tectonic framework and basinal development

The Otway Basin is one of a series of extensional basins along the southern margin of Australia, which developed in Late Jurassic and Early Cretaceous times before the breakup of eastern Gondwanaland. These basins vary in character from predominantly rift related in the Great Australian Bight, to mixed rift and wrench related in the Otway Basin, to predominantly wrench related on the western margin of Tasmania. The abrupt termination of most of the basins and the accompanying offsets of the continental shelf can be attributed to the development of major transform or transfer faults. The Otway Basin trends west-northwest over all and is extensively faulted, but relatively little folded; major movements mostly terminated in the earliest Tertiary. Structural trends in the basin are either west-northwest or north-northeast (Figs. 3 & 4).

It is generally believed that before breakup eastern Antarctica and/or the

South Tasmania Plateau adjoined the Otway Basin (Fig. 5). Cande & Mutter (1982) revised the age identification of the east-west-trending oceanic magnetic anomalies, and concluded that the margin started to form 90 Ma ago (Turonian). Other workers have assumed older ages; e.g. Crook & Taylor, (1985) 125 Ma; Frakes & Bolton (1985), 112 Ma. Cande & Mutter postulated a period of slow spreading from 90 to 43 Ma ago (Turonian to Eocene), before the commencement of the fast spreading that has continued to the present day. The South Tasmania Plateau and eastern Antarctica apparently moved southward past Tasmania along a transform fault zone, leaving oceanic crust behind, with the plateau separating from Antarctica in the Oligocene, according to the results from a recent R/V *Sonne* cruise (Hinz & shipboard party, 1985). The Late Cretaceous age of breakup suggests that sediments of this age should rest on oceanic basement at the present southern edge of the Otway Basin. Most Otway Basin sequences thin toward basement ridges at the foot of the continental rise (Figs. 1 & 6); the ridges were probably topographically high until breakup.

The Otway Basin first formed in the latest Jurassic to earliest Cretaceous, as an easterly trending trough caused by initial rifting. The oldest known sediments are of transitional Jurassic-Cretaceous age on floral and microfloral evidence (Dettmann & Douglas, 1976). The basin was part of the Bassian Rift, which continued eastward into the Bass and Gippsland Basins, and cut across the major Palaeozoic structures, which trend northwards. The basin filled with up to 5000 m of volcaniclastic sediment of the essentially Lower Cretaceous Otway Group, derived from contemporaneous volcanism (Gleadow & Duddy, 1981).

In the Late Cretaceous, as rifting continued and then slow spreading started, the basin began to assume its present shape. The eastern side terminated against the King Island-Mornington Peninsula Ridge (Fig. 3), and the basin was cut into two unequal portions by the Otway Ranges High and Cape Otway-King Island High. The smaller eastern portion is the Torquay Sub-basin, which remained a non-marine sub-basin until late Eocene times, being filled by 3000 m of Eastern View Formation coal measures.

The western part of the basin was affected by a number of developing structures from early in the Late Cretaceous. Major north-northeast-trending highs in the north included the Dartmoor Ridge and Warrnambool High, which separated that part of the basin into the Gambier, Tyrendarra, and Port Campbell Embayments. The Gambier Embayment overlies two Early Cretaceous troughs: the westerly trending Robe Trough,and the west-northwest-trending Penola Trough adjoining it to the east. In the east the Sorell Fault transform separated the non-depositional Cape Otway-King Island High from the Mussel Platform (Fig. 3), which extended as far west as a Late Cretaceous hinge line associated with the Warrnambool High. South and west of the Mussel Platform the basin was subsiding rapidly to form the west-northwest-trending Voluta Trough (Figs. 3 & 7) as breakup occurred; north of the Voluta Trough the smaller Portland Trough was developing as a parallel feature. East of the hinge line, west-northwest-trending normal faults cut basement, the Otway Group and the lower Upper Cretaceous (Fig. 6).

West of the Dartmoor Ridge (Fig. 3), numerous west-northwest-trending normal faults progressively downthrow both Upper Cretaceous and Tertiary sediments southward, and faulting appears to have been synsedimentary (Ellenor, 1976). Upper Cretaceous transgressive-regressive detrital sediments of the Sherbrook Group were deposited in much of the basin as it sank, reaching a

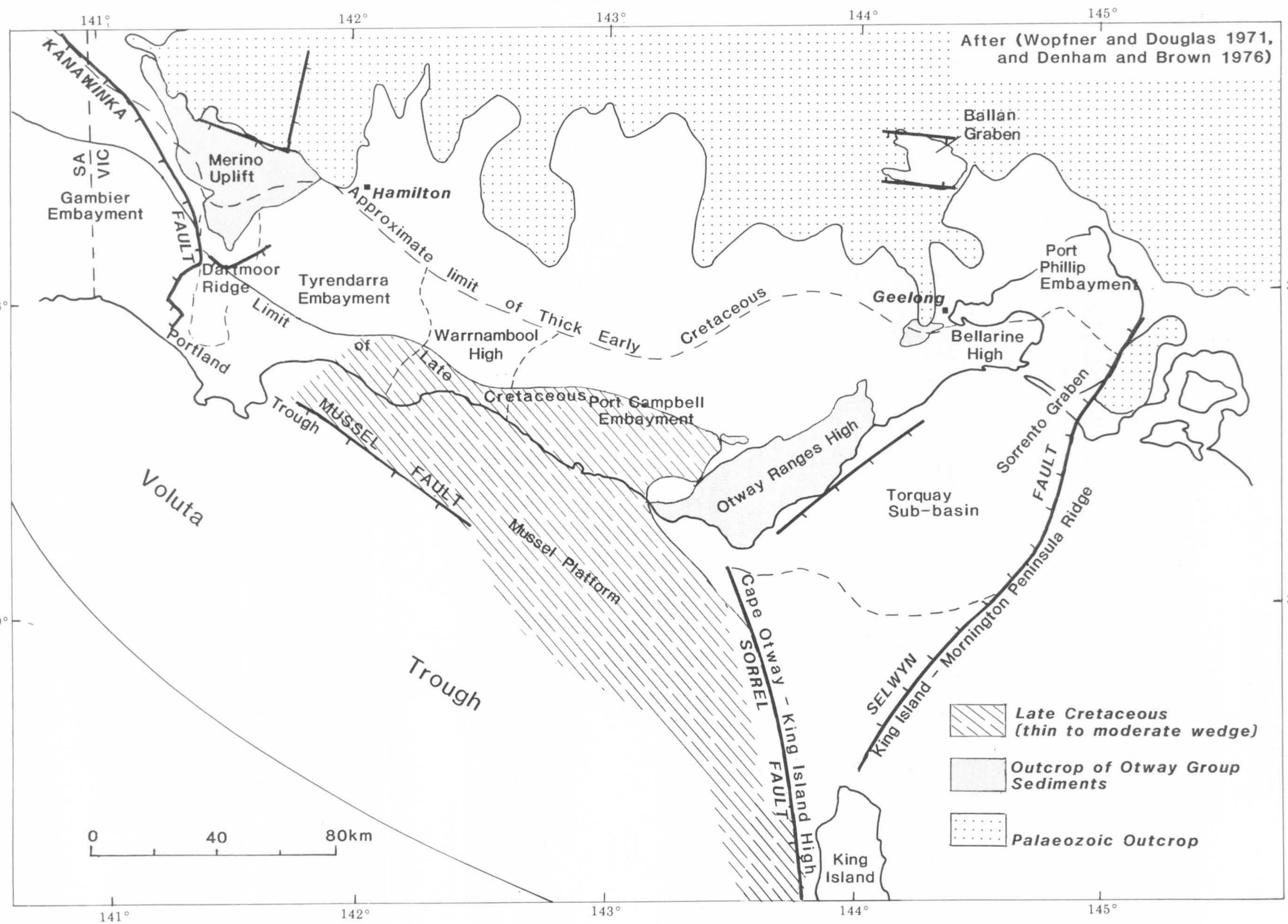


Figure 3. Major structural elements of the Otway Basin (after Megallaa, 1986).

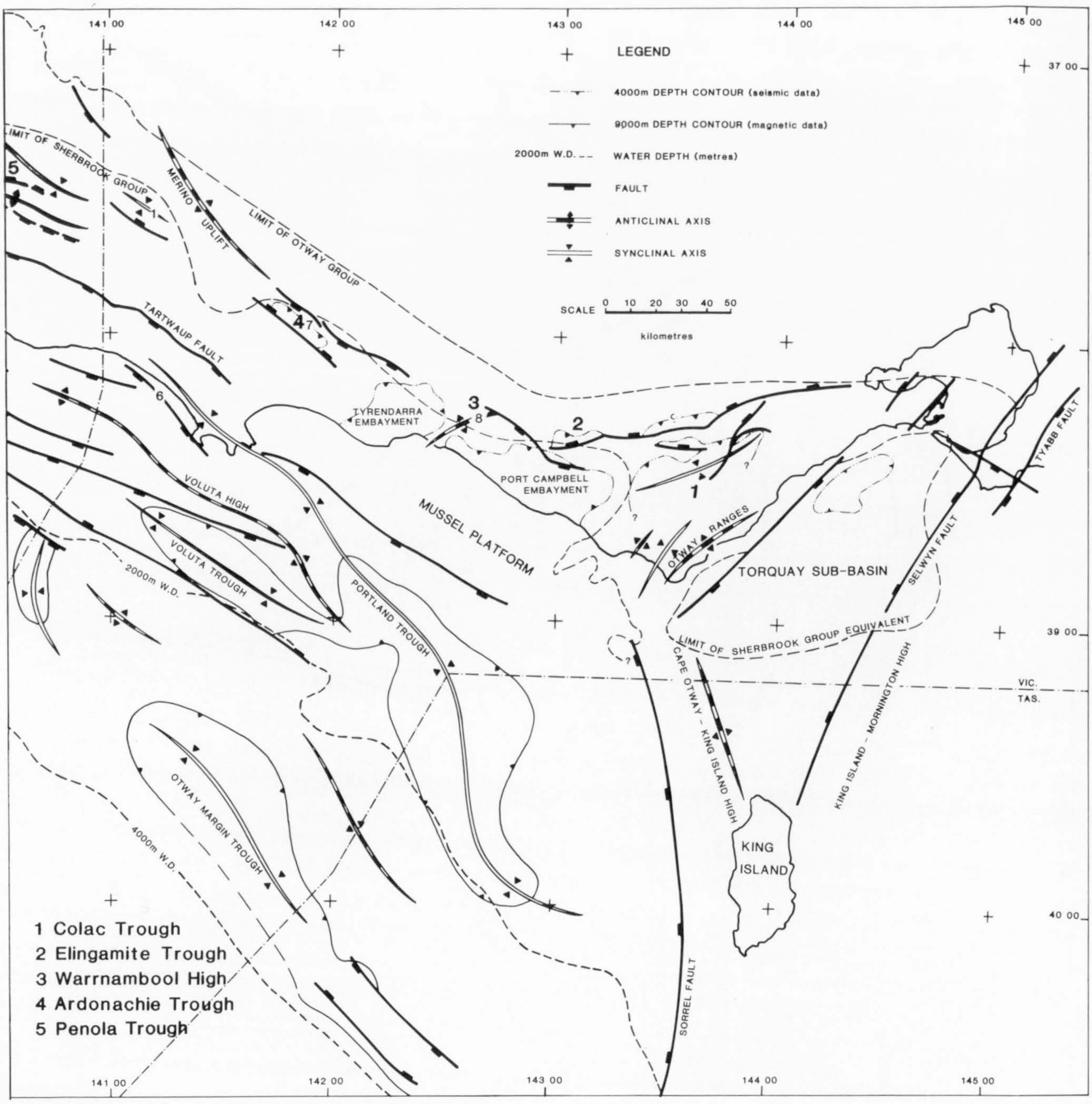


Figure 4. Structure contour map at the top of the Otway Group (after Megallaa, 1986).

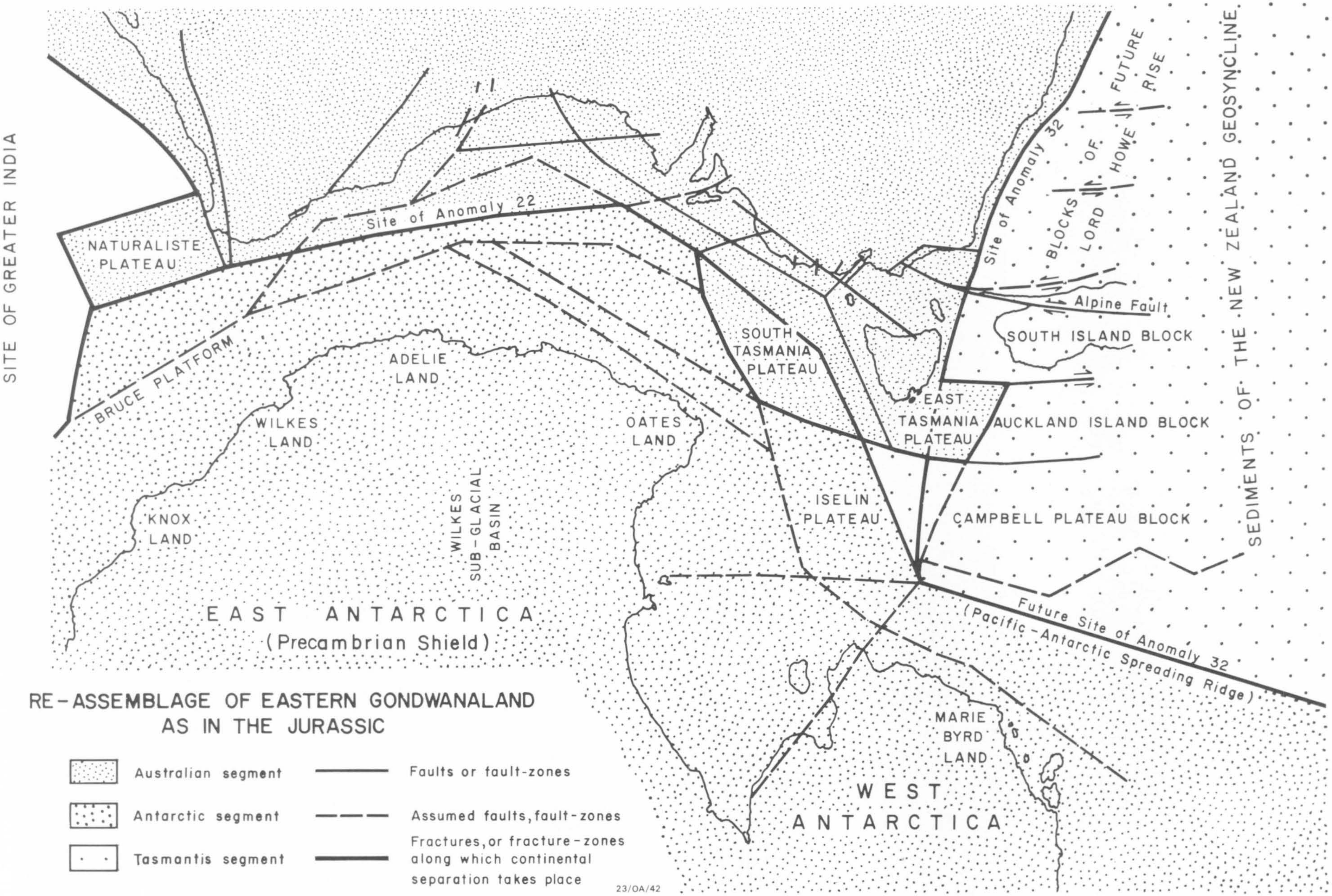


Figure 5. Reconstruction of eastern Gondwanaland in the Jurassic (after Robertson & others 1978).

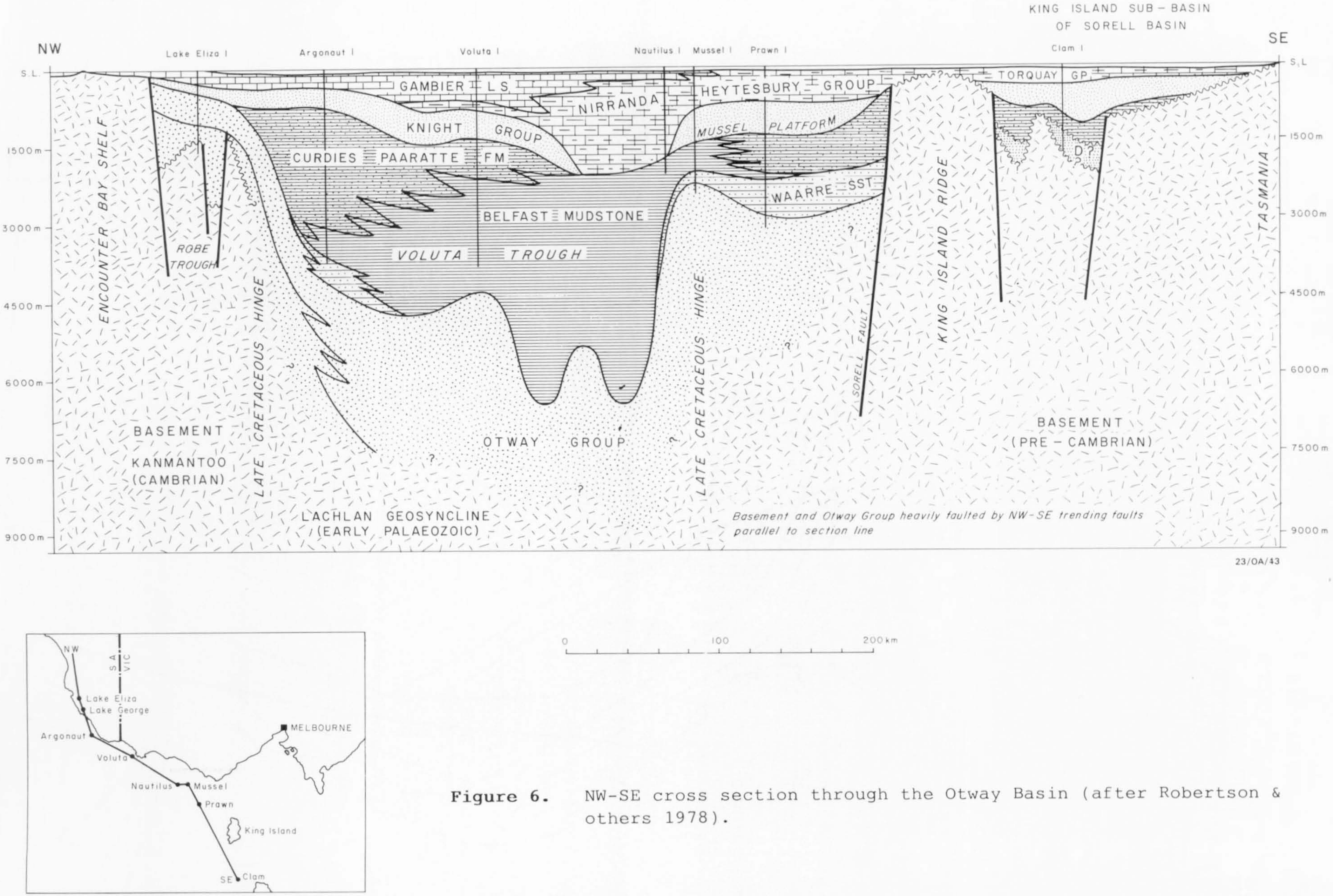
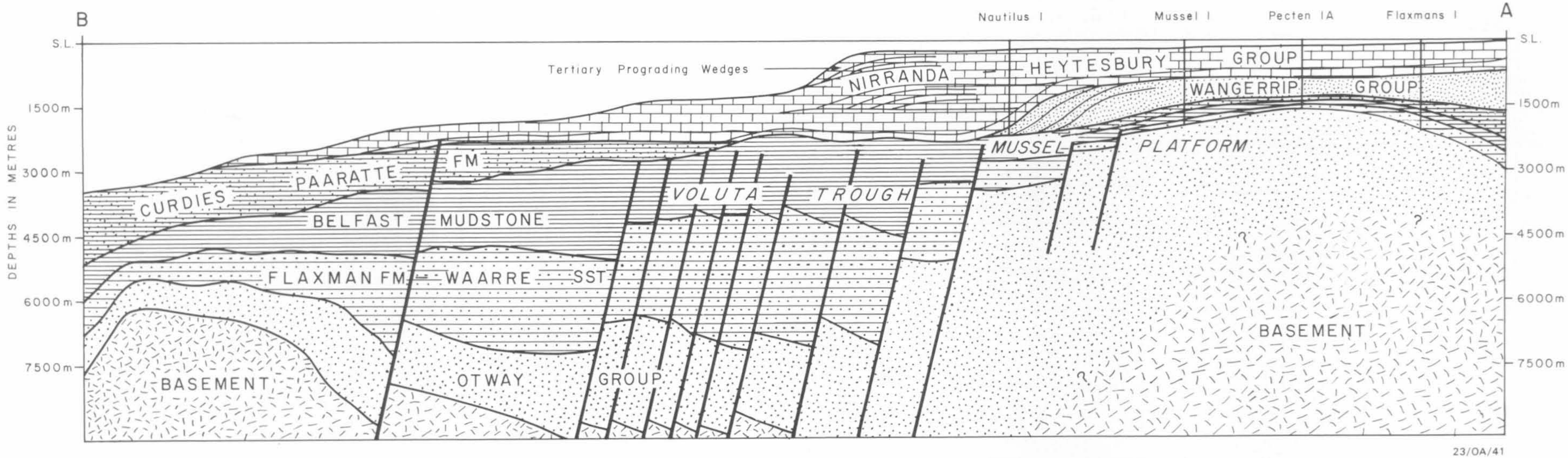
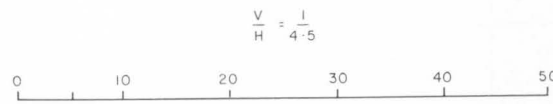


Figure 6. NW-SE cross section through the Otway Basin (after Robertson & others 1978).





