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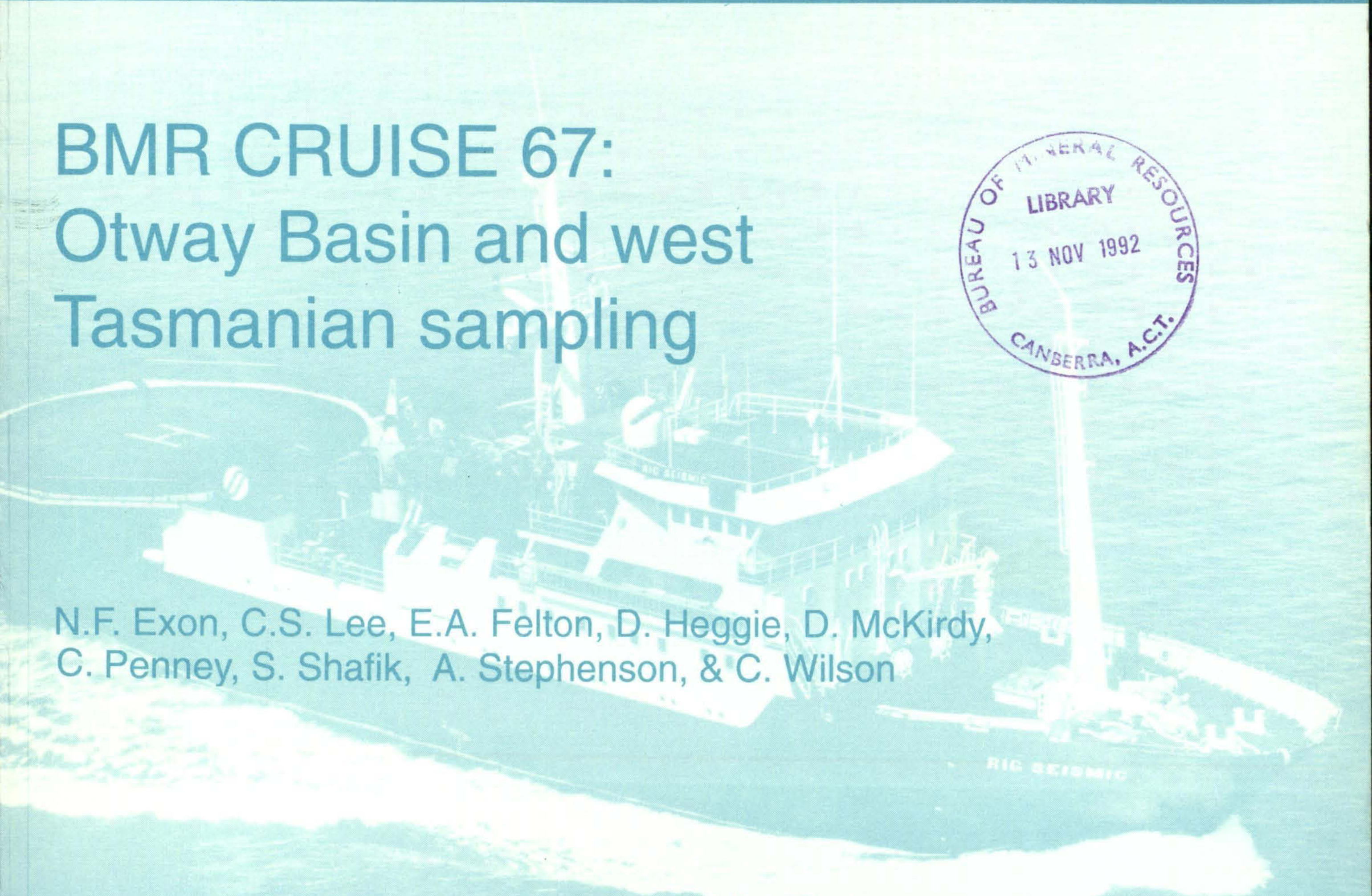
BMR CRUISE 67: Otway Basin and west Tasmanian sampling



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REPORT 306

BMR CRUISE 67:

OTWAY BASIN AND WEST TASMANIAN SAMPLING

by

N.F. Exon, C-S Lee, E.A. Felton, D. Heggie, D. McKirdy*, C. Penney, S. Shafik, A. Stephenson & C. Wilson**

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ABSTRACT

In early 1987, scientists aboard R.V. Rig Seismic carried out a 29 day research cruise over the Otway Basin and the Sorell Basin of the west Tasmanian margin, to provide new geological, geochemical and heatflow data, in an area with considerable petroleum potential. Altogether, 130 sampling stations were occupied using dredges, corers, grabs and a heatflow probe.