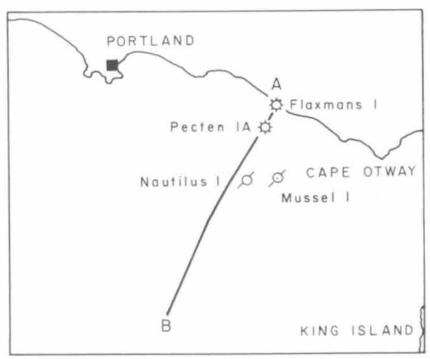


Figure 7. NE-SW cross section through the Otway Basin (after Denham & Brown, 1976).

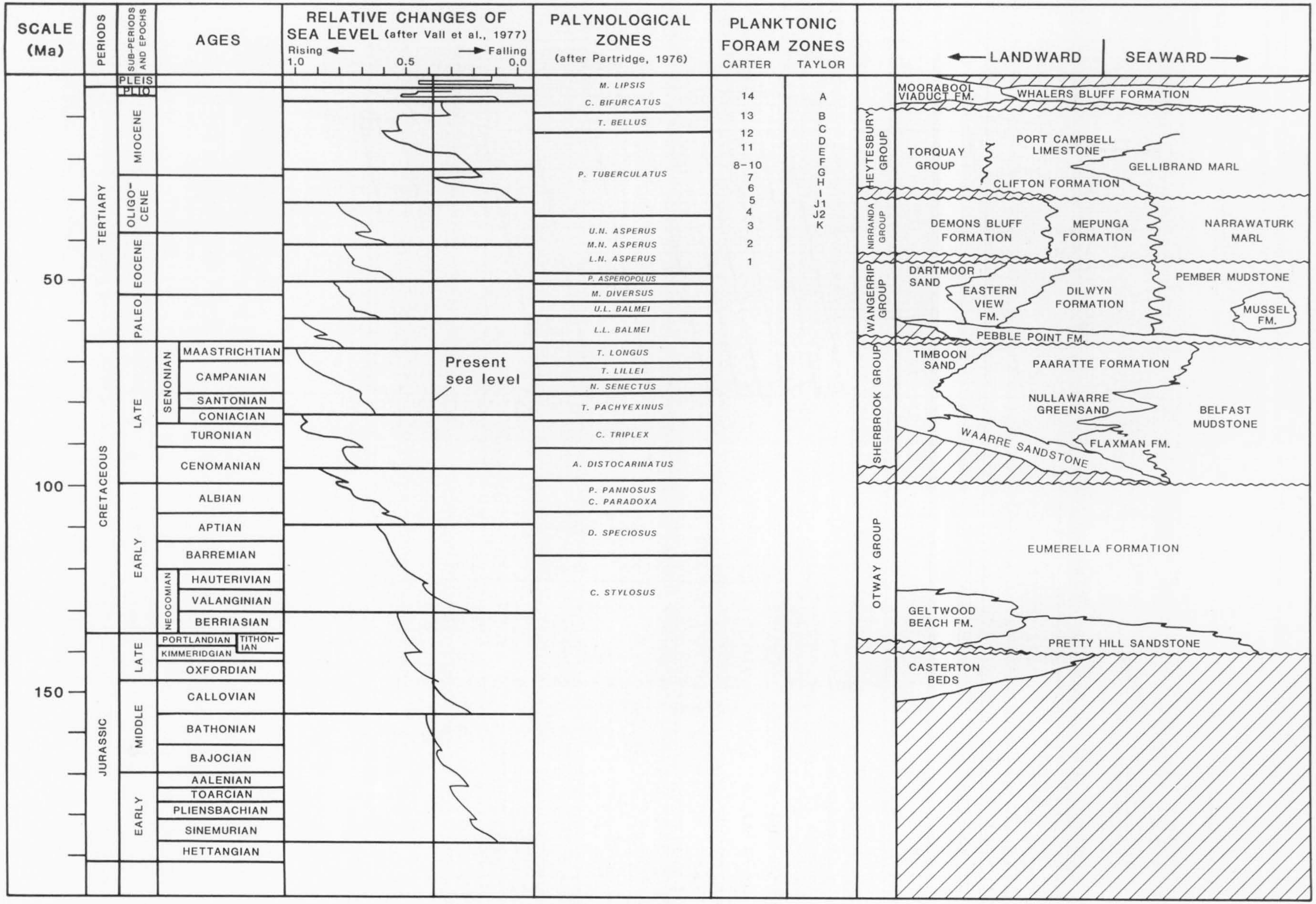


Figure 8. Eastern Otway basin stratigraphy (after Megallaa, 1986).

maximum thickness in the Voluta Trough (Fig. 7). They did not transgress far enough northward to cover the entire Otway Group, which was the source of much Sherbrook Group detritus. The initial transgression came from the west.

Tertiary marine strata overlap all older Otway Basin sequences in the north (Wopfner & Douglas, 1971), but are not extensive south of the present continental shelf. During the Paleocene, breakup was well advanced, the margin sank steadily, and a widespread transgressive-regressive detrital sequence, the Wangerrip Group, was deposited in the north, prograding southwestward across the Mussel Platform and into the Voluta Trough, where it reaches a maximum thickness of 1000 m (Fig. 7; Abele & others, 1976). As the margin continued to subside, normal marine conditions were slowly established and, outside the Torquay Sub-basin, thin sandstones and marls of the Nirranda Group were overlain by thick marine carbonates of the late Oligocene and Miocene Heytesbury Group, which also prograded southwestward, more than keeping pace with subsidence on the shelf.

The Torquay Sub-basin was relatively stable in the Late Cretaceous and Early Tertiary, but Late Tertiary wrench faulting and folding produced northwest trending anticlines along a mid-embayment high, making it structurally more like the Bass and Gippsland Basins than the rest of the Otway Basin.

Stratigraphy

The sedimentary fill of the Otway Basin has a total thickness of at least 10 000 m, and can be subdivided into four depositional packages, consisting of latest Jurassic-Early Cretaceous, Upper Cretaceous, Paleocene-Eocene, and Oligocene-Miocene sediments. These rocks overlie metasediments of probable Palaeozoic age throughout most, if not all, of the basin, and were deposited in a predominantly extensional basin that formed in response to the breakup of Australia and Antarctica. The Otway Basin stratigraphic nomenclature used below is the regional nomenclature being implemented by the Victorian and South Australian Geological Surveys (Fig. 8).

Late Jurassic-Early Cretaceous

Casterton beds. The oldest sediments in the Otway Basin belong to the Casterton beds, a sequence that ranges in age from latest Jurassic to earliest Early Cretaceous (Wopfner & others, 1971). The Casterton beds consist predominantly of interbedded non-marine siltstones, mudstones, and minor coals, and at their type section in Casterton No.1 they are 380 m thick. The unit rests unconformably on Palaeozoic metasediments and represent the earliest rift-related continental sediments. They were probably deposited in topographically low areas in a variety of lacustrine, swamp, and floodplain environments. While the Casterton beds have been intersected in numerous wells onshore, their thickness and distribution offshore are unknown. Thin basalt flows and pyroclastics in the Casterton beds at Casterton No.1 show that volcanism was active during the earliest phase of rift-related sedimentation in the Otway Basin. Sedimentation in the Otway Basin was probably continuous from the latest Jurassic into Early Cretaceous time, when deposition of the Otway Group commenced.

Early Cretaceous

Otway Group. The Early Cretaceous Otway Group consists of non-marine clastics and volcanogenic sediments. It conformably overlies the Casterton beds, and is subdivided into two units, the Pretty Hill Sandstone and the overlying Eumeralla Formation. The Otway Group has been assigned an Early Cretaceous age on the basis of palynological and megafloral evidence (Douglas & others, 1976), though age control is poor, particularly in the Pretty Hill Sandstone.

Pretty Hill Sandstone. The Pretty Hill Sandstone is a widespread unit, whose thickness probably exceeds 3000 m in the deeper areas of its principal depocentre, the Robe-Penola Trough. It is the main exploration target in the Upper Cretaceous, and comprises two lithofacies:

1. The Quartz Facies; consisting of quartz-rich, highly porous sands, whose thickness can exceed 2500m.

2. The Lithic Facies; comprising lithic sandstones, siltstones, and shales, which contain abundant volcanogenic material and generally have very poor reservoir characteristics.

Some authors have referred to the Lithic Facies as the 'Mixed Facies' or the 'Geltwood Beach Formation', and its similarity to the overlying Eumeralla Formation has been noted (BMR, 1966; Reynolds, 1971). It seems likely that both the Quartz and Lithic Facies were deposited in a variety of fluvial environments, and that their differences are due principally to a higher volcanogenic content (and thus generally poorer sorting) in the Lithic Facies. A continuum of rock types probably exists between the Quartz and Lithic Facies end members.

An abundance of garnets in both facies suggests that the quartz in them was derived from an exposed high-grade metamorphic or granitic hinterland. The Pretty Hill Sandstone thins markedly over basement highs, indicating that local basement topography helped control both the distribution and thickness of the sands.

From isopach, sand-shale, and percentage-of-porous-sand studies, Wopfner & others, (1971) suggested that, in South Australia, the Pretty Hill Sandstone was shed in radiating directions from the east-west trending Kalangadoo Ridge. In Victoria, they suggested that the sand was mainly derived from outcropping basement along the basin's northern margin, probably with some contribution from outcropping basement south of Cape Otway. The Pretty Hill Sandstone, and its lateral equivalents, appear to occur widely, but sporadically onshore. Offshore, they probably extend at least to the shelf-break, and, possibly, for a considerable distance down the continental slope, perhaps almost to the ocean-continent boundary (Boeuf & Doust, 1975).

The Quartz Facies typically has excellent reservoir characteristics: porosity in the Crayfish No. 1A offshore well is commonly 20-25% at depths of 2000-2500 m. In contrast, diagenesis of the volcanogenic material in the Lithic Facies has produced abundant zeolites and clay minerals which have reduced effective permeability to less than 1 milliDarcy.

Deposition of the Pretty Hill Sandstone ended in the Early Cretaceous, and was followed by a fairly brief period of non-deposition and possibly erosion, at least in the western part of the basin. An unconformity thus exists in places between the Pretty Hill Sandstone and the overlying unit, the Eumeralla Formation.

Eumeralla Formation. The Eumeralla Formation consists predominantly of massive, thickly bedded chloritic mudstones and shales, with less abundant thinly bedded lithic (volcanogenic) sandstones and coaly horizons (BMR, 1966).

The formation is probably thicker than 3000 m in the Port Campbell Embayment, and was deposited in a variety of continental environments during a period of active volcanism. The Eumeralla Formation has almost basin-wide distribution, and along with the Casterton beds and Pretty Hill Sandstone, was deposited during the 'pre-rift basin' phase of basin development. As with the Lithic Facies of the Pretty Hill Sandstone, diagenesis of the volcanogenic material has destroyed potential reservoirs throughout most of the formation. An exception is the 'Heathfield Sandstone', a relatively thin (up to 20 m), porous quartz sandstone, which commonly occurs towards the top of the formation. Thin coal beds within the formation may provide a hydrocarbon source to the 'Heathfield Sandstone'.

<u>Late Cretaceous</u>

Sherbrook Group. Otway Group sedimentation was terminated by a mid-Cretaceous period of block faulting, differential uplift, and slight to considerable erosion. The basin became divided into several sub-basins, and the Otway Ranges and the Cape Otway-King Island Highs became prominent structural and topographic features, effectively dividing the basin into two distinct sedimentary provinces. The western part of the basin was by far the larger, and consisted of the Gambier, Tyrendarra, and Port Campbell Embayments, and the Voluta Trough. To the east of the Otway Ranges was the Torquay Sub-basin. The sub-basins west of the Otway Ranges received sediment throughout the Late Cretaceous, whereas the Torquay Sub-basin remained largely non-depositional until the latest Cretaceous and the Paleocene.

The basal Upper Cretaceous sediments belong to the Waarre Sandstone, a continental to paralic (shoreline) sequence consisting of fine to very coarse-grained carbonaceous quartz sandstones, siltstones, mudstones, and coaly horizons. In contrast to the Otway Group, volcanogenic sediments are characteristically absent (Douglas & others, 1976) and reservoir quality in the sands is typically good. Consequently, the Waarre Sandstone is a prime petroleum target within the Upper Cretaceous section. The Waarre Sandstone (and indeed the rest of the Sherbrook Group) was probably largely derived from uplifted and eroded Otway Group sediments. On the northwestern and northern margins of the basin, the embryonic Otway Ranges High was probably an important sediment source throughout Late Cretaceous time (Wopfner & others, 1971). The Waarre Sandstone has a thickness of 30-200 m (Wopfner & others, 1971), and it appears to be restricted to the Gambier and Port Campbell Embayments. In the Tyrendarra Embayment, the Belfast Mudstone rests unconformably on the Otway Group. Well data from Voluta No.1 suggest that the Waarre Sandstone thins offshore and may be absent from the central Voluta Trough.

Increased subsidence combined with a eustatic high sea-level stand resulted in a marine transgression from the west. The Waarre Sandstone was slowly inundated by the first undoubtedly marine transgressive unit in the western Otway Basin, the Flaxman Formation (Douglas & others, 1976). The sequence was described by Hawkins & Dellenbach (1963) as 'sandstone and sandy mudstone. The sandy mudstone contains ferruginous chlorite ooliths and pellets with related siderite and minor phosphate, all of which are diagnostic of the formation'.

Continued transgression established a marine and marginal marine regime within the basin (Douglas & others, 1976), in which a thick sequence of glauconitic mudstone, dark-grey shales, siltstones and minor sandstones, the Belfast Mudstone, was deposited. A number of distinct, markedly time-transgressive lithofacies were present during the deposition of the Belfast Mudstone. By early Belfast time, the Voluta Trough was a well-developed, relatively deep marine embayment in which fine-grained mudstones accumulated. Taylor (1964) proposed that the Belfast Mudstone was deposited in a largely anaerobic barred basin. While this might suggest that the Belfast Mudstone would have good oil source-rock characteristics, studies to date (Felton & Jackson, 1985) indicate that the sequence is largely gas-prone. Coarser grained siltstones and sandstones accumulated around the shallower, nearshore margins of the Voluta Trough. Because of the strongly diachronous nature of the Upper Cretaceous sequences, it seems likely that sedimentation of the Waarre Sandstone, Flaxman Formation, and Belfast Mudstone was at least partly contemporaneous (see table 7.12, Douglas & others, 1976). In this scenario, the Waarre Sandstone would have been deposited in upper and lower delta plain or other paralic environments; the Flaxman Formation would represent lower delta plain to prodelta or marginal to shallow marine environments; whereas the Belfast Mudstone would represent prodelta to deeper marine environments. This proposal is supported by the observation that both the Waarre Sandstone and Flaxman Formation thin offshore and appear to be absent from the centre of the Voluta Trough.

The Belfast Mudstone is thickest offshore, exceeding 1570 m in Voluta No.1, and provides both a regional seal and a possible hydrocarbon source to the underlying Waarre Sandstone, and a possible source to the overlying Paaratte Formation. It is also widespread, occurring through most of the Late Cretaceous depocentres, though its thickness in the Tyrendarra Embayment is only about 300 m.

Towards the end of Belfast Mudstone time (probably middle Late Cretaceous; see table 7.12 Douglas & others, 1976), deposition of the Nullawarre Greensand Member commenced; the change in depositional character was probably related to the beginning of a marine regression. The Nullawarre Greensand is a shoreward facies of the Belfast Mudstone and, according to Douglas & others (1976), was probably deposited in littoral marine to paralic environments. It has been called either a chloritic sandstone (Hawkins & Dellenbach, 1963) or glauconitic sand (Bock & Glenie, 1965).

Continued regression during late Belfast Mudstone time initiated sedimentation of the paralic to shallow marine Paaratte Formation, which intertongues with the Belfast Mudstone and Nullawarre Greensand Member (Douglas & others, 1976). The formation consists predominantly of quartz sandstones, siltstones and minor coals. Thickness can exceed 850 m (at Glenelg No.1), and, though they are present throughout most of the Late Cretaceous depocentres, the Paaratte sandstones thin markedly into the offshore areas, and appear to be absent from the central Voluta Trough. On structural highs such as the Warrnambool High, the Paaratte Formation rests directly on the Flaxman

Formation or, in some cases, on the Otway Group (Douglas & others, 1976). On these highs, the transgression was never extensive enough to allow deposition of truly marine Belfast Mudstone. The Paaratte Formation eventually graded into the continental to paralic quartz sands, silts, and coals of the Curdies Formation. Like the Paaratte Formation, the Curdies Formation tends to thin offshore, and is likely to be, at least in part, time equivalent to the youngest Belfast Mudstone in basinal areas. Thickness ranges from 30 to 300 m. The quartz sandstones of both the Paaratte and Curdies Formations generally have good to excellent reservoir charactistics. In addition, the coals in both formations provide potential hydrocarbon sources.

Tertiary

Sedimentation in the Otway Basin during the Paleocene and Eocene was partitioned into western and eastern sedimentary provinces, which were separated by the Otway Ranges High and the Cape Otway-King Island High. Non-deposition and erosion were common throughout the western Otway Basin during the earliest Tertiary (Abele & others, 1976). Consequently, the Tertiary sediments commonly unconformably overlie the Upper Cretaceous Sherbrook Group. This unconformity is considered to represent a "break-up" unconformity (Falvey, 1974). However, Abele & others, (1976) stated that deposition of the continental Curdies Formation (therein called the "Timboon Sand Member") was continuous from the latest Cretaceous through into the Early Tertiary near the present-day coastal and offshore parts of the Port Campbell Embayment.

Throughout most of the western province, sedimentation of the middle to late Paleocene Wangerrip Group began with a marine transgression from the west. The Paleocene sediments correspond to the "neo-breakup" phase of Deighton & others, (1976); the initial continental breakup caused the marine transgression. The earliest Wangerrip sediments belong to the transgressive Pebble Point Formation, a sequence of pebbly and commonly oolitic sandstones. In places the sandstones are glauconitic or dolomitic, and probably were deposited in various shallow to marginal marine environments (Abele & others, 1976). Depositional strike probably paralleled the present coastline; clastics were probably derived mostly from the north (Abele & others, 1976). The Pebble Point Formation prograded seaward, progressively thinning and pinching out before the centre of the Voluta Trough. Wangerrip sediments deposited during the period of greatest transgression belong to the pyritic, carbonaceous mudstones of the Pember Mudstone Member, a thin sequence onshore that contains common arenaceous foraminifera (Abele & others, 1976). In the Portland Trough its thickness exceeds 500 m (Holdgate & others, in press). The Pember mudstones were probably deposited in a variety of marginal marine environments, such as lagoons, tidal flats, and tidal marshes.

A marine regression in the late Paleocene established predominantly paralic to continental environments, in which the Dilwyn Formation, a sequence of (?deltaic) highly porous quartz sandstones, argillaceous sandstones, lignitic siltstones, and minor coals, was deposited. Deposition of the Dilwyn Formation may have commenced slightly earlier on structural highs in the west, where the effects of the mid-Paleocene transgression were less marked (Abele & others, 1976). Thus the Pember Mudstone and the Dilwyn Formation are in part time-transgressive, but contemporaneous in some areas. Neither the Pember Mudstone nor the Dilwyn Formation appear to have prograded seawards as far as the central Voluta Trough.

The coals within the Dilwyn Formation appear to have moderate to good hydrocarbon source potential, and could charge the abundant reservoir-quality sands that are present in both the Pebble Point and Dilwyn Formations. The Wangerrip Group attains a maximum thickness of approximately 1500 m, and is probably thermally immature throughout most, if not all, of the basin.

East of the Otway Ranges, in the Torquay Sub-basin, the Palaeocene and part of the latest Cretaceous were characterised by the deposition of a thick (possibly exceeding 3000 m) fluvio-deltaic sequence, the Eastern View Formation. The formation consists of interbedded porous quartz sandstones, siltstones, claystones, and coals. Thus, source, reservoir, and intra-formational seals probably exist in close proximity, and the formation may be prospective for petroleum deep in the Torquay Sub-basin. Like the Wangerrip Group, however, the formation is generally thermally immature where it is intersected in wells.

Marine regression continued throughout the early Eocene, and over much of the basin sediments were exposed and eroded (Abele & others, 1976). As a consequence, upper Eocene sediments rest unconformably on the Wangerrip Group over most of the basin. In the Torquay Sub-basin, the upper Eocene sequence consists of fluviatile quartz sands (Boonah Sandstone) and overlying continental to shallow-marine sand, clay, and dolostone (Demon's Bluff Formation). Intermittent basaltic volcanism (Older Volcanics) characterises the Eocene to Miocene sequences (Wopfner & others, 1971; Abele & others, 1976).

Sedimentation of the middle Eocene to early Oligocene Nirranda Group was initiated by a marine transgression (Abele & others, 1976), resulting from continental breakup. The initial sediments were the paralic to shallow marine ferruginous and calcareous quartz sandstones of the Mepunga Formation. Planktonic foraminifera recovered from the formation indicate that open marine conditions were well established by the middle Eocene in South Australia, and probably by the late middle Eocene in the Port Campbell Embayment (Abele & others, 1976). Continued transgression initiated sedimentation of the Narrawaturk Marl, a fossiliferous neritic marl.

Sedimentation and progradation of the Narrawaturk Marl continued until the mid-Oligocene, when a minor regression ended deposition in structurally high areas, though sedimentation may have been continuous in basinal areas. A rapid marine transgression occurred in the mid-Oligocene, initiating sedimentation of the mid-Oligocene to Miocene Heytesbury Group. These sediments typically rest unconformably on the Wangerrip Group, and, according to Abele & others, (1976), the basal sediments were littoral to shallow-marine bryozoal calcarenites (Clifton Formation); in somewhat deeper water, the sediments were predominantly marls (lower Gellibrand Marl). Transgression continued throughout the early to middle Miocene; Gellibrand Marl sedimentation continued in neritic environments, while in deeper water, further offshore, the fine-grained limestones of the Port Campbell Limestone accumulated. The Heytesbury Group typically has a thickness of 150-600 m, but pinches out northward. It prograded seaward, attaining a thickness of over 1500 m in Nautilus No.1. The Heytesbury Group has little source or reservoir potential, and is thermally immature throughout the basin.

From the very late Miocene to the Quaternary, the Otway Basin was generally uplifted with accompanying gentle faulting; in the west, however, some areas continued to accumulate a little sediment. Volcanism was widespread, and the resultant basaltic flows, tuffs, and scoria (Newer Volcanics) cover much of the onshore basin, masking the landward limits of the Mesozoic and Tertiary sediments. The southern coastline probably assumed its present configuration in the Quaternary.

Petroleum exploration

Potential petroleum source rocks

Potential source and seal units in the Otway Basin sequence are indicated in Figure 9. Organic geochemical data from the basin have been reported by Jackson & others (1983). Felton & Jackson (1985), from a limited suite of samples, identified the Tertiary Dilwyn Formation and intervals within the Otway Group as having the best oil potential, in terms of source-rock richness and oil-prone organic matter, compared with other formations in the basin. The Belfast Mudstone, commonly regarded as a good petroleum source, was found to be gas-prone, although of moderate organic richness, as was much of the Otway Group. The considerable thickness of Otway Basin sediments and the reconnaissance nature of Felton & Jackson's (1985) sampling offer encouragement for more detailed studies. McKirdy & others (1986) reported organic compounds apparently derived from the alga *Botryococcus* from within the Otway Group, and linked this occurrence with similar compounds from the inspissated oil strandings known from along the southern coast, which he suggested were derived from a mature Otway Group source offshore.

Potential reservoirs and seals

Both the Pretty Hill Sandstone and the Waarre Sandstone are fairly clean quartz sandstone units, and have moderate to good porosity where drilled. Seals for both are fine-grained or otherwise tight sediments of the Eumeralla Formation and Belfast Mudstone, respectively. Clay linings in pores, siliceous cement and, in places, carbonate cement and compacted lithic fragments reduce reservoir potential in both these units and make regional reservoir evaluation difficult. Sands at the top of the Sherbrook Group are clean, but are commonly freshwater-flushed where they have been drilled on structural highs onshore. Seals in this interval are poor.

Tertiary sands include the Dilwyn Formation, a regionally important, highly porous and permeable aquifer onshore, which may be hydrocarbon-bearing in suitable traps both onshore and offshore. Other sands low in the Tertiary sequence have variable, but often good, reservoir potential. The Pember Mudstone may act as both seal and source for the Dilwyn Formation.

Traps and timing

Exploration wells have mainly tested structural traps in the basin. The majority of these are rollovers associated with the north-northwest-trending fault system, which dominates basin structural trends. Such traps rely on sealing of the fault for their integrity. Because of the highly faulted nature of the Cretaceous sequence, rollover traps are numerous, but generally small. Simple anticlinal or domal traps are uncommon. Potential stratigraphic traps within the basin are numerous, but almost completely untested. Pinchouts of coarse clastic detritus adjacent to rising basement blocks are certainly present at the base of the Otway Group and probably the Sherbrook Group. Potential unconformity traps exist at the tops of all the major sequences.

Published geohistory analyses (Middleton & Falvey, 1983) of the offshore wells Voluta No. 1 and Pecten No. 1A were used by Felton & Jackson (1985) to suggest relationships for hydrocarbon generation and trap formation in two structurally distinct parts of the basin. Major block faulting and down-to-basin normal faulting occurred during continental breakup in Mid to Late Cretaceous time (100-65 Ma ago), with minor movement continuing until the end of the Paleocene (65-55 Ma ago). Fault-related traps were thus fully developed 55 Ma ago. Peak oil generation (at Ro=1.0%) would have occurred in the Otway Group in the Voluta Trough between 80 and 60 Ma ago, permitting substantial hydrocarbon loss. The Upper Cretaceous section here is early mature at the present day. At Pecten No. 1A on the Mussel Platform, the Otway Group is at present entirely within the 'oil window', its base having reached peak generation 60 Ma ago, so that there too most of its hydrocarbons would have been generated since fault trap development. The Upper Cretaceous at Pecten No. 1A is still largely immature.

<u>Prospectivity</u>

The best prospects for oil and gas discoveries in both structural and stratigraphic traps are in areas where the underlying sedimentary section has reached maturity later than 55 Ma ago, given the amount of structural disturbance in the basin up to that time. The Otway and Wangerrip Groups appear to have the best oil source potential, so oil plays might include

1. Waarre/upper Otway reservoirs, sourced by Otway Group, and sealed by Otway/Belfast mudstones in the Mussel Platform area;

2. Pretty Hill Sandstone reservoir, sourced and sealed by Eumeralla Formation mudstone in the western part of the basin.

Gas prospects are more widespread, but appear best onshore, particularly in the central and western areas of the basin, where a mature Belfast source may charge both Waarre and Tertiary reservoirs.

GEOPHYSICAL RESULTS

<u>Reflection seismic</u>

Interpretation of 48-channel reflection seismic data collected during the study shows the presence of horst and graben rifted structures and thick sedimentary sequences. Ties to wells indicate possible reservoir, source, and seal facies, suggesting good potential for hydrocarbon exploration.

Final interpretation of the seismic reflection data will be made after full processing. However, data quality of the onboard monitor and preliminary processed records was sufficiently good to allow an initial structural and stratigraphic interpretation. On the raw records the long gun pulse (110 ms) tends to mask events under strong reflectors, and water-bottom reverberations and refractions often obscure data in shallow water. More detailed interpretation required further processing, particularly deconvolution and

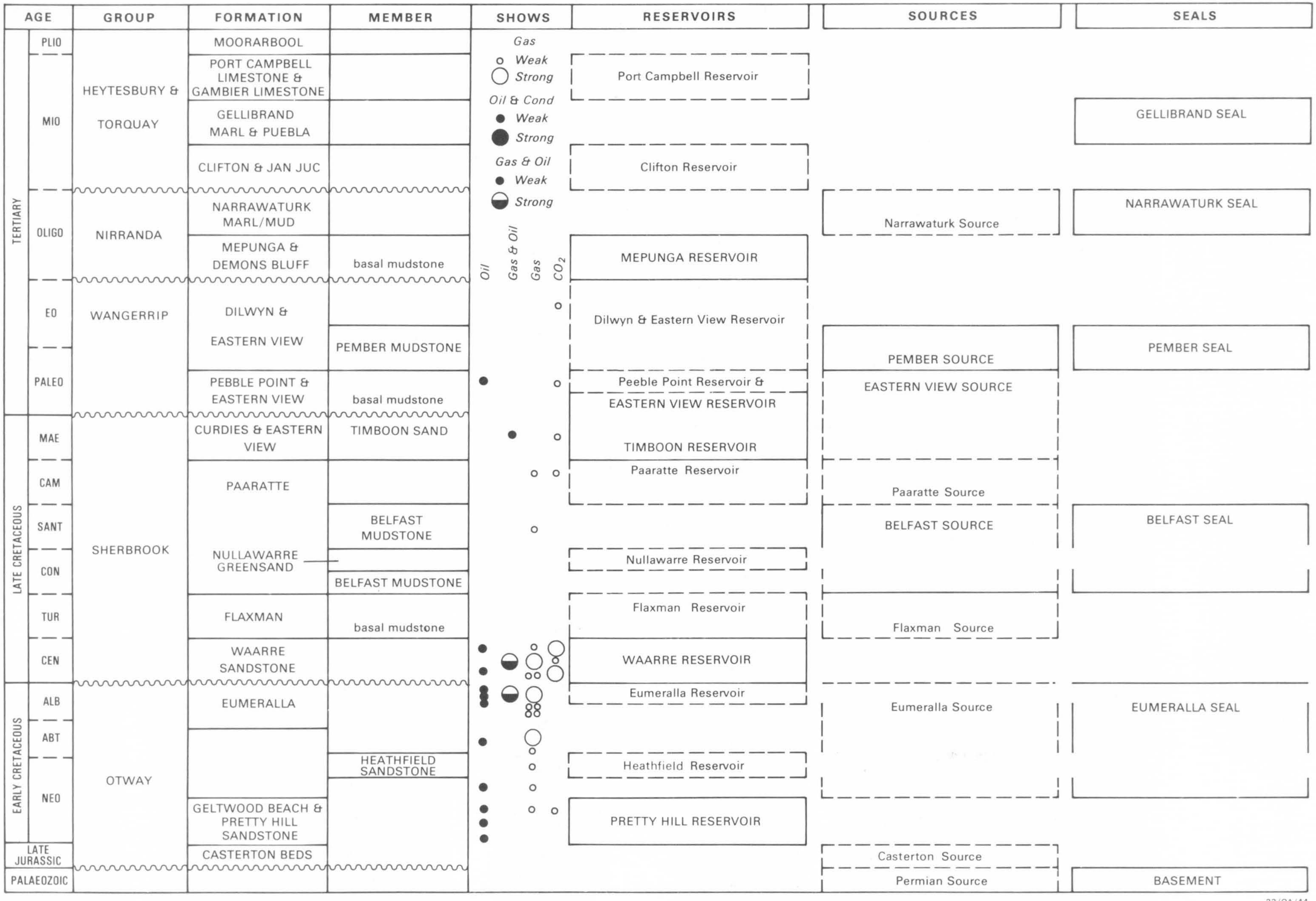


Figure 9. Eastern Otway Basin stratigraphy related to oil and gas shows and potential reservoirs, sources, and seals.

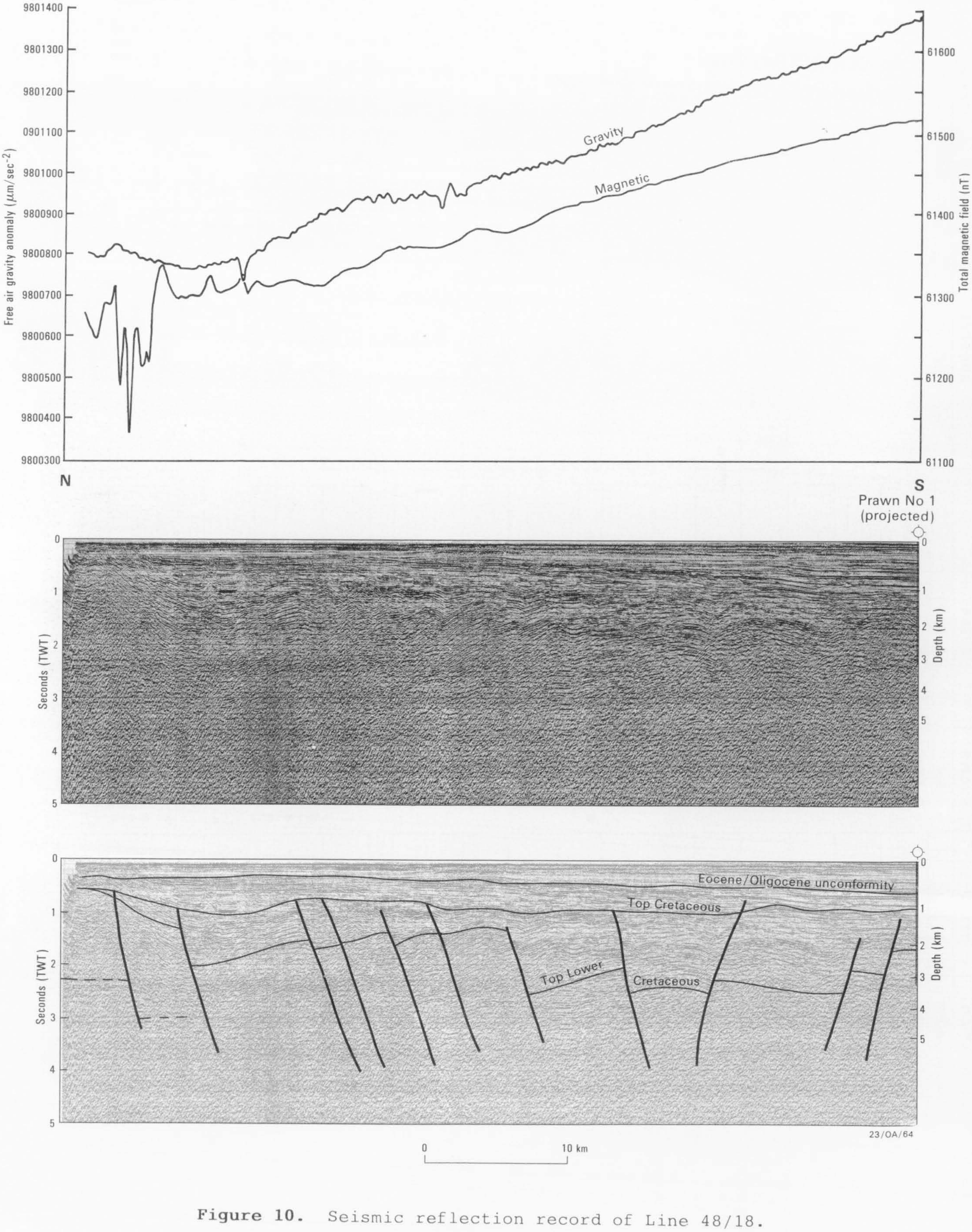


Figure 10. Seismic reflection record of Line 48/18.

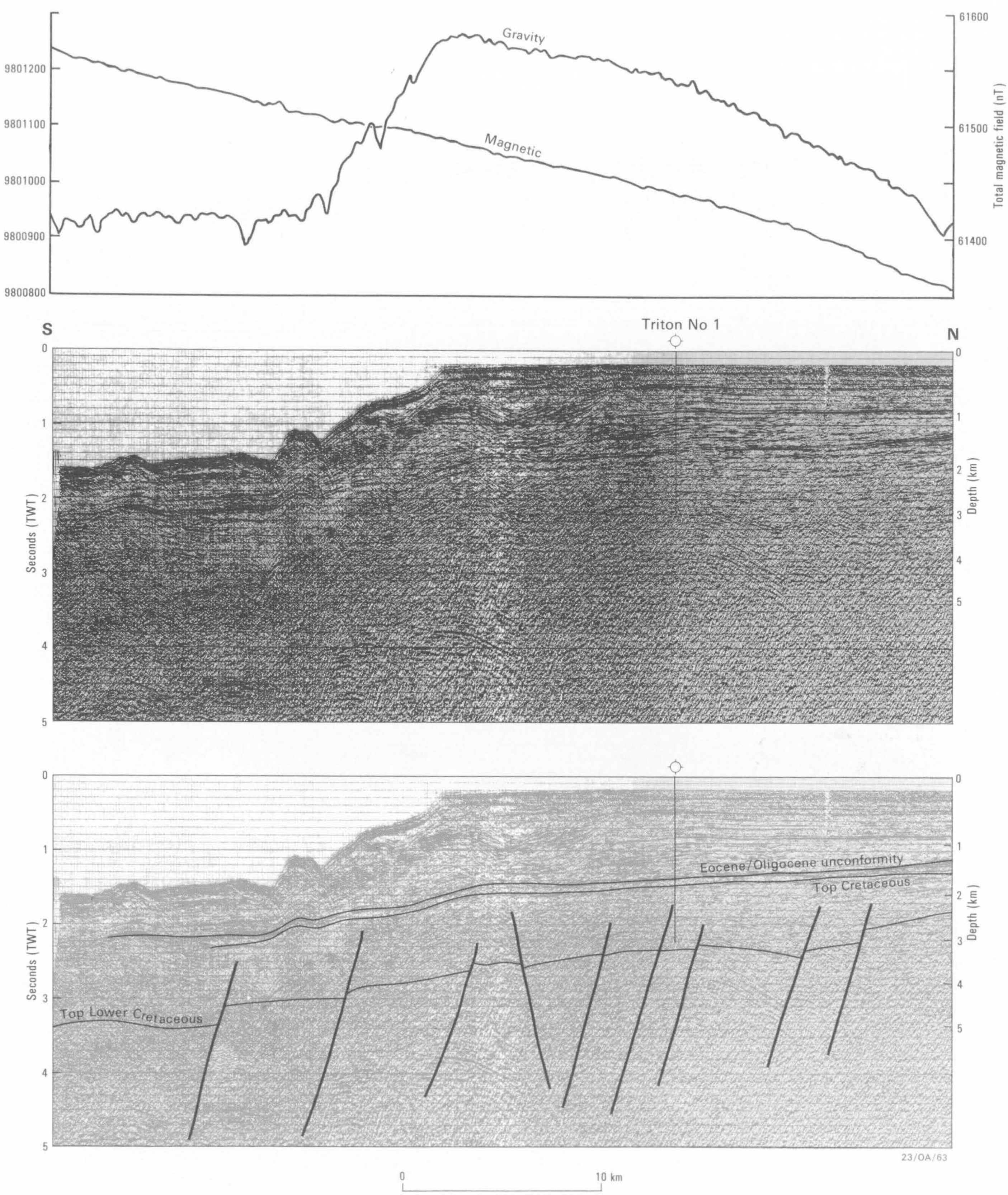


Figure 11. Seismic reflection record of Line 48/12.