Among the rocks recovered were: Palaeozoic volcanics and metasediments; Late Cretaceous sandstones, siltstones and mudstones; early Tertiary siltstones; and late Tertiary carbonates. All samples were taken along seismic profiles, so that the results can be easily incorporated into the regional geological framework. In general, the further down the continental slope, the older the rocks. Palaeontological results indicate that there has been very considerable post-Eocene subsidence of the slope. A great variety of Quaternary sediments were recovered, and these have allowed a detailed sedimentation model to be developed.

Heatflow calculations from 20 stations suggest that the present zone of thermal maturation of hydrocarbons is 2-4 km deep. Headspace gas analyses of many cores indicate that thermogenic hydrocarbons are widespread, with particularly high readings in both the eastern and the western Otway Basin and on the west Tasmanian margin. Thus, mature hydrocarbon source rocks must also be widespread.

INTRODUCTION

We here report the initial results of a 1987 geological cruise of R.V. Rig Seismic in the Otway Basin and in the Sorell Basin along the west Tasmanian margin. The cruise concentrated on geological sampling, but also carried out some measurements of the earth's heatflow. The aim of the work was to provide complementary information to that already existing, so that a full review of the geological framework and petroleum potential of the region could be carried out.

Earlier, and critically important, were two co-operative cruises in 1985 with the Bundesanstalt fuer Geowissenchaften und Rohstoffe (BGR) using R.V. Sonne (Hinz & others, 1985), and one BMR cruise using R.V. Rig Seismic (Exon & others, 1987b). The cruises provided 3700 km of regional multichannel seismic data in the Otway Basin, and 1000 km of similar data on the west Tasmanian margin. They also recovered 34 geological samples from the west Tasmanian margin and six from the Otway Basin.

The present cruise, BMR Cruise 67, was the first step in carrying out BMR Project 1C.09, a study of the geological development of the offshore Otway Basin and west Tasmanian margin. It was essentially a sampling cruise, with limited under-way geophysics between some stations. The vessel sailed from Adelaide on 15 January, called at Portland to repair some equipment on 29-30 January, and at King Island on 4 February to put ashore an injured crew member, and arrived in Sydney on 13 February. The field techniques included dredging and coring of older sequences, coring of younger sediments, heatflow measurements in younger sediments, and headspace analysis of gas in the surface sediments. Altogether 130 stations were occupied - 23 dredge, 54 core, 33 grab and 20 heatflow - in water depths of 50 to 5000 m (Figs. 1 and 2). A preliminary post-cruise report was provided by Exon & others (1987a).

A later cruise on the west Tasmanian margin, BMR Cruise 78, was reported on by Exon & others (1989), and its palynological results are discussed in this volume by M.K. Macphail (Appendix D).

Acknowledgements

The work benefited greatly from pre-cruise discussions with the late J. Branson (BMR); M. Megallaa and B. Thompson (Victorian Department of Industry, Technology and Resources); P.W. Baillie (Tasmanian Mines Department); R.W. Laws, D.I. Gravestock and C.D. Cockshell (South Australian Department of Mines and Energy; SADME); S.M. Yu (Gas & Fuel Corporation of Victoria); G. Cullen (BP Australia Ltd.). We thank SADME for the financial support they provided for the participation of D. McKirdy, and are grateful to the Geological Survey of Victoria for the report on foraminifera by C. Abele (Appendix C). The BMR technical support staff on the cruise were : J. Bedford, E. Chudyk, R. Curtis, P. Davies, J. Mowat, D. Pryce, H. Reynolds, G. Saunders, R. Schuler, T. Stone, J. Stratton, and P. Walker.