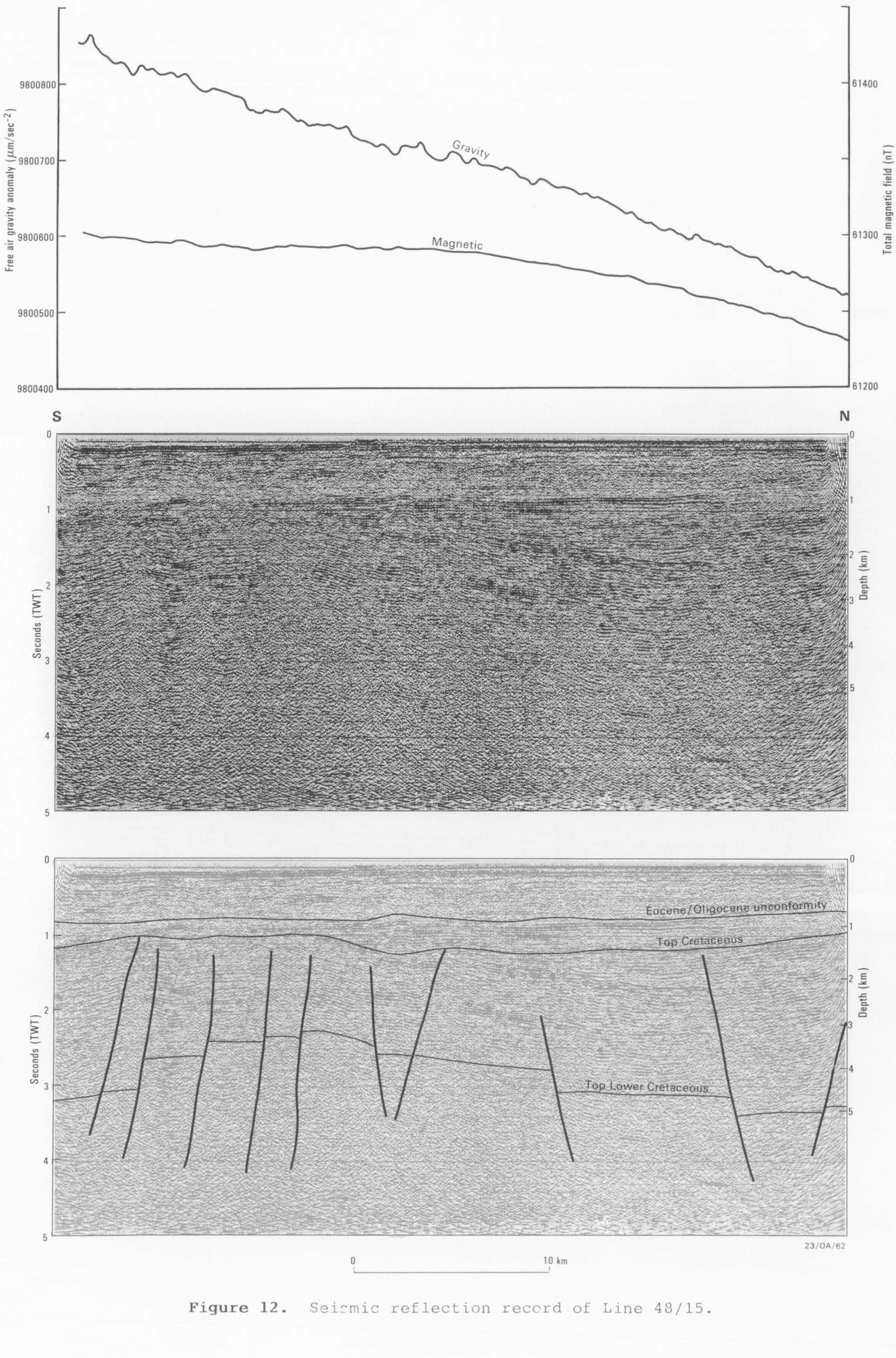


Figure 12. Seismic reflection record of Line 48/15.

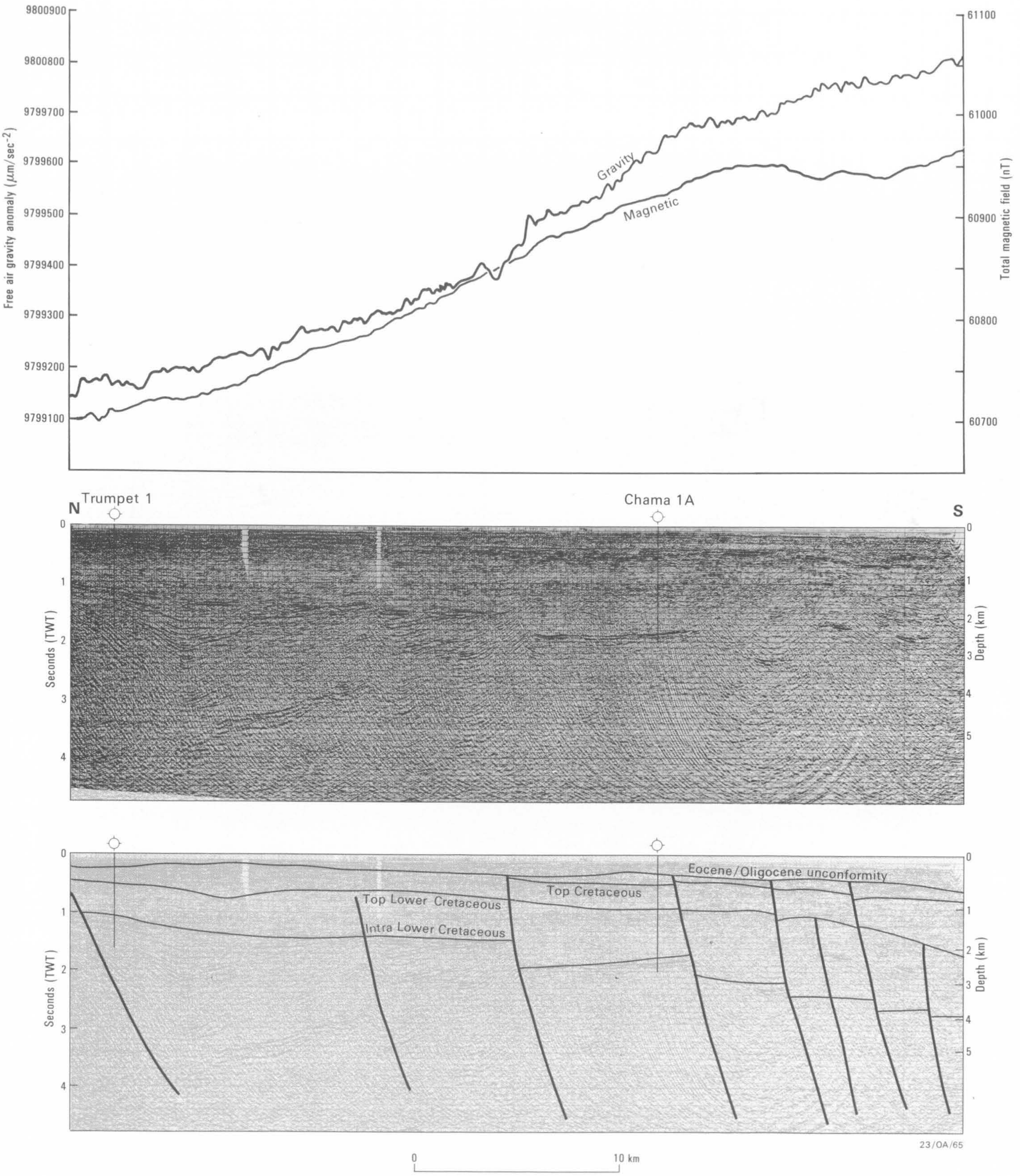


Figure 14. Seismic reflection record of Line 48/37.

muting to reduce those noise types. This was effected during seismic data processing at the BMR processing centre, using a Digicon Disco system encorporationg a DEC VAX 11/780 computer with multiple array processors.

Interpretations of selected lines (Figs. 10-14) illustrate the structure and stratigraphy of the main basinal areas. Seismic sections shown are processed sections. Stratigraphic ties were made using publicly available well data. Original well-stratigraphic interpretations were honoured, although a number of these are currently under review as part of the BMR Otway Basin study. Reference points on the seismic lines are given with respect to Julian day and hours of GMT.

Eastern Mussel Platform

The eastern Mussel Platform is delimited by a line trending southwest from Cape Otway to a point approximately 2 km east of Prawn No. 1, and from there south to the edge of the shelf. The platform shows block faulting, often with a transcurrent component and volcanic activity. The trend of the elevated blocks is mostly southwest, but becomes less distinct as the shelf is approached.

Prawn No. 1 well allows identification of regional reflection horizons, which can be traced on seismic lines in this area and onto the western Mussel Platform. Three horizons that could be traced regionally were: Eocene/Oligocene unconformity at 752 m well depth; top Upper Cretaceous-Sherbrook Group at 1265 m; and top Lower Cretaceous-Otway Group at 2945 m, below which approximately 249 m of the Otway Group was penetrated to a total depth of 3194 m.

Line 48/18 (Fig. 10) ties the Prawn No. 1 well north-south to the northern Mussel Platform. Rift faulting is developed at top Lower Cretaceous (top Otway Group) and has more subdued expression at the top Cretaceous level (top Sherbrook Group). A deeper intra-Lower Cretaceous event, thought to be associated with Lower Cretaceous coal measures, is present on the north of the line.

Line 10 connects Whelk No. 1 (off King Island) to Prawn No. 1 and trends northnorthwest. Major regional normal faulting some 12 km north of the Whelk extends to the top of the Upper Cretaceous. Similar faulting occurs near the Prawn No. 1, near the eastern boundary of the Mussel Platform. The Lower Cretaceous strata show normal faulting typical of rift basin formation. Major and minor drape structures can be seen. A gravity high is associated with the uplifted Whelk area, and gravity values reduce occur towards the basin.

Line 48/9, trending nearly east-west, shows a section of the continental shelf near Whelk No. 1, the continental slope and rise and the abyssal plain. Stepping down of the top Otway Group horizon can be observed under Upper Cretaceous and Tertiary strata, along with sedimentary infill in sub-basins on the slope. The magnetic intensity data and preliminary seismic interpretation suggest that volcanics are associated with fault zones on the upper slope.

The southern part of the Torquay Sub-basin is transected by line 48/4 in a southwest direction, and tied to line 48/5 in the vicinity of the Cape Otway-King Island High. Significant faulting has occurred in a number of locations on this line, probably in Late Cretaceous times, and is associated with volcanic flows. Reactivation of these faults occurred in the Paleocene, causing drape structures. The section also shows a major fault downthrown towards the northeast (Torquay Sub-basin) with minor associated volcanism, probably of Eocene age. The gravity values confirm the interpreted basinal structure, but magnetic intensity values are probably more influenced by volcanics extending throughout most of the sub-basin. Folding of all strata is interpreted at the southwestern end of this line.

<u>Western Mussel Platform</u>

The western Mussel Platform extends 100 km west of Cape Otway, and underlies the continental shelf from the coast to a water depth of 200 m (Fig. 3). The platform is divided into a number of structural highs and lows within the Mesozoic and Cenozoic strata. Five wells have been drilled offshore into the platform since 1967. Most of the wells penetrated the Lower Cretaceous Otway Group, a major target, along with the overlying Waarre Sandstone, for hydrocarbon exploration in the Otway Basin. A number of reflection seismic lines from the study crossed the western Mussel Platform and tied the offshore exploration wells.

Line 48/12 traverses the continental slope and shelf from south to north, west of Cape Otway (Fig. 11). Near the outer continental shelf, the profile ties Nautilus No. 1 and Triton No. 1. The Triton No. 1 well ties the Eocene/Oligocene unconformity at 1720 m well depth and the top of the Late Cretaceous Sherbrook Group at 1730 m. Total depth is at 3406 m in Late Cretaceous Waarre Sandstone. Along Line 48/12, the Eocene/Oligocene and top Cretaceous unconformity rise to the north near the continental shelf. The line shows rifted structure at the top Lower Cretaceous (Otway Group) level on the continental shelf and little reactivation of faulting at top Cretaceous level. The Tertiary section in the region is 1.7 km thick, which is unusually thick for the offshore Otway Basin and indicates later subsidence of the southwestern Mussel Platform. Tertiary channelling is well developed on the edge of the continental shelf.

Line 48/5 extends along the shelf from south of Cape Otway some 75 km to the northwest to Pecten No. 1, which encountered significant gas shows in the Waarre Sandstone. All three major horizons can be traced updip on Line 48/5 from the area of the well to the area south of Cape Otway, where the horizons are deformed into a structural high, representing the northern continuation of the Cape Otway-King Island High.

Line 48/6 extends from the end of Line 48/5 at Pecten No. 1 to the northwest, sub-parallel to the coast. The reflecting horizons interpreted on Line 48/6 are continuations of horizons picked on Line 48/5. The Eocene (Dilwyn Formation) and Upper Cretaceous (top Sherbrook Group) reflectors rise to the northwest from the well site. The Lower Cretaceous (top Otway Group) reflector, in contrast, deepens to more than three seconds (two-way travel time) to the northwest of the well, and the Cretaceous section above the Otway Group thickens considerably to the northwest as Line 48/6 crosses the Port Campbell Embayment into the Voluta Trough.

<u>Eastern Voluta Trough</u>

The eastern Voluta Trough is west of the Mussel Platform and has Cretaceous and younger sediment thicknesses up to approximately 10 km.

Structure in the eastern Voluta Trough largely consists of landward dipping Lower Cretaceous fault blocks cut by down-to-ocean normal rift faults. There has not been much reactivation of faults to Upper Cretaceous levels in the area.

The Portland Trough is a Late Cretaceous sub-basin of the Eastern Voluta Trough. It has been delineated onshore by seismic reflection mapping and data from water and stratigraphic wells. The trough contains a markedly thicker Upper Cretaceous section than exists on the adjacent highs, which developed concurrently. Onshore, the trough depocentre is situated north of Portland and the basin axis trends northwest. The main structural trends are controlled by faulting which, offshore, appears to have begun in the late Early Cretaceous. To the west the trough is terminated by the Dartmoor Ridge, and to the north it is separated from the Tyrendarra Embayment by a major southwest-dipping normal fault. The only oil exploration well within the trough, Portland No. 1, is onshore and was dry. It has been plugged and abandoned. However, the Lindon No. 1 well drilled on the margin of the trough had petroleum shows at the base Tertiary level.

Seismic reflection data were obtained in this region partly to investigate the offshore extension of the Portland Trough and the structural relationships between the Portland Trough, the Voluta Trough to the south, and the Mussel Platform to the east.

Four wells have been drilled in the eastern Voluta Trough. Voluta No. 1 had a total depth of 3974 m and appears to have intersected the Waarre Sandstone at 3746 m. The reflection data show a faulted uplifted structure at the well location, and other fault-bounded structures in the Voluta Trough. Line 48/15 (Fig. 12) running from the Voluta Trough northeast to the Portland Trough shows a faulted high at top Lower Cretaceous level and down faulting into the offshore extension of the Portland Trough accompanied by thickening of Upper Cretaceous and lower Tertiary strata.

Western Voluta Trough

The western Voluta Trough (Fig. 3) is offshore to the Gambier Embayment and extends for 300 km from the Dartmoor Ridge in the east to the western edge of the Tertiary Otway Basin. Structure in the western Voluta Trough consists predominantly of down-to-ocean normal faulting of Cretaceous strata that dip back towards the coast. The Argonaut No. 1 well was one of two wells drilled in the area and targeted the Waarre Sandstone of the Sherbrook Group.

Line 48/43 (Fig. 13) ties to Argonaut No. 1 and extends southward over the continental slope and rise onto the abyssal plane. The line illustrates the rifted structures in the western Voluta Trough. The main reflector ties at Aragonaut No. 1 on the continental shelf are the Eocene top Wangerrip Group (298m), the base Tertiary top Sherbrook Group (727 m) and the mid-Cretaceous, base Sherbrook Group, Waarre Sandstone (3524 m). These reflectors are traced oceanward where, the Wangerrip Group pinches out. On Line 48/43 Cretaceous strata dip landward and are progressive faulted oceanward, by normal rift faulting; the Upper Cretaceous strata thin oceanward until the Lower Cretaceous Otway Group subcrops near the continental rise.

In the strike direction, horst and graben structures continue to be present on Line 48/23 and 48/24 on the Continental Shelf in the western Voluta Trough. Faulting is strongest at the top Otway Group (Lower Cretaceous) but reactivation at base Tertiary level occurs, particularly in the west towards the Crayfish Platform margin.

Crayfish Platform

On the Crayfish Platform, in the west of the Gambier Embayment, Lower Cretaceous strata are encountered shallow in the section. The top Lower Cretaceous Otway Group and Lower Cretaceous Pretty Hill Sandstone have been encountered in Trumpet No. 1 at 457 m and 1303 m, respectively. Line 48/37 (Fig. 14) ties the Trumpet No. 1 and the Chama No. 1 wells and shows thickening of the Upper Cretaceous Sherbrook Group towards the south of the platform and greater structural relief at top Otway level. At the north of the line, the shallow Otway surface is displaced by growth faulting in the shaly Lower Cretaceous Eumeralla Formation; the faulting terminates at the base of the Eumeralla Formation. The major faulting occurs at the top of the Lower Cretaceous Pretty Hill Sandstone.

On the continental slope the Upper Cretaceous thins, with the Lower Cretaceous Otway Group interpreted as subcropping at the continental rise. On Line 48/40, normal faults in the continental slope are downthrown oceanward. Cretaceous strata again dip landward.

Lines 48/25 and 48/26 on the continental shelf tie the Trumpet No. 1 and Crayfish No. 1 wells in a strike direction. The top Otway reflector on the Crayfish Platform does not display, on these lines, the large fault throws, that are associated with the angular unconformity at the top of the Pretty Hill Sandstone. An intra-Pretty Hill Sandstone reflector can be traced in the region.

To the east, along Line 48/25, strata are downthrown to the western Voluta Trough, where the Eocene to Wangerrip Group reflector and the top Cretaceous unconformity can again be traced.

Deepwater areas

The general results of interpretation of seismic reflection lines on the continental slope, rise, and abyssal plane show pinching out of the Eocene-Paleocene Wangerrip Group high on the continental slope, followed oceanward by thinning of Upper Cretaceous sediments until the Lower Cretaceous Otway Group subcrops at the continental rise.

The general pattern of the deep-water lines 41, 42, 43, 44 and 8 is of southward normal faulting of backdipping Lower Cretaceous strata; e.g. Line 48/43 (Fig. 13). The transition from continental to oceanic crust is probably not present on these lines and occurs south of this data set. The transition normally corresponds to a change in seismic reflection character, from moderately continuous continental reflectors interrupted by down-to-ocean normal faulting, representing continental crust, to masses of diffractions underlying surficial sediments and representing oceanic crust (Bouef & Doust, 1975). However, continental volcanics or basement can also give rise to diffractions, and the nature of the magnetic quiet zone on the abyssal plane remains problematical.

The base Tertiary unconformity can be traced in the abyssal plain data and is represented in the shallow ponded sediments. Eocene-Paleocene equivalents of the Wangerrip Group, which pinch out on the continental slope, are not interpreted as occurring on the abyssal plain. This implies that Upper Cretaceous sediments are present beneath younger Tertiary to Recent, probable probable pelagic sediments on the abyssal plain, and supports the concept of an initial mid to Late Cretaceous seafloor-spreading stage followed by a faster early Tertiary spreading stage, the onset of which could modify oceanic circulation and produce a base Tertiary unconformity in sediments on the abyssal plain and continental rise and slope. This scheme is similar to that proposed by Cande & Mutter (1982).

Continental crust is still present on the abyssal plain on Line 48/43 (Fig. 13). The upper and lower crust are interpreted as being separated by a decollement and extended by different low-angle fault regimes. The whole crust of the abyssal plane is cut by a number of later normal faults, possibly associated with later stage thermal subsidence.

Refraction seismic

Introduction

There have been two previous sonobuoy surveys in the Otway Basin. The first was conducted by Shell in 1967; the second, by Haematite Petroleum during 1972-74. From the latter survey Denham & Brown (1976) concluded that in the deeper parts of the basin the top of the Lower Cretaceous Otway Group could be identified by an increase in velocity of about 600 m/s to a fairly uniform 4600 m/s.

Data from 14 sonobuoys were collected by *Rig Seismic*. Eight of these were on the continental shelf and the remainder in deep water (Fig. 2). They gave velocity information on the recent to Cretaceous sedimentary column, continental basement, and upper and lower continental crust. Fifteen sonobuoys were deployed in all; one failed when its aerial broke on deployment. The performance of the sonobuoys was found to vary with sea state. Discernible arrivals were received from up to 30 km in moderate seas, or from as little as 25 km in rough seas. Figure 15 shows the record from sonobuoy 48/13, a deep water sonobuoy with good data quality to 25 km. Sonobuoy data were digitally recorded for later processing.

The resolution of the refraction method is related to the velocity distribution in the subsurface as well as to the power and the frequency and amplitude spectra of the source. In general, the vertical resolution is an order of magnitude less than for the reflection method, so exact detailed one-to-one relationships between reflectors and refractors are unlikely. Subsequent computer processing was used to enhance coherent weaker arrivals for further interpretation of the data. The sonobuoy data were found to be generally of good quality. Signal levels were high and many refractions were evident. The high amplitude of the data is due to an AGC amplifier in the sonobuoy itself, but that unfortunately has the effect of producing similar reflection and refraction amplitudes, so that interpretation cannot use amplitude as a criterion for distinction.

Seafloor refractions were rarely seen on the sonobuoy data, and it is also difficult to accurately determine the intercept times for deep refractors.

Acoustic basement was often the last refraction at long offsets, many in excess of 25 km. On the shelf, the basement refraction is often seen to arrive at an offset of about 5-8 km, then to persist as the first arrivals from then on. Deep crustal events however, observed on several sonograms, will allow the nature of the crust to be investigated.

Sonobuoy results

Sonobuoy record 48/13, on Line 48/43 (Fig. 13), was obtained on the lower continental rise and abyssal plain. The water depth was 4173-4341 m along a traverse where the interpretation of seismic reflection records shows ponded sediments overlying landward-dipping rotated blocks of Lower Cretaceous Otway Group. The dip on the tops of the blocks and the relief of the faulting are not extreme and are consequently not expected to affect the sonobuoy record significantly. The main refractors can be tied to events on the reflection record (Fig. 15). Refractor 1 (3.16-3.30 km/s) represents top Otway Group (Lower Cretaceous) with the lower than usual velocity reflecting little burial. Refractor 2 (3.7-5.0 km/s) appears to be an additional Otway event. Refractor 3 (5.6-7.0 km/s) represents basement rocks with velocities similar to those of the Lachlan Geosyncline on shore. The deepest event with apparent velocity of greater than 8 km/s is interpreted as a precritical arrival, and is thus not considered usable. Reference to the work of Talwani & others (1979) would suggest, however, that this event represents the base of the crust. The lack of any substantial deviation of refractions from straight lines fits with the relatively low structural complexity.

The uncorrected velocity values from all sonobuoys show a broad range, but can be classified into three basic groups. The first includes over 60% of the identified refractions and consists of shallow sedimentary refractors with a velocity of 1.6-3.0 km/s. Reflection character suggests that the second group is also sedimentary. It has a velocity range of 3.1-5.0 km/s and is generally pegged to the Otway Group, the range reflecting both degree of burial and structural effects. Basement returns, with apparent basement velocities of 5.6 km/s and greater, make up the third group. Some deep water, very fast arrivals (>8 km/s) are believed to be precritical reflection phases, possibly from the base of the crust.

Magnetics

Magnetic data were recorded during multichannel seismic profiling and in transit, with 2 Geometrics G801/803 proton precession magnetometers. Gradiometer data were collected initially; after the gradiometer was damaged data were recorded by a single magnetometer. Diurnal magnetic effects during the survey were monitored by onshore magnetic stations. Details of magnetic data collected are given in Appendix A and raw magnetic data are plotted with the seismic profiles on Figures 10 to 14.

Magnetic high and low anomalies broadly correspond to structural highs and lows on the shelf, as on Line 48/15 (Fig. 12), where there is a decrease in anomaly amplitude into the Portland Trough. In some areas in the eastern basin, however, magnetic anomalies are reversed over structural highs, suggesting reverse remanent magnetisation.

On deep-water lines, such as Line 48/43 (Fig. 13) the magnetic anomaly increases onto the abyssal plain. Data collected during this survey probably

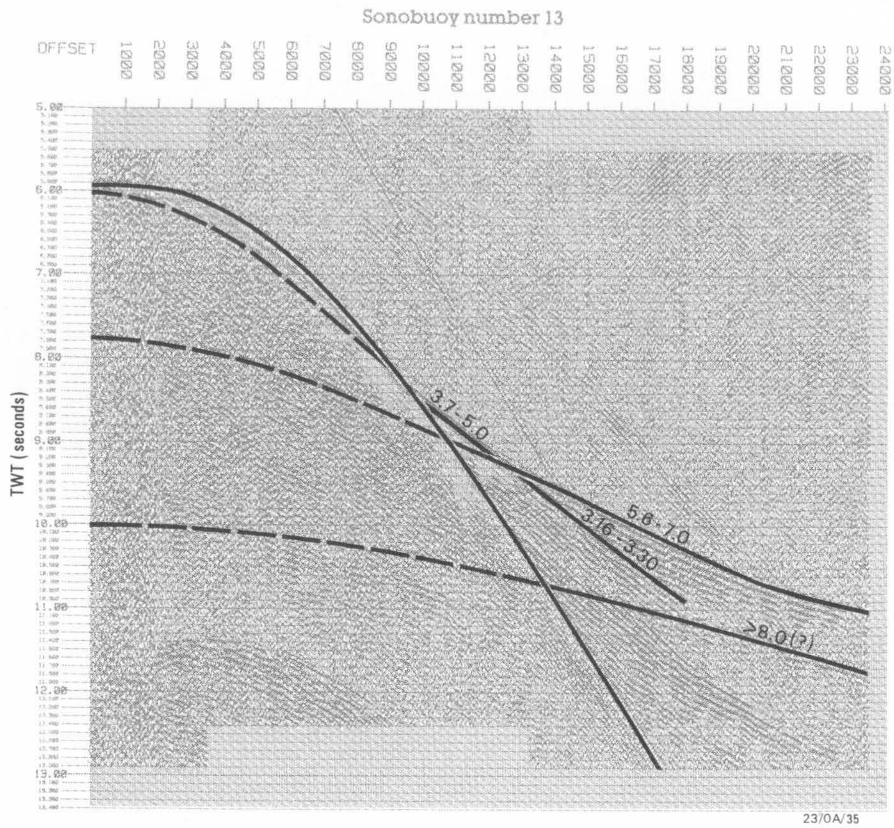


Figure 15. Record of sonobuoy 48/13.

did not encroach onto oceanic crust, or only barely, and cannot be used to investigate seafloor spreading anomalies, since the deep-water data were obtained over the magnetic quiet zone.

Gravity

Gravity data were recorded, during multichannel seismic data acquisition and transit phases, with a Bodenseewerk Geosystem KSS-31 Marine Gravity Meter. Locations of traverses are given in Appendix A and free air gravity anomaly data are displayed with seismic profiles on Figures 10 to 14.

Gravity anomalies tend to reflect gross basement structure on the shelf. On Line 48/15 (Fig. 12), for example, downfaulting into the Portland Trough coincides with a decrease in gravity values relative to the regional trend.

On deep-water lines, such as Line 48/43 (Fig. 13), gravity values increase onto the abyssal plain, probably reflecting higher crustal densities and a thinner crust overlying denser mantle material, as implied by the refraction results of Talwani & others, (1979).

GEOLOGICAL RESULTS

This was the first *Rig Seismic* research cruise on which the coring winch was functioning, albeit with teething troubles. On the two shakedown cruises, which immediately preceded the Otway Basin cruise, four sampling stations yielded seafloor samples from the Tasmanian margin. On this cruise six stations were occupied, all successfully, and the recovered material gives us additional insight into the nature of the deep-water part of the basin. Winch problems, and a final breakdown, drastically curtailed the planned sampling program.

Station position, water depth, related seismic line, and a brief description of the sediments recovered, are given in Table 1. The location of each station and its relationship to the bathymetry of the basin are shown in Figure 1.

Table 1: Otway Basin cruise sampling stations (BMR cruise 48)

Station	Bottom contact Lat (S)	Bottom contact Long (E)	Seismic profile	Depth (m)	Recovery	Description and age
5DR (West Otway Basin	38 39.4'	140 50.5'	Shell N411	1650-1450	1 kg	Late Oligocene chalky white marl and grey calc. silty clay-stone. Recent greenish-grey mud.
6DR (West Otway Basin	38 50.0'	139 06.9'	Shell N410	3800-3750	200 kg	Sheared, hard grey-green mudstone with quartz veins, ?plant remains; minor black mudstone.?Palaeozoic.
7DR (West Otway Basin)	38 31.4'	139 37.5'	BMR 16/081	3250	60 kg	Quaternary calc. mud Middle Eocene and L.-E. Oligocene calc. siltstone, L.?Oligocene silicified calc.siltst. M.Eocene calc mud carbonaceous micaceous mud,brown plastic mud, pebbles marlstone and iron-stone; Quaternary mud.
8DR (West Otway Basin)	38 41.7'	141 22.8'	None	345	10 kg	Greenish brown shelly mud.
9DR (West Otway Basin	38 50.8'	141 06.4'	BMR 16/031	2200-2100	50 kg	E.Miocene light brown calcarenite, calc. siltstone, calc. mudstone and plastic mud; white calc. siltstone; Quaternary light-brown mud.
10DR (West Otway Basin)	38 46.1'	140 38.2'	BMR 16/83	2500-2200	2 kg	L.Miocene white silty calc. claystone

Sampling methods and shipboard studies

At all stations but one, sampling was by chain bag dredging on slopes steeper than 10 degrees. A small pipe dredge was attached to the rear of the chain bag, to provide a soft sediment sample to complement the more consolidated material which could be recovered in the chain bag dredge. The 18 mm cable of the coring winch was attached to the dredge by a swivel and a shear pin of 9 tonnes breaking strain. The shear pin protects the 18 mm cable, which has a yield point of some 13 tonnes, should the dredge become irretrievably anchored to an outcrop. A safety cable of 14 mm wire connected the 18 mm wire to the rear of the dredge bage to allow the dredge's recovery should the shear pin break. In the event, the shear pin did not break and no equipment was lost.

At station 8DR, in shallow water, a moderate sized pipe dredge was deployed rather than the chain bag dredge, to recover young unconsolidated sediment. At stations 9 and 10 a Benthos time-depth recorder was attached to the main cable by D clamps several hundred metres above the dredge, with the aim of better defining the water depths from which rocks were dredged.

The technique used at the deep-water stations was to run an echosounder profile down a slope selected from seismic profiles, and to stop just beyond the target slope. Lack of a functioning single-channel seismic system was a distinct disadvantage, as this would have allowed more definite correlation to seismic reflectors on nearby seismic profiles. The dredge was run down at 20-40 m/min. for the first few hundred metres, and at up to 80 m/min thereafter. Experience on the preceding shakedown cruises had shown that the dredge would plane and be overrun by the winch cable at higher speeds.

Once the amount of wire out equalled the water depth, the ship was got underway at 1-2 knots, heading up the slope, and wire was paid out simultaneously until the amount of wire out exceeded the water depth at the foot of the slope by 20%. The electronic control system of the winch was set to pay out should the load on the shear pin become critical. Generally, the sampling was fairly straightforward (apart from winch failures), but on one occasion the dredge had to be freed by reversing the ship's heading.

Soon after samples came aboard they were washed clean and split into groups of similar types, each type being designated by a number, and individual rocks within each type by a postscript letter. Thus individual rocks from the dominant lithology at station 7 were designated 48/7DR1A, 1B, 1C etc. (DR indicating dredge). They were then described in hand specimen, having been sawn to give fresh surfaces where necessary. Smear slides were made later from weakly lithified specimens, and sedimentological and nannofossil descriptions were made. The smear slide descriptions were used to refine the hand specimen descriptions made earlier. More detailed laboratory studies are continuing, and some are included in this report.

Description of dredge stations occupied

Station 5

The target was the southeastern slope of a southwest-trending canyon on the upper continental slope southwest of Portland, in 1700-2000 m of water, selected from Shell seismic line N411. The echosounder profile obtained over the site prior to dredging showed an even southeastern slope of 15 degrees in water depths of 1450-1930 m. A mud sample and 1 kg of rocks were recovered. Two rock types were present;

5DR1 - 50% of haul; chalky white marl, consisting of clays and coccoliths, with minor sponge spicules, faecal pellets and foraminiferal tests. Two types of borings were present in the rock: small (to 2 mm diam) and branching, and large (10 mm diam). Both kinds were lined with a veneer of manganiferous material. A flat siliceous concretion was noted, formed about a disrupted greenish lamina 5 mm thick. From nannofossil identification, this rock is dated as Late Oligocene.

5DR2 - yellowish-grey calcareous silty claystone, consisting of abundant coccoliths, some large; abundant forams; spicules; minor microbored shell fragments; minor silt- and clay-sized quartz; rare brown fish bone fragments. This rock is also Late Oligocene.

The pipe dredge sample consisted of greenish grey calcareous mud without visible forams.

Station 6

The station was located west-southwest of Portland in 4500 m of water. The target was a possible basement ridge, block-faulted Otway Group, or mixed basement/Otway Group, trending northwest-southeast, near the base of the continental slope, apparent on Shell seismic line N410. The echosounder profile showed an even slope of 17 degrees on the landward side of the ridge, in 3650-4600 m of water. Two rock types were collected in the 200 kg sample, along with mud in the pipe dredge.

6DR1 - 99% of haul; grey-green hard quartz-poor mudstone or argillite, sheared and brecciated in part, with pyritic quartz veins. Siliceous, pyritic concretions are present. The rock is weathered, with ferruginous and manganiferous staining. Rare, poorly preserved ?plant remains are present.

Thin section examination of two samples showed that 6DR1 consists largely of phyllosilicates containing up to 10% detrital silt-sized angular quartz. A poorly developed primary lamination is defined by variations in size and abundance of quartz silt. Opaques are minor and consist mainly of pyrite; often associated with the coarser quartz-rich laminae. Large siliceous pyritic nodules, possibly concretions, have formed sporadically, prior to compaction, giving rise to deformed lamination around them.

Chlorite clots and micaceous aggregates are probably replacements of other material, possibly volcanic rock fragments. They may also represent vesicle fills, possibly of organic remains. A foliation (cleavage) is developed oblique to the primary lamination. It is marked by preferred orientation of phyllosilicates, including some muscovite, in the matrix.

Chlorite, iron oxide and quartz/chlorite veining are common; the quartz/chlorite veins are large and consist of deformed and strained coarsely crystalline quartz with sheaves of pale green chlorite. Inclusions of foliated and crenulated brown argillite are present in these veins, with minor calcite and interstitial ?iron-rich chlorite. The chlorite and iron oxide veins are generally thin and irregular.

The thin section studies show that 6DR1 is a weathered foliated argillite, metamorphosed to chlorite/muscovite grade.

6DR2 - 1% of haul; sheared black mudstone or argillite.

Thin section examination of four samples shows that 6DR2 consists of laminated and foliated argillite, whose dark colour is due to fine scattered opaques, mainly pyrite, with some organic matter. Up to 10% silt-size detrital quartz grains occur, mainly concentrated in, and defining, primary lamination. Silt-size muscovite parallel to lamination, is probably also detrital. Siliceous spherules, both as aggregates and single spheres, probably represent organic remains such as radiolaria or similar organisms. Volcanic fragments with spherulitic texture are commonly glassy and are unlikely to have survived intact through the diagenesis/low grade (chlorite) metamorphism which this rock has undergone.

The elongate chalcedony fragments noted in 6DR2A and 6DR2D are almost certainly replacements of organic debris, possibly bony material. One curved and recurved fragment in 6DR2A resembles an oblique section of a trilobite cranidium; further work is being carried out on this material.

None of the dispersed organic matter showed fluorescence, indicating the dominance of inertinite and/or overmaturity for petroleum generation, consistent with chlorite grade metamorphism.

Attempted palaeontological dating of these samples was unsuccessful. The grey-green rock type resembles fine-grained Otway Group rocks in which concretions are present in outcrop. However, the metamorphic grade, with shearing, brecciation, quartz veins, and crenulation cleavage, suggests that these rocks are probably of Palaeozoic age. While not common, black carbonaceous mudstones are known from the Otway Group; however, black shales are common in Lower Palaeozoic basement in central and western Victoria. Both the grey-green and black mudstones are tentatively assigned to the Palaeozoic, and the quartz-poor nature of the green mudstones suggests an Early Palaeozoic age.

The pipe dredge mud sample consisted of Recent coccolith ooze.

Station 7

The target was a 20 degree seaward slope, a possible fault scarp, on the continental slope southwest of Portland, in 3750 m of water. It is located on BMR seismic line 16/081. The echosounder profile showed a 13 degree even slope in water depths of 3470-3750 m. The sampled depth, at which the only good 'bites' were obtained, was considerably shallower at 3250 m; 60 kg of largely calcareous rocks and a mud sample were obtained.

7DR1A - 35% of haul; calcareous silty mudstone, consisting of comminuted shell debris; clays; minor quartz, coccoliths and faecal pellets; rare forams and glauconite. Dated from nannofossils as late Eocene to early Oligocene.

7DR1B - 35% of haul; calcareous mudstone composed of abundant clays and coccoliths; sponge spicules; rare glauconite; possible very rare quartz. Dated as middle Eocene from nannofossils.

7DR1C - calcareous claystone composed of abundant clays and coccoliths; common glauconite and faecal pellets (some aggregates); fish bone debris; minor sponge spicules and quartz. Dated as ?Eocene-?Oligocene.

7DR1D - calcareous claystone composed of abundant clays; some coccoliths; fish bone fragments; spicules; siliceous material; possible radiolaria. Undated at present.

7DR1E - 35% of haul; calcareous claystone composed of abundant clays; some coccoliths, including large forms; spicules; other siliceous material; one fish bone fragment. Dated as middle Eocene from nannofossils. debris; quartz; minor spicules. Possible late Oligocene age.

7DR3 - 10% of haul; white semi-consolidated nannofossil ooze; composed of 95% coccoliths; 5% spicules and other siliceous debris. Dated from coccoliths as middle Eocene.

7DR4 - 10% of haul; dark brown carbonaceous sandy mudstone with earthy friable texture; composed of clay, woody fragments, pyrite, very fine quartz sand. No nannofossils; undated at present.

7DR5 - light-brown plastic mud; composed of clay, very fine quartz and feldspar, woody material, pyrite, very minor coccoliths (possible contamination). Undated at present.

7DR6 - (from pipe dredge) light-brown mud; composed of clay and coccoliths; minor forams and spicules. Recent.

7DR7 - consists of two pebbles of soft white sandy marlstone. Dated as late Oligocene.

7DR8 - one small pebble of pisolitic ironstone. Undated.

Station 8

Station 8 was located on the upper continental slope southwest of Portland. A small pipe dredge was deployed to collect a Recent mud sample in 400 m of water; 10 kg of sample were collected. The sample was divided and one part washed to remove the mud from the coarse fraction.

8DR1 - coarse fraction: calcareous shelly and coralline debris.

8DR2 - calcareous greenish-brown mud, with admixed calcareous silt and sand.

Station 9

This station was located on the upper continental slope southwest of Portland in 2000 m of water. The target was probable Upper Cretaceous on the 10 degree eastern slope of a complex southwest-trending canyon, located on BMR seismic line 16/081. The echosounder profile showed an even slope of 13 degrees in 1800-2550 m water depth.

A Benthos time-depth recorder was deployed at this site and recorded a sampled depth interval of 2200-2100 m on the canyon slope; 60 kg of calcareous rocks and muds were obtained.

9DR1 - 25% of haul; light-brown bioclastic calcarenite consisting of abundant sand-sized shelly debris (usually microbored); polyzoan fragments; abundant coccoliths; minor spicules and quartz; rare fishbone fragments, forams, Discoaster spp. remains. Dated from nannofossils as early Miocene.

9DR2 - 25% of haul; light-brown sticky calcareous mudstone, composed of abundant clay and coccoliths; common forams; rare polyzoan fragments and Discoaster spp. remains. Dated as early Miocene.

9DR3 - 20% of haul; light-brown calcareous silty claystone with light manganese staining; consists of abundant coccoliths and forams; minor microbored shell debris; spicules; rare bone fragments and Discoaster spp.

9DR4 - 18% of haul; light-brown silty calcareous claystone with large (to 10 mm diam) borings, manganese-lined. Consists of abundant clay and coccoliths; common forams; rare spicules, faecal pellets and Discoaster spp. Dated from nannofossils as early Miocene.

9DR5 - 10% of haul; white calcareous silty mudstone; composed of abundant coccoliths and clay; minor forams; rare bored shelly fragments and polyzoan fragments. Age date from nannofossils as possibly Miocene.

9DR6 - 2% of haul; light-brown plastic mud; consisting of abundant coccoliths; common microbored shelly remains, faecal pellets and forams; minor spicules; one fish bone fragment.

9DR7 - light-brown mud from pipe dredge; Recent age.

9DR8 - sample of 3 solitary corals from pipe dredge. Undated.

The target was a southwest-trending canyon with a steep northwest face dropping from 2200 to 2750 m, located southwest of Portland, on BMR seismic line 16/83. The echosounder profile showed an even 20 degree slope on the face, in water depths of 2200-2750 m. Two cobbles of calcareous rock (total mass 1 kg) and a mud sample were obtained.

10DR1 - 100% of haul; white silty calcareous claystone with slight ferruginous staining, with large (to 10 mm) burrows, some manganese-lined, and many small burrows. Consisted of abundant coccoliths (95%); large and small forams; Discoaster spp. remains; rare angular quartz grains, polyzoan fragments; minor shell debris; rare clay. Dated as late Miocene.

Post-cruise geochemical studies

A variety of geochemical studies was carried out in BMR laboratories at the instigation of G.W. O'Brien, and we are grateful for the contributions of I. Crick, J. Pyke and J. Kamprad. The results are summarised below.

Total Organic Carbon

Eighteen rocks from five locations were submitted for total organic carbon (TOC) determinations (Table 2). TOC was generally low (less than 0.1%), though it ranged between 0.66 and 1.28% in five samples. Four of these were dark claystones of ?Palaeozoic age (or possibly Early Cretaceous age) from location 6DR (samples 6DR 2A-2D). All samples from location 6DR, which was a "basement" ridge at the base of the continental slope (3800 m water depth), were barren of palynomorphs, and thus have not been dated palaeontologically.

The other organic-rich sample was of Palaeogene age and came from location 7DR (7DR-4A). Sample 7DR-4A was a dark grey-green, poorly consolidated mudstone, with a TOC concentration of 1.28%. This sample has an abundant suite of dinoflagellates, and is probably of late middle Eocene age (E.M. Truswell, pers. comm.). This time interval appears to be absent in several offshore wells.

Rock-Eval

The five previously mentioned TOC-rich samples and two others were chosen for Rock-Eval analysis (Table 3). Probable ?Palaeozoic rocks from location 6DR have no hydrocarbon-generative potential, as their hydrogen indices (HI) are 0-10. The late middle Eocene sample 7DR-4A has the best generative potential, with a TOC of 1.28%, and a HI of 60. Even so, this still constitutes a very poor hydrocarbon source. Because of the low HIs (i.e. small S2 peak), the Tmax value in these rocks cannot be considered an accurate indication of thermal maturity, though 7DR-4A appears to be immature.

Vitrinite reflectance

Samples 6DR2A-2D and 7DR-4A were submitted to I. Crick (Division of Continental Geology, BMR) for organic petrology and vitrinite reflectance work. The predominant organic matter in the ?Palaeozoic 6DR samples is considered to be a form of Pyrobitumen. The mean maximum reflectivities (Rv) range from 4.13% to 4.59%, which is overmature with respect to hydrocarbon generation, but still lower than greenschist facies.

The organic matter in the middle Eocene sample 7DR-4A has Rv values between 0.56 and 0.76% (mean 0.66%), which is in the lowermost part of the oil generation window. Providing the organic matter is not reworked, this suggests that this rock has been much more deeply buried (more than 1000 m) or has been subjected to a strong thermal event, or both. The clayey matrix of the rock fluoresces, suggesting that hydrocarbons have been generated within the rock, and apparently confirming the proposal that the rock has been in the oil window. The possibility that the upper slope has been subjected to a strong thermal event should be investigated in the Otway sampling cruise of January-February 1987.

Bulk chemistry

Bulk chemical analyses of six samples were carried out by J. Pyke of BMR's Division of Continental Geology (Table 4). The five ?Palaeozoic claystones (6DR-2A/D) are of similar composition, with considerable quantities of reduced iron (but little pyrite). This reduced iron is principally present within chlorite. The middle Eocene mud (7DR-4A) is lower in silica, FeO, and K O and higher in Fe O and Na O than the other four samples. These chemical variations can be ascribed principally to the significant differences in clay mineral composition between the ?Palaeozoic and Cainozoic rocks.

Table 2. Total organic carbon (TOC) concentrations in Otway Basin dredge samples (BMR Cruise 48).

Sample No	TOC(wt%)	Description	Age
5DR-1A	0.09	Marl, white	Recent
2A	0.13	Marl, white	Recent
6DR-1A	0.04	Mudst, hard, lt gray, silicified	?Palaeozoic
1B	0.03	Mudst, gray-green	"
1C	0.04	Mudst, gray-green c pyritic concretions	"
1D	0.04	Breccia c quartz veins, grit, sedimentary frags	"
1E	0.05		
2A	0.66	Clayst, black, hard, siliceous, carbonaceous	"
2B	0.67	Clayst, black, hard, cleaved	"
2C	0.74	Clayst, dark gray, hard	"
2D	0.91	Clyst, black	"
7DR-1A	0.22	Calcilutite, sandy	middle Eocene/early Oligocene
	0.25	Calcilutite,	"
	0.06	Chert nodule	"
	1.28	Mud, dark gray-green, greasy, unconsol middle Eocene	middle Eocene
9DR-1A	0.07	Grainstone, bryozoal, lt cream	early Miocene
4A	0.08	Calcilutite, white-cream, silty	"
10DR-1A	0.04	Calcilutite, white, bored, soft	late Miocene

Table 3. Rock-Eval organic geochemical data for Otway Basin dredge samples (BMR Cruise 48).

Sample No.	Tmax (°C)	S_1	S_2	S_3	S_1+S_2	S_2/S_3	PI	PC	TOC(%)	$\frac{PC \times 100}{TOC}$	HI	OI
6DR-2A	275	0.00	0.01	0.05	0.01	0.20	0.00	0.00	0.66	0.00	2	8
6DR-2B	355	0.01	0.07	0.07	0.08	1.00	0.13	0.00	0.67	0.0	10	10
6DR-2C	372	0.02	0.03	0.04	0.05	0.75	0.40	0.00	0.74	0.0	4	5
6DR-2D	435	0.01	0.00	0.07	0.01	0.00	1.00	0.00	0.91	0.0	0	8
7DR-IA	313	0.04	0.10	2.51	0.14	0.04	0.29	0.01	0.22	3.4	45	1141*
7DR-IB	403	0.03	0.13	1.92	0.16	0.07	0.19	0.01	0.25	4.0	52	768*
7DR-4A	423	0.17	0.77	1.74	0.94	0.44	0.18	0.07	1.28	5.5	60	136*

* Carbonate-rich samples; OI unreliable

Table 4. Bulk chemical analyses of Otway Basin dredge samples. (BMR Cruise 48)

	6DR-2A	6DR-2B	6DR-2C	6DR-2D	7DR-4A
SiO_2	56.00	56.88	53.59	56.86	50.33
TiO_2	1.17	1.19	1.24	1.11	0.98
Al_2O_3	22.96	23.34	25.11	22.17	21.65
Fe_2O_3	1.56	1.48	1.20	1.45	4.91
FeO	4.37	3.94	3.56	3.78	1.75
MnO	0.14	0.10	0.08	0.10	0.05
MgO	1.53	1.48	1.81	1.40	1.48
CaO	0.24	1.13	0.21	0.30	0.45
Na_2O	0.58	1.07	0.33	0.61	1.29
K_2O	4.34	2.62	5.60	3.87	1.63
P_2O_5	0.12	0.12	0.13	0.10	0.09
S	0.01	0.01	0.01	0.02	1.96
TOTAL	99.52	100.03	99.23	98.20	99.50
L.O.I.	6.48	6.68	6.35	6.42	12.93

Bulk mineralogy

X-ray diffraction analyses, by J. Kamprad (BMR, Division of Continental Geology), of four ?Palaeozoic claystones (6DR-2) and one middle Eocene mud (7DR-4A), show that there are differences in the mineral composition as listed below:

6DR-2A: quartz, major chlorite and illite
6DR-2B: quartz, ?trace feldspar, major chlorite and illite
6DR-2C: quartz, major chlorite and illite
6DR-2D: quartz, major illite and kaolinite and/or chlorite, possible trace montmorillonite
7DR-4A: quartz, ?trace feldspar, major kaolinite, minor montmorillonite, trace illite.

Discussion

The older samples from station 6DR (?Palaeozoic) are clearly different chemically from the Palaeogene samples (7DR, 9DR and 10DR) analysed. Total organic carbon (TOC) is low in the green argillite of 6DR, but relatively high in the black claystone (Table 2). The only other relatively high TOC value is from the middle Eocene mud 7DR-4A. Vitrinite reflectance is very high in the black claystone of 6DR, and moderate in 7DR-4A.

There are other differences between the two sets of samples with high TOC values, e.g. the black claystone of 6DR, and the calcilutite and mud of 7DR. SiO , FeO and K O values are higher in the former, and Fe O and Na O in the latter. Major clay minerals are generally chlorite and illite in the former, and kaolinite in the latter.

These results clearly reflect differences in the source rocks and depositional environment for the two sets of samples.

Coccoliths from Otway Basin dredge samples

Summary

The samples from the six dredge stations successfully occupied during BMR Cruise 48 have been subject to nannofossil studies by S. Shafik. Their coccolith content showed that Tertiary sediments were recovered at four stations. At two others (6DR and 8DR), sediments are thought to represent the Early Palaeozoic (6DR), on lithological grounds, or to have been deposited recently (8DR). Coccolith assemblages identified cover several parts of the Tertiary: middle Eocene, latest Eocene to early Oligocene, late Oligocene, early Miocene, middle Miocene, and late Miocene. Based on coccolith age determinations and the lithology of the Tertiary sediments recovered at Station 7DR, it is suggested that the Gambier Embayment Tertiary lithostratigraphic sequence (Knight Group, Lacepede Formation with the Kongorong Sand at its base, and the Gambier Limestone extends offshore, without major changes in facies. Offshore, the Lacepede Formation is more calcareous; however the Knight Group remains free of coccoliths, indicating subsidence of more than 300 m at Station 7DR since the middle Eocene. Coccolith evidence from sediments dredged at other stations suggests a good correlation with the shallow-water onshore Gambier Limestone, and, accordingly, these stations have subsided substantially since the mid to late Tertiary: a subsidence of about 1500 m at Station 5DR

since the late Oligocene, more than 2000 m at Station 9DR since the early to middle Miocene, and about 2500 m at Station 10DR since the late Miocene.

Introduction

The six dredge stations (5DR - 10DR) occupied are between longitudes 139 E and 141 E in the western part of the Otway Basin (Fig. 1). All dredges attempted successfully recovered rock and/or sediment, although specific targets in the stratigraphic sequence could not always be sampled. Only three sediment samples were found to be lacking coccoliths, these being among the material recovered at stations 6DR and 7DR.

Shipboard light microscopy of smear slides was carried out during dredging to determine the age and any other parameters that could help in identification of the lithostratigraphic units to which the dredge samples may belong. g assumptions are: 1) that it is possible to correlate the dredge sample level to the seismic profile, using depth and navigational data; and 2) that the onshore lithostratigraphic sequence extends offshore and is probably discernible there.

Assemblages and age determinations

Coccoliths identified are middle Eocene and younger, and, evidently, a reasonable representation of the Tertiary sequence was sampled. The coccolith successions include middle Eocene, latest Eocene to early Oligocene, late Oligocene, early Miocene, middle Miocene, and late Miocene. The Otway Basin sections sampled become younger eastward.

Station 7DR

This station lies on the continental slope west-southwest Portland, (Lat. 38 31.53 S - Long. 139 7.25 E). Water depth ranges between 3250 m and 3750 m. Seven main sediment types were differentiated, the dominant being a medium brown sandy siltstone (48/7DR-1).

Preparation 48/7DR-1b. A subsample of the brown sandy siltstone (48/7DR-1). Coccoliths are common and of moderate preservation. They include *Chiasmolithus expansus, ? C. grandis, C. solitus, Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus reticulatus, Cyclococcolithus formosus, Daktylethra punctulata, Discoaster elegans, D. saipanensis, D. tani nodifer, Helicosphaera salebrosa, Markalius inversus, Neococcolithes dubius, Pontosphaera multipora, Reticulofenestra scissura* and *R. umbilica*.

Age. The co-occurrence of *Daktylethra punctulata* and *Reticulofenestra scissura* in the presence of *Cyclicargolithus reticulatus* and *Discoaster saipanensis* was considered by Shafik (1983) to indicate a middle Eocene level correlatable within the low-latitude foraminiferal zone P.13. The presence of *Chiasmolithus solitus* in 48/7DR-1b in association with *Reticulofenestra scissura* is, however, puzzling. According to data from the onshore Gambier Embayment, this species disappears below the lowest occurrence of *Reticulofenestra scissura. Chiasmolithus solitus* is thought to become extinct within the foraminiferal zone P.12, but its occurrence in 48/7DR-1b may suggest a younger correlation.

Depositional environment. Because of the occurrence of *Daktylethra* *punctulata* and *Pontosphaera multipora*, and the almost equal ratio of discoasters to chiasmoliths, the depositional environment is interpreted as shallow water, nearshore or shelf, with temperate surface water temperatures.

Preparation 48/7DR-1e. A subsample of the brown sandy siltstone (48/7DR-1). Coccoliths are more common and better preserved than in 48/7DR-1b. The assemblage is, however, only slightly richer. In addition to the taxa recorded in 48/7DR-1b, the assemblage includes *Blackites spinulus, Cyclicargolithus floridanus, Discoaster tani ornatus*, and *Reticulofenestra daviesi*.

Age. Similar to the age of 48/7DR-1b, i.e. middle Eocene (43-42 Ma). The occurrence of *Chiasmolithus solitus* in association with *Reticulofenestra scissura* in 48/7DR-1e reinforces the possibility that this species may have lingered longer in the offshore Otway Basin than in the onshore Gambier Embayment.

Depositional environment. As with 48/7DR-1b, the palaeoenvironment is thought to have been nearshore, i.e. shallow-water environment on the continental shelf, with temperate surface waters.

Preparation 48/7DR-3. A white calcareous semi-consolidated mud containing a rich coccolith assemblage. Preservation of the taxa is good. The assemblage is dominated (in decreasing order) by *Cyclicargolithus reticulatus, Reticulofenestra umbilica, Cyclicargilithus floridanus* and the related species, *Coccolithus pelagicus* and *Chiasmolithus expansus*. Other taxa present include *Blackites spinulus, ?Chiasmolithus grandis, Clausicoccus cribellum*, and *Coccolithus eopelagicus*, very rare *Cyclococcolithus formosus, Discoaster saipanensis, D. tani nodifer, Neococcolithes dubius, Reticulofenestra scissura, R. scrippsae, Sphenolithus moriformis, Transversopontis zigzag, and Zygrhablithus bijugatus bijugatus*.

Chiasmolithus expansus as identified in 48/7DR-3 includes forms very similar to *C. grandis* minus their teeth. The chiasmoliths also include a form similar to *Chiasmolithus oamaruensis*, except that the angle between the crossbars along the short axis of the ellipse is not as small as in typical *C. oamaruensis*.

Age. The assemblage is assigned to the late middle Eocene on account of the occurrence of *Reticulofenestra scissura, Cyclicargolithus reticulatus*, and *Chiasmolithus expansus*, in the absence of typical *Chiasmolithus oamaruensis* and *Daktylethra punctulata*. The co-occurrence of forms of chiasmoliths similar to both *Chiasmolithus grandis* and *C. oamaruensis* supports the age assignment.

The assemblage is placed within the biostratigraphic interval bracketed by the lowest occurrences of *Reticulofenestra scissura* and *Chiasmolithus oamaruensis*. This indicates a correlation with the low latitude foraminiferal zone P.14 (42-41 Ma).

Depositional environment. The presence of the taxa *Blackites spinulus, Transversopontis zigzag* and *Zygrahblithus bijugatus bijugatus* suggests nearshore or shallow-water environments on the continental shelf. *Reticulofenestra umbilica* is represented mostly by large specimens typical of oceanic assemblages, suggesting more open marine conditions than those prevailing earlier in the middle Eocene during the deposition of 48/7DR-1b and

48/7DR-1e. The surface water temperature must have been less than that prevailing earlier in the middle Eocene during the deposition of 48/7DR-1b and 48/7DR-1e, because specimens of chiasmoliths are much more abundant than specimens of discoasters. The rarity of some species in the assemblage of 48/7DR-3, notably *Cyclococcolithus formosus*, could be due to environmental factors.

Preparation 48/7DR-1a. A subsample of the brown sandy siltstone (48/7DR-1). Coccoliths are common and moderately to well preserved. Taxa identified include *Blackites tenuis*, *Braarudosphaera bigelowii*, *Chiasmolithus oamaruensis*, *Coccolithus pelagicus*, *Cyclococcolithus formosus*, *Helicosphaera seminulum*, *H.* sp. cf. *H. bramlettei*, *Isthmolithus recurvus*, *Lanternithus minutus*, *Orthozygus aureus*, *Pontosphaera multipora*, *Reticulofenestra daviesi*, *R. hampdenensis*, *R. scissura*, *R. umbilica*, *Transversopontis pulcher*, *Z. zigzag*, and *Zygrhablithus bijugatus bijugatus*.

Age. The presence of *Isthmolithus recurvus*, *Reticulofenestra hampdenensis*, and *Cyclococcolithus formosus* indicates a late Eocene to early Oligocene age range. The apparent absence of *Cyclicargolithus reticulatus*, *Discoaster saipanensis and D. barbadiensis* may restrict the age range to the early Oligocene. *Cyclicargolithus reticulatus* disappears from the southern Australian sections within the late Eocene and well below the extinction level of *Discoaster saipanensis*, at a level high in the low-latitude foraminiferal zone P.16 (Shafik, 1981). *Discoaster saipanensis* is usually rare above the extinction level *Cyclicargolithus reticulatus* in the southern Australian onshore sections, and its absence from 48/7DR-1a may not be biostratigraphically significant. *Discoaster barbadiensis*, although found in the middle Eocene of the onshore Gambier Embayment, has not been encountered yet in the upper Eocene sections of the Otway Basin (Shafik, 1983). Thus the evidence suggests that the age of 48/7DR-1a is latest Eocene or early Oligocene.

Depositional environment. The assemblage of 48/7DR-1a includes ample evidence (the presence of, e.g., *Braarudosphaera bigelowii*, *Lanternithus minutus*, *Orthozygus aureus*, and *Zygrhablithus bijugatus bijugatus*) to indicate deposition in a shallow-water environment. Surface waters were apparently cold, as attested to by the presence of *Isthmolithus recurvus* and *Reticulofenestra hampdenensis*, and the abundance of *Chiasmolithus oamaruensis*. Deposition of 48/7DR-1a may have taken place on the continental shelf, not far from the shore. Surface waters were reasonably cold.

Preparation 48/7DR-2. Greyish white silicified siltstone, with chert nodules and a little glauconite. A few moderately preserved coccoliths were recovered. These include *Cyclicargolithus abisectus*, *C. floridanus*, *Reticulofenestra scissura*, *Coccolithus pelagicus* and *Helicosphaera* sp..

Age. The meagre assemblage of 48/7DR-2 is tentatively assigned a late Oligocene age, essentially on the presence of *Cyclicargolithus abisectus* in association with *Reticulofenestra scissura*.

Depositional environment. Not deducible from the poor assemblage.

Preparation 48/7DR-7. White sandy marlstone, rich in moderately preserved coccoliths. These include common to abundant *Chiasmolithus altus* *Cyclicargolithus abisectus*, *Reticulofenestra scissura* and *Zygrhablithus* *bijugatus bijugatus*. Other taxa present, in lesser numbers, include *Cyclicargolithus floridanus*, *Discoaster deflandrei* 'group', *Reticulofenestra daviesi*, and *Sphenolithus moriformis*.

Age. The co-occurrence of *Cylicargolithus abisectus* and *Reticulofenestra scissura* suggests a late Oligocene age. The abundance of *Chiasmolithus altus* supports this age assignment. Coeval low-latitude coccolith assemblages would usually contain several sphenoliths in abundance; they are used to subdivide the later part of the Oligocene.

Depositional environment. The abundance of *Zygrhablithus bijugatus bijugatus* suggests shallow water depths. The abundance of *Chiasmolithus altus*, and the absence of low latitude key taxa (such as *Sphenolithus distentus* or *S. ciperoensis*), together with the low diversity of the assemblage, suggest cold surface waters.

Preparation 48/7DR-4. A dark brown carbonaceous semi-consolidated mud with a little glauconite and mica. It is devoid of coccoliths, but contains late middle Eocene dinoflagellates, probably of the *Achilleodinium biformides* Zone, corresponding to the P12 foraminiferal zone, 44-45 Ma old. (E.M. Truswell, pers. comm.).

Preparation 48/7DR-5. A brown plastic mud. No coccoliths were found.

Station 5DR

This station lies on the southern side of a southwest trending canyon, southwest of Portland (Lat. 38 39.09 S, Long. 140 50.16 E). Water depth ranges between 1450 m and 1650 m. Two sediment types were recovered, in addition to Recent greenish grey mud.

Preparation 48/5DR-1. Chalky white marl with distinct borings. Coccoliths are abundant and of good preservation. The assemblage includes *Chiasmolithus altus*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Pontosphaera multipora*, *Reticulofenestra daviesi*, *R. scissura*, *R. scrippsae*, *Sphenolithus moriformis*, *S. predistentus*, and *Zygrhablithus bijugatus bijugatus*.

Age. Age assignment of the assemblage is based partly on negative evidence. Thus the absence of late Eocene key taxa, such as *Discoaster saipanensis* and *Cyclicargolithus reticulatus*, suggests an Oligocene age. The absence of *Cyclococcolithus formosus* and the late Eocene taxa suggest an early Oligocene or younger age. This is partly supported by the occurrence of abundant *Chiasmolithus altus* and *Reticulofenestra scissura*; the latter disappears from the record at or near the top of the Oligocene. The age of the assemblage is considered to be early late Oligocene.

Depositional environment. Low assemblage diversity and the great abundance of *Chiasmolithus altus*, together with the occurrence of *Zygrhablithus bijugatus bijugatus*, suggest a paleoenvironment of cold surface waters on the continental shelf.

Preparation 48/5DR-2. Grey calcareous silty claystone. Coccoliths are abundant and of good preservation. The assemblage is similar to that recorded in 48/5DR-1, with the addition of *Coronocyclus nitescens* and a form very similar to *Calcidiscus leptoporus*.

Age. The absence of several key taxa, such as *Discoaster saipanensis*, *Cyclococcolithus formosus* and typical *Cyclicargolithus abisectus*, indicates that the age of the assemblage is early late Oligocene. The presence of the form resembling *Calcidiscus leptoporus* is unusual, though the possibility of some contamination could not be ruled out.

Depositional environment. Cold surface waters on the continental shelf.

Station 6DR

This station lies on a northwest-southeast-trending basement ridge or block-faulted Otway Group, west-southwest of Portland (Lat. 38 50.0 S, Long. 139 06.9 E). Water depth ranges between 3750 m and 3800 m. Sheared, hard grey-green mudstone with quartz veins, ?plant remains, and minor black mudstone were recovered. Coccoliths were not found in the grey-green mudstone, or in the black mudstone. Late Quaternary coccoliths were recovered from the calcareous unconsolidated mud obtained in the pipe dredge.

Station 9DR

This station lies southwest of Portland (Lat. 38 50.89 S, Long. 141 06.4 E). The target was Upper Cretaceous sediments. Water depth ranges between 2100 m and 2200 m. Six sediment types were differentiated, in addition to some light-brown mud in the pipe dredge. The three main sediment types are light-brown bioclastic calcarenite (9DR-1), light-brown calcareous siltstone (9DR-2), and light brown calcareous mudstone (9DR-3).

Preparation 48/9DR-1. Light-brown calcarenite. Coccoliths are few to common and preservation is moderate. Taxa identified include *Braarudosphaera bigelowii*, *Calcidiscus leptoporus*, *Coccolithus pelagicus*, *Coronocyclus nitescens*, *Cyclicargolithus abisectus*, *C. floridanus*, *Discoaster deflandrei* 'group', a group of Helicosphaera resembling *H. carteri*, *H. obliqua* and *H. parallela*, *Pontosphaera multipora*, *Sphenolithus moriformis*, and *Sphenolithus* sp. resembling *S. belemnos*.

Age. In the absence of *Reticulofenestra scissura* and the presence of *Calcidiscus leptoporus*, *Cyclicargolithus abisectus* and *C. floridanus* the age is thought to be early Miocene. This is supported by the occurrence of *Sphenolithus* sp. cf. *S. belemnos*.

Depositional environment. The occurrence of taxa such as *Braarudosphaera bigelowii* and *Pontosphaera multipora* suggests deposition in shallow waters, nearshore on the continental shelf. Surface waters must have been fairly cold, as the discoasters present are not as diversified as in low latitude assemblages.

Preparation 48/9DR-2. Light-brown calcareous siltstone. Coccoliths are common to abundant, and well preserved. The main elements of the assemblage are *Coccolithus miopelagicus*, *C. pelagicus*, *Cyclicargolithus floridanus*, *Discoaster deflandrei*, *D. druggii*, *Helicosphaera carterii*, *?H. euphratis*, *H. parallela*, *Pontosphaera multipora*, *Sphenolithus moriformis*, and *Sphenolithus* sp..

Age. Thought to be early Miocene because of the occurrence of *Discoaster druggii*.

Depositional environment. The occurrence of *Pontosphaera multipora* and the low diversity of discoasters indicate deposition on the continental shelf, with surface waters being cool.

Preparation 48/9DR-3. Light-brown calcareous mudstone. Coccoliths are common and of good preservation. They include *Calcidiscus leptoporus*, *C. macintyrei*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Discoaster variabilis* 'group', *Helicosphaera carterii*, *Pontosphaera multipora*, *Sphenolithus heteromorphus*, and *S. moriformis*.

Age. The assemblage is assigned an early middle Miocene age (15-14 Ma), on the presence of *Sphenolithus heteromorphus* and the absence of *Helicosphaera ampliaperta*.

Depositional environment. Deposition may have occurred on a continental shelf, with temperate surface waters.

Preparation 48/9DR-4. Light-brown calcisiltite with Mn-lined borings. Coccoliths are common and of moderate preservation. The assemblage includes *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, frequent to common *Discoaster deflandrei* 'group', *Helicosphaera carterii*, *H. euphratis*, *H. parallela*, *Pontosphaera multipora*, *Sphenolithus moriformis*. A small placolith similar to *Calcidiscus leptoporus* occurs rarely in the assemblage.

Age. Tentatively assigned an early Miocene age; good age-diagnostic taxa are lacking.

Depositional environment. The occurrence of *Braarudosphaera bigelowii* and *Pontosphaera multipora*, together with the low diversity, suggests deposition in a shallow-water environment, nearshore on the continental shelf, with cool surface waters.

Preparation 48/9DR-5. White muddy calcisiltite. Coccoliths are common and their preservation is poor to moderate. The assemblage is meagre, consisting of *Calcidiscus macintyrei*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Discoaster* sp. cf. *D. variabilis*, *Helicosphaera carterii*, and *Reticulofenestra pseudoumbilica*.

Age. Tentatively assigned a middle Miocene age.

Depositional environment. Surface water temperatures must have been low as indicated by the low diversity of the coccolith and discoaster assemblages.

Preparation 48/9DR-6. Light-brown unconsolidated mud. Coccoliths are common and of moderate preservation. The assemblage includes *Calcidiscus leptoporus*, *C. macintyrei*, *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens*, *Cyclicargolithus abisectus*, *C. floridanus*, *Discoaster deflandrei* 'group', *Helicosphaera sp. cf. H. carterii*, *?H. euphratis*, *Pontosphaera multipora*, and *Sphenolithus moriformis*.

Age. The assemblage is assigned an early Miocene age, based on the overlap in the ranges of *Cyclicargolithus abisectus*, *Helicosphaera euphratis* and *Calcidiscus macintyrei*.

Depositional environment. Cool surface waters on the continental shelf.

Station 10DR

This station lies on the northern slope of the same southwest trending canyon as Station 5DR, southwest of Portland (Lat. 38 46.1 S, Long. 140 38.2 E. Water depth ranges between 2200 m and 2500 m. White silty calcareous claystone (sample 10DR-1) was recovered in the chain bag dredge.

Preparation 48/10DR-1. Coccoliths are common and of moderate preservation. They include *Calcidiscus leptoporus*, *C. macintyrei*, *Coccolithus pelagicus*, *Discoaster brouweri*, *D. challengeri*, *D.* sp. cf. *D. decorus*, *D.D. pseudovariabilis*, *D. variabilis*, *Helicosphaera carterii*, *Minylitha convalis*, *Reticulofenestra antarticum*, *R. pseudoumbilica*, and *?Triquetrorhabdulus rugosus*.

Age. Assigned a late Miocene age, from the presence of *Minylitha convalis*.

Depositional environment. Surface waters were not too cold, as attested to by the reasonably high diversity of discoasters.

<u>Geological implications</u>

All dredges in the western Otway Basin recovered Tertiary sediments, except for two stations (6DR and 8DR). At Station 6DR, the recovered rock is likely to be from the Palaeozoic, purely on lithological grounds. At Station 8DR, the sampled sediment is Recent; Recent or Quaternary sediments were also recovered in a dredge pipe at all other stations.

Similarities between the middle Eocene to early Oligocene sample 7DR-1 and the Lacepede Formation of the Gambier Embayment, studied by Shafik (1983), in terms of age as well as lithology, suggest that the Lacepede Formation extends offshore, while becoming more calcareous as indicated by the middle Eocene sample (7DR-3).

The late Oligocene samples 7DR-2 and 7DR-7 correlate well with the Gambier Limestone of the onshore western Otway Basin, on age and lithological grounds.

The lithostratigraphic sequence in the Gambier Embayment includes (in an ascending order) the Knight Group, Lacepede Formation with the thin Kongorong Sand at its base, and the Gambier Limestone. The Kongorong Sand/Lacepede Formation and the Gambier Limestone contain coccoliths (Shafik, 1983, and unpublished data), but several attempts by the present investigator to recover coccoliths from the Knight Group have failed. Samples 7DR-4 and 7DR-5 of the present study also lack coccoliths, and are similar lithologically to the Knight Group, and may, therefore, represent this formation offshore.

It is suggested that the sediments recovered at Station 7DR represent the offshore equivalent of the Gambier Embayment lithostratigraphic sequence. This implies a subsidence of more than 3000 m at station 7DR since the middle Eocene to early Oligocene.

In the onshore western Otway Basin (Gambier Embayment) the middle Eocene coccoliths in the Kongorong Sand and the Lacepede Formation represent short-lived marine ingressions. Deposition immediately before and after these ingressions was devoid of any calcareous microfossils (Shafik, 1983). The evidence from Station 7DR suggests a possibility that middle Eocene marine deposition was extensive offshore.

Coccolith evidence from sediments dredged at Stations 5DR, 9DR, and 10DR suggests a good correlation between these sediments and the onshore Gambier Limestone. This means a subsidence of about 1500 m at Station 5DR since the late Oligocene, more than 2000 m at Station 9DR since the early to middle Miocene, and about 2500 m at Station 10DR since the late Miocene.

SYSTEMS RESULTS

Data acquisition system

Navigation

Precise navigation was needed for the Otway Cruise, so three totally independent navigation techniques were run simultaneously. They were, in order of preference;

(1) Magnavox Global Positioning System (GPS) T-Set, giving continuous 2-D positioning to within 35 m RMS, depending on the availability of satellites.

(2) Motorolla Miniranger Radio Navigation System, utilizing four shore-based transponders.

(3) A dead reckoning system, incorporating a satellite navigator, gyro compass, and sonar doppler. The primary system, consisting of a Magnavox MX1107RS dual-channel satellite navigator, obtained speed from a Magnavox MX610 sonar doppler and heading from an Arma-Brown gyro-compass. A secondary system, consisting of a Magnavox MX1142 single channel-satellite navigator, obtained speed from a Raytheon DSN450 sonar doppler and heading from a Robertson gyro-compass.

The percentage of the total time that each system was the primary navigation system during the cruise is;

T-Set	: 27%
Radio Nav.	: 12%
Dead Reckoning	: 61%

T-set. A requirement for precision navigation prompted the use of a Magnavox Global Positioning System T-Set. It proved to be highly successful, but was limited by the availability of the GPS satellites, with nearly all the coverage occurring between 1600 and 2200 GMT. It was far superior to the other two navigation techniques used. Unlike the radio navigation, it was not tied to shore-based transponders with limited distance, but was a complete system within itself, needing no input of information from other sensors.

Mini-Ranger. In an attempt to provide accurate navigation data inshore, between scheduled GPS coverage, a Motorola Mini-Ranger radio navigation system was employed. The equipment was provided by the Division of National Mapping and comprised a ship-board transceiver operating at approximately 5 GHz (radar frequencies) and four shore-based transponders.

Using this system, direct distance measurement from ship to each transponder was obtained, any two ranges being sufficient to give a position fix. This information, along with all other navigation data, including satellite and sonar doppler, was then digitised and processed by the BMR data acquisition system. National Mapping provided the shore-based personnel to position the transponders and supply the survey coordinates for the shore stations. The survey was divided into two sections to help minimise the relocation of transponders. In the most easterly area there were five sites, extending from Cape Otway (Lawry's Hill) to Richmond. For the western component of the survey, the units were moved to sites extending from Mount Gambier to Seagull in South Australia.

Technical problems with the equipment caused loss of navigation data in the early inshore work. These were rectified and, as the survey progressed, it became apparent that the system was stretched beyond its operational limits. The long length of coastline (500 km), coupled with the beam-width limitations of the transponders (80 deg), meant that stations had to be shifted or rotated by the ground crew constantly. This was not easily achievable, especially at night. Many of the shore stations also lacked sufficient elevation to give reasonable line-of-sight range. Nevertheless, ranges in excess of 90 km were obtained, and on some occasions up to three transponders were interrogated at the same time. An electrical fault in the last two days of the survey caused further down-time.

Despite a generally disappointing coverage by the Mini-Ranger, good data were at times obtained in the inshore area. These helped to supplement the main satellite navigation equipment on the ship, and to improve navigation coverage over all.

<u>Sonar dopplers</u>. The Magnavox 610D and Raytheon DSN450 dual-axis, sonar doppler systems both performed fairly satisfactorily. On several occasions whilst in deep water the Magnavox 610D showed speeds of 18 knots, suggesting instability in the sensor.

<u>Bathymetry</u>

An updated 3.5 KHz system was installed in Melbourne before the Otway cruise. This included 8 more transducers, bringing the array to 16 and giving a better beam pattern. Precision Depth Digitizer (PDD), Power Transceiver (PTR) & Correlator (CESP-3) were used. Coverage in deep water was patchy, especially when the weather was bad and the ship's course unfavourable.

<u>Magnetics</u>

Both the magnetometer and gradiometer were used during the seismic acquisition phase of the cruise. Performance was not optimum, owing to noise, which was detected and monitored on the W & W (DAC 2) recorder. These problems appear to reflect more on the installation of the equipment than on equipment performance, though the latter needs investigation. During the geological phase, the magnetometer was deployed while in transit on some lines between dredging sites. One head on the gradiometer was lost while in shallow water in the latter part of the seismic acquisition phase, so a minimum depth of 50 m was set for subsequent deployment.

Gravity

The Bodenseewerk Geosystem KSS-31 marine gravity meter installed in March 1985 continued to function satisfactorily. Data from this source were collected whenever the DAS system was operational. The manufacturer has responded to previous complaints about sea state compensation by issuing new eproms containing the correct software.

Seismic system

Oscillator tests

Extensive oscillator tests, using the SMF-1 Amplifier's internal oscillator as a differential input, were carried out at the start of the cruise to verify amplifier performance. These tests helped to establish criteria for a standard oscillator test, using the SMF-1 internal oscillator, to be performed at selected times during the data acquisition.

Cable noise tests

Acceptable cable noise figures were obtained during the initial setting up phase, with the cable being streamed at a depth of between 10 and 12 m. The worst noise figures came from sections closest to the vessel. When a rough sea state was encountered, noise levels quickly became unacceptable. This situation was remedied by forcing the cable to stream deeper, at a depth of 16 to 17 m.

The high streamer-towing point on the rear of the vessel encourages a 'twanging' in the cable in heavier seas, producing higher noise levels than could be anticipated for a particular sea state. Two stretch sections (100 m in total) were added after the leader section, to increase the elasticity at the front of the cable and so to counteract the tugging action of the ship. Initial results obtained from the shot logger for this test, performed in a moderate sea state, indicate that the benefit from the additional stretch sections did not become significant until the streamer was towed at speeds in excess of 5.5 knots. It is believed that benefits would occur at lower speeds in rougher sea states.

For standard cable noise test the data are collected using the same parameters intended to be used in the seismic acquisition, but the airguns are not operating.

Airguns

Airgun performance during the multi-channel seismic survey was very good, and this can be attributed to a complete over-haul of the guns before the cruise. The gun signatures were used to synchronise the two 500 cubic inch (8.2 L) guns and these were recorded for further analysis of the wave shape. Pressure was kept at between 1800 and 2000 p.s.i., and gun depths varied little from 10 to 12 m.

Seismic system development

The data acquisition system is about to enter a new era of development, using a dual processor system and new Telex high-density magnetic tape drives. Furthermore, plans are advanced for a ten gun array. It was therefore considered to be an appropriate time to formalise and restructure some of the more basic functions in the system. A formal input wiring convention has been implemented, allowing users to be more familiar with the system. The trace headers have been reordered to ensure that they meet the SEG-y format. Reloading of the initial programs has been made easier to allow the novice user to reinitiate the system quickly. Many of the quality control displays have been pre-set.

A thorough series of acceptance tests and calibration of the SMF-1 Amplifiers, done pre-cruise, showed the over-all performance of the amplifiers to be good, and that significant noise reduction could be obtained by using a better designed power supply. Computer control of the SMF-1 amplifiers, still in a fledgling state, has been extended and improved. Standard oscillator and cable noise tests, which can be accessed during the data acquisition, have been formulated. Access is through the operator program CHAOS. Once the standard test has been performed, the amplifier parameters are returned to the pre-test condition so that data acquisition can continue as previously As a further extension to the SMF-1 amplifier calibration, the Phoenix A/D convertors have been zeroed and calibrated.

Sonobuoys

Fifteen new REFTEK 1 & 2 sonobuoys were used. They proved to be very successful, with thirteen transmitting data back to the ship for periods of between 2.5 to 3.5 hours. Signals received from the sonobuoys were treated as an additional seismic channel (49) and recorded using the same parameters as for the reflection seismic. They were displayed on the seismic monitor as a 6 s record, with effective use of the record skip to give the fullest information from the 7.5 seconds of data acquired.

CONCLUSIONS

The Otway Basin cruise of the *Rig Seismic* met most of its data-gathering objectives. Altogether, 3700 km of 48-channel seismic reflection profiles with associate bathymetric, magnetic, and gravity data were recorded (Fig. 2). Approximately half these data were obtained on the continental shelf: two regional strike lines extending the length of the basin, and a number of shorter zig-zag lines at an angle to pre-existing data grids. Virtually all the petroleum exploration wells have been tied, and the entire data set is internally tied. Six regional deep-water lines extend from the shelf to the abyssal plain. Four of these lines have been tied by a slope-parallel tie line in about 3000 m of water, and all are tied to the shelf data. Fifteen sonobuoys were deployed to obtain refraction seismic data, the majority on the continental shelf, and all but one gave useful results, giving Otway Group and basement refractors in many cases.

Seismic reflection data quality is good, in part because of the generally excellent weather encountered. Preliminary interpretation of data was carried out using shipboard monitors, on which visible penetration averages 3 s (two-way-time). Initial structural interpretation indicates the likelihood of potential petroleum-trapping structures in the Cretaceous, and this is the subject of continuing study. Processing of the data has brought them to a standard comparable to that of most recent company data. The deep-water data, which lack the multiple problem, show that the Eocene-Paleocene apparently pinches out high on the continental slope. Further offshore the Upper Cretaceous sequence thins and the Lower Cretaceous Otway Group apparently subcrops on the continental rise.

The planned sampling program had to be curtailed because of winch failures, but six dredge stations were successful. The oldest material, sheared and lithified green mudstone of probable Palaeozoic age, came from a ridge rising from the edge of the abyssal plain. Four other deep-water stations recovered shelfal carbonates of a variety of ages and lithologies - nannofossil determinations gave ages ranging from middle Eocene to early Pliocene.

The sampling of the older Tertiary sediments indicates that there is little facies change from onshore to what is now deep offshore, for rocks of similar ages. At the sites sampled there has been subsidence of 3500 m since the middle Eocene, 3250 m since the late Oligocene, and 2000 m since the Miocene. This indicates that, although continental breakup was in the Late Cretaceous, most margin subsidence is post Oligocene.

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APPENDIX A: GEOPHYSICAL DATA SET

LINE	TIME START	FINISH	WAY-POINT LATITUDE	LONGITUDE	EOL	DATA COLLECTED
	GMT	GMT	S	E	km	
1	154.2206	160.1230	Winch Commissioning			g
2	160.1240	165.0140	Winch Commissioning			g
3	165.2230	167.0227	Transit from Port			g,G
4	167.0227	167.1123	38 37.200	144 14.400	78	g,G,S,12
5	167.1123	167.1915	39 03.500	143 25.999	120	G,GR,S,12
6	167.1915	168.1042	38 40.700	142 39.901	86	G,GR,S,12
7	168.1042	168.1943	38 24.720	141 04.351	86	G,GR,S,12,3,5
8	168.1943	169.0839	39 07.000	141 29.000	124	G,GR,S,12,e.5,R
9	169.0839	170.0431	40 14.000	141 30.000	179	G,GR,S,12,3.5,R
10	170.0431	170.1150	39 56.250	143 45.001	74	G,GR,S,12
11	170.1150	170.2004	39 19.600	143 05.400	71	G,GR,S,12
12	170.2004	171.0614	39 42.000	142 24.999	96	G,GR,S,12
13	171.0614	171.1734	38 50.500	142 33.250	119	G,GR,S,12
14	171.1734	171.2035	38 23.500	141 17.999	29	G,GR,S,12
15	171.2035	172.0155	38 38.700	141 24.199	51	G,GR,S,12
16	172.0155	172.0622	38 24.000	141 54.500	44	G,GR,S,12
17	172.0622	172.1842	38 47.000	141 46.000	114	G,M,S,12
18	172.1842	173.0201	38 45.000	143 05.001	67	G,M,S,12,3.5
19	173.0201	173.0357	39 23.200	143 06.841	24	G,M,S,12,3.5
20	173.0357	173.0847	39 13.000	143 16.500	48	G,M,S,12,3.5,R
21	173.0847	174.0125	38 58.300	142 48.701	159	G,M,S,12,3.5,R
22	174.0125	174.0223	38 31.000	141 04.501	9	G,M,S,12,3.5
23	174.0223	174.0825	38 26.000	141 06.599	52	G,M,S,12,3.5
24	174.0823	174.1325	38 09.660	140 36.480	33	G,M,S,12

25	174.1325	175.0001	37	54.700	140	13.099	106	G,M,S,12
26	175.0001	175.0646	37	07.750	139	27.700	66	G,M,S,12,R
27	175.0646	175.0909	36	45.500	138	52.700	22	G,M,S,12
28	175.0909	175.1850	36	53.750	138	42.400	96	G,M,S,12,3.5
29	175.1850	175.2121	37	26.750	139	34.600	26	G,M,S,12
30	175.2121	176.0134	37	39.000	139	46.000	40	G,M,S,12
31	176.0134	176.0750	37	45.600	140	12.250	63	G,M,S,12,3.5
32	176.0750	176.1426	38	18.900	140	21.899	63	G,M,S,12,3.5
33	176.1426	176.1751	38	12.800	141	04.299	33	G,M,S,12,3.5
34	176.1751	177.0448	38	31.000	141	04.501	91	G,M,S,12,3.5
35	177.0048	177.1054	38	06.000	140	09.999	61	G,M,S,12
36	177.1054	177.1228	37	39.000	139	46.000	14	G,M,S,12
37	177.1228	177.1845	37	36.300	139	36.899	63	G,M,S,12,R
38	177.1845	178.0225	37	03.750	139	23.901	72	G,M,S,12,3.5
39	178.0225	178.1131	37	19.000	138	39.000	90	G,M,S,12,3.5,R
40	178.1131	178.2154	36	37.000	139	09.999	99	G,M,S,12,3.5
41	178.2154	179.1307	37	34.200	139	14.200	111	G,M,S,12,3.5,R
42	179.1307	180.0839	38	38.700	138	17.999	187	G,M,S,12,3.5,R
43	180.0839	181.0537	37	55.000	140	16.000	191	G,M,S,12,R
44	181.0537	181.2218	39	36.240	139	55.800	181	G,M,S,12
	END WAY-POINT		38	24.200	141	20.599		
45	Das down		Transit to Portland					
46	183.0524	184.1452	38	25.750	141	40.300	78	G,12,3.5
47	184.1452	184.2121	38	40.000	140	50.001	107	G,12,3.5
48	184.2121	185.1228	38	32.000	139	37.000	50	G,M,12,3.5
49	185.1228	185.2132	38	49.000	139	09.999	52	G,12,3.5
50	185.2132	186.1103	38	31.000	139	38.000	167	G,M,12,3.5

51	186.1103	187.0038	38 25.400	141 40.999	67	G,M,12,3.5
52	187.0038	187.1532	38 51.000	141 09.000	41	G,12,3.5
53	187.1532	188.0605	38 41.000	140 35.001	124	G,12,3.5
54	188.0605	189.1318	38 10.440	139 19.440	291	G,S',12,3.5
	END WAY-POINT		39 32.460	141 58.260		

G gravity meter
M magnetometer
GR gradiometer
S 48-channel seismic reflection 2100 m active length
S' 48-channel seismic reflection 2400 m active length
12 12 kHz bathymetry
3.5 3.5 kHz bathymetry
R sonobuoy refraction survey

APPENDIX B: CABLE GEOMETRY

The cable configuration chosen was 8 x 12.5 m groups for the front of the cable and 40 x 50 m groups for the rear. The choice of 12.5 rather than 25 m groups for the front was aimed at increasing resolution in the shallow section. It will not affect the stretch muting pattern, which is the limiting factor on effective cable length for shallow reflectors. The use of 50 m group lengths for the rear of the cable will improve the amount of energy collected from deep reflectors, at the cost of degrading the performance in medium water depths. The hydrophone configuration is given in Figure 16.

The cable geometry has been defined to give a maximum usable frequency of 75 Hz, with the first notch in the frequency response at 80 Hz. Therefore, the gun and cable depths should be such that the first notch due to normal incidence ghosting effects is at 80 Hz. The notch frequency f, is given by $f=v/2d$, where d is the source of receiver depth, and v is the water velocity. For f = 80 Hz, v = 1500 m/s., the depth d should be 9.4 m. This should be achievable for both the gun and cable.

Hydrophone streamer configureation

Deck leader. Sea state determined the length of deck leader that was needed to control the depth of the front sections of the cable. In the heaviest sea, 127 m was used, the maximum that could be safely deployed. In moderate seas or with a following sea and currents, the deck leader was retrieved in 10 m intervals to prevent the front sections of streamer from sinking.

Stretch sections. An evaluation of shot records showed that the direct wave arrived later than predicted by the assumed streamer geometry. Calculating back suggests that a correction length of 15 m (15%) be applied to the stretch sections.

Active sections. Because of the acquisition factors mentioned in this appendix a hybrid cable was constructed with hydrophone groups distributed: 8 groups of 10 for the first 100 m of active sectin and 2 groups of 40 for the next 20 active sections.

Water break sections. Four water break sections included in the streamer were closely monitored over specified intervals when the recording delay was 0 secs.

Depth detectors and controllers. On initial deployment, depth detectors were calibrated at 0 and 10 m. The high precision 100 m mini cable was added to form the hybrid configuration, and depth detectors 1 to 8 recalibrated. Number 9 was not recalibrated as it was in an inactive section of cable. Considering sea conditions, cable balance on the whole was good.

Tail buoy. The tail buoy was attached to the streamer by a 300 m rope with a strobe light fitted to the buoy.

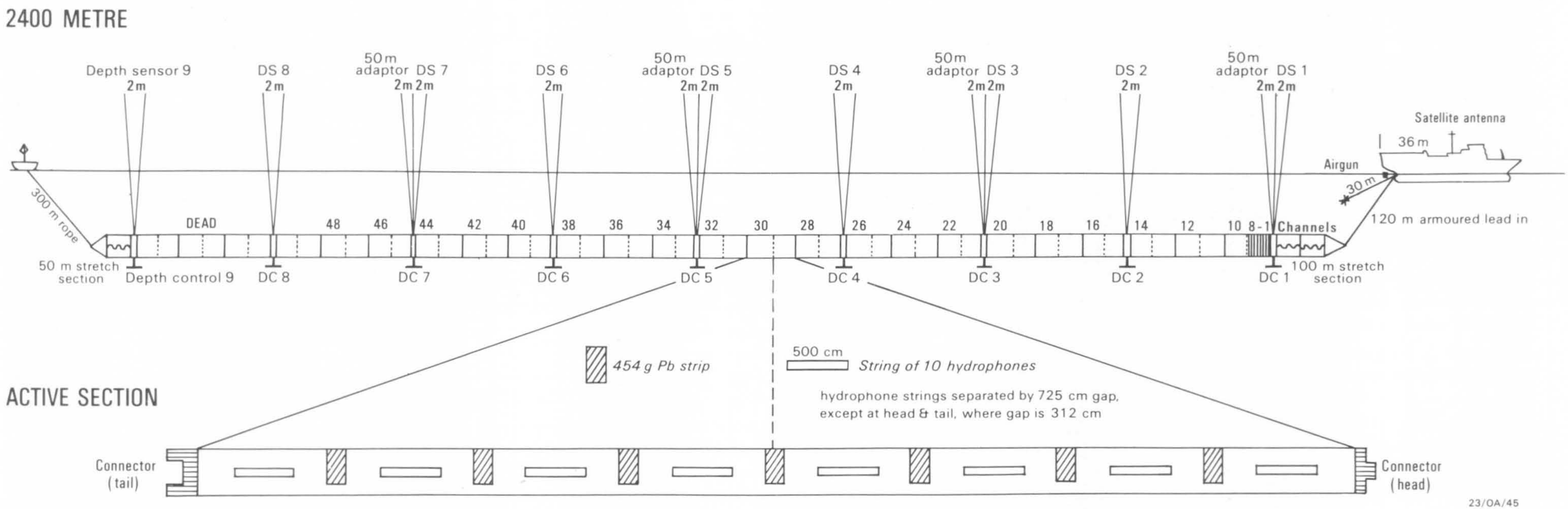

Figure 16. Hydrophone streamer configuration used on the Otway Basin survey.

APPENDIX C: EQUIPMENT LIST

Primary seismic systems

- 1200 m Teledyne hydrophone streamer cable; minimum group length of 12.5 m; maximum 96 channels.
- 2400 m Teledyne hydrophone streamer cable; minimum group length of 12.5 m; maximum 96 channels.
- Syntron RCL-2 individually addressable cable levelers.
- 3 BOLT 1500C airguns, each of 500 cu in (8.2 L) capacity, with wave-shape kits; one or two guns, fired simultaneously, would normally be used.
- Teledyne gun signature phones and gun-depth sensors, and Input/Output SS-8 shot-instant transducers (1 each per gun).
- 3 Price A-300 compressors, 300 scfm each; output pressure 2000 psi.
- 1 Price AGM W2 compressor, 200 scfm; output pressure 2000 psi.
- BMR-designed and built computer-controlled preamp/filters (48 channels).
- BMR designed seismic acquisition and display system (MUSIC) based on Hewlett-Packard 1000-Series computers.

Secondary seismic systems

- 2 Teledyne 28420 single-channel hydrophone streamers.
- 1 BOLT 1500C airgun of 100 cu in (1.6 L) capacity, with wave-shape kit.
- Teledynme 28990 acoustic beacon cable location system.

Bathymetric systems

- Raytheon deep-sea echo sounder; 2 kW maximum output at 3.5 kHz.
- Raytheon deep-sea echo sounder; 2 kW maximum output at 12 kHz.

Magnetic and gravity systems

- 2 Geometrics G801/803 proton precession magnetometers; may be used as standard single-sensor cable or in horizontal gradiometer configuration.

- 1 Bodenseewerk Geosystem KSS-31 marine gravity meter.

Navigation

Prime system

- Magnavox MX1107RS dual channel satellite receiver.
- Magnavox MX610D sonar doppler speed log.
- Arma-Brown SGB1000 gyro-compass.

Secondary system

- Magnavox MX1142 single channel satellite receiver.
- Raytheon DSN450 sonar doppler speed log.
- Robertson gyro-compass.

Computer equipment

Non-seismic acquisition system (DAS)

- Hewlett-Packard 2113E-Series 16-bit minicomputer with 256 kb of memory.
- Hewlett-Packard 7905 Mb, moving-head disc and multi-access disc controll
- Hewlett-Packard 7970E 1600 bpi, 9-track magnetic tape drives.
- Facit cassette recorder.
- Hewlett-Packard 12979 I/O extender.
- Hewlett-Packard 2748A paper tape reader.
- BMR-designed and built 16-channel digital multiplexer (up to 3).
- BMR-designed and built 16-bit gyro/speed log interface.
- Phoenix 6915 15-bit analogue-to-digital multiplexer.
- GED, NCE, or CHRONOLOG digital clocks (x2).
- KSR-43 teletypes, TELEVIDEO TVI-910 VDU's, and EPSON RX-80 line printers (various combinations).
- KAGA RGB colour monitors (up to 7) driven through RCA microcomputers.
- W & W 6-pen strip-chart recorders (x3.
- CALCOMP 1044 8-pen high-speed 36-inch drum plotter.

Seismic acquisition system (MUSIC)

- Hewlett-Packard 2113 E-Series 16-bit minicomputer with 256 kb of memory (development system).
- Hewlett-Packard 2117 F-Series 16-bit minicomputer with 768 kb of memory (acquisition system).
- Hewlett-Packard 7905 15 Mb moving-head disc drive and multi-access disc/ cpu controller.
- Hewlett-Packard 7970E 1600 bpi, 9-track magnetic tape drives.
- Phoenix 6915 15-bit analogue-to-digital multiplexer.
- BMR-designed 48-channel SMF-1 computer-controlled preamp/filters.
- KSR-43 teletype and TELEVIDEO TVI 910 VDU.
- EPSON MX-100 dot-matrix line printers (x4).
- EPSON MX-100 shot logger.
- Tektronix 611 X-Y storage CRO.
- BWD 804 single-channel CRO.
- BWD 845 dual-channel storage CRO.
- CHRONOLOG digital clock.
- BMR-designed and built NTM-1 marine timing unit.

Geological equipment

- Chain bag dredges
- Moderate sized pipe dredges
- Small pipe dredges
- BMR piston corer
- Benthos piston corer
- Benthos time depth recorders

APPENDIX D: COORDINATES OF MINI-RANGER TRANSPONDERS

Station	Latitude		Longitude		Height (m)
Mt. Clay	38	05.096	141	42.121	200
Lawry's Hill	38	50.456	143	30.738	153
Crowes	38	41.898	143	21.233	430
Warnambool	38	18.430	142	44.303	220
Richmond	38	16.153	141	24.972	240
Mt. Gambier	37	50.508	140	45.287	200
Mt. Burr	37	36.209	140	28.847	246
Bray	37	17.258	139	56.743	80
Seagull	36	59.505	139	45.069	70

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Figure 13. Seismic reflection record of Line 48/43.