The enthusiasm and skill of the Rig Seismic crew was vital to the success of the cruise, especially when equipment started to fail. The ship's crew was:

Master	D. Harvey
Chief Officer	R. Hardinge
Second Officer	P. Mosley
Chief Engineer	S. Johnson
Second Engineer	P. Pittiglio/R. Thomas
Electrical Engineer	P. Jiear
EA/Seaman	K. Halliday
AB	N. Luscombe

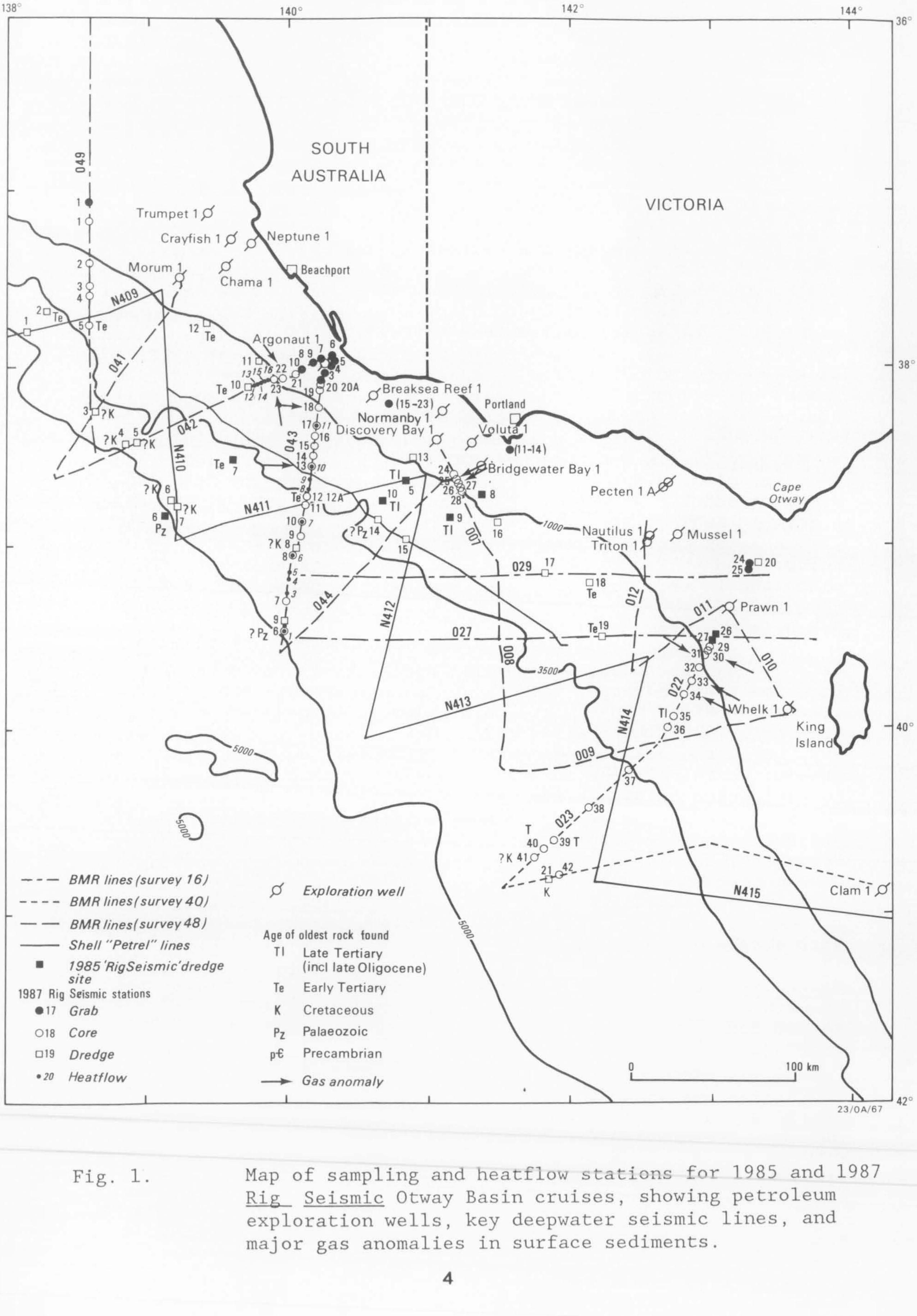


Fig. 1. Map of sampling and heatflow stations for 1985 and 1987 Rig Seismic Otway Basin cruises, showing petroleum exploration wells, key deepwater seismic lines, and major gas anomalies in surface sediments.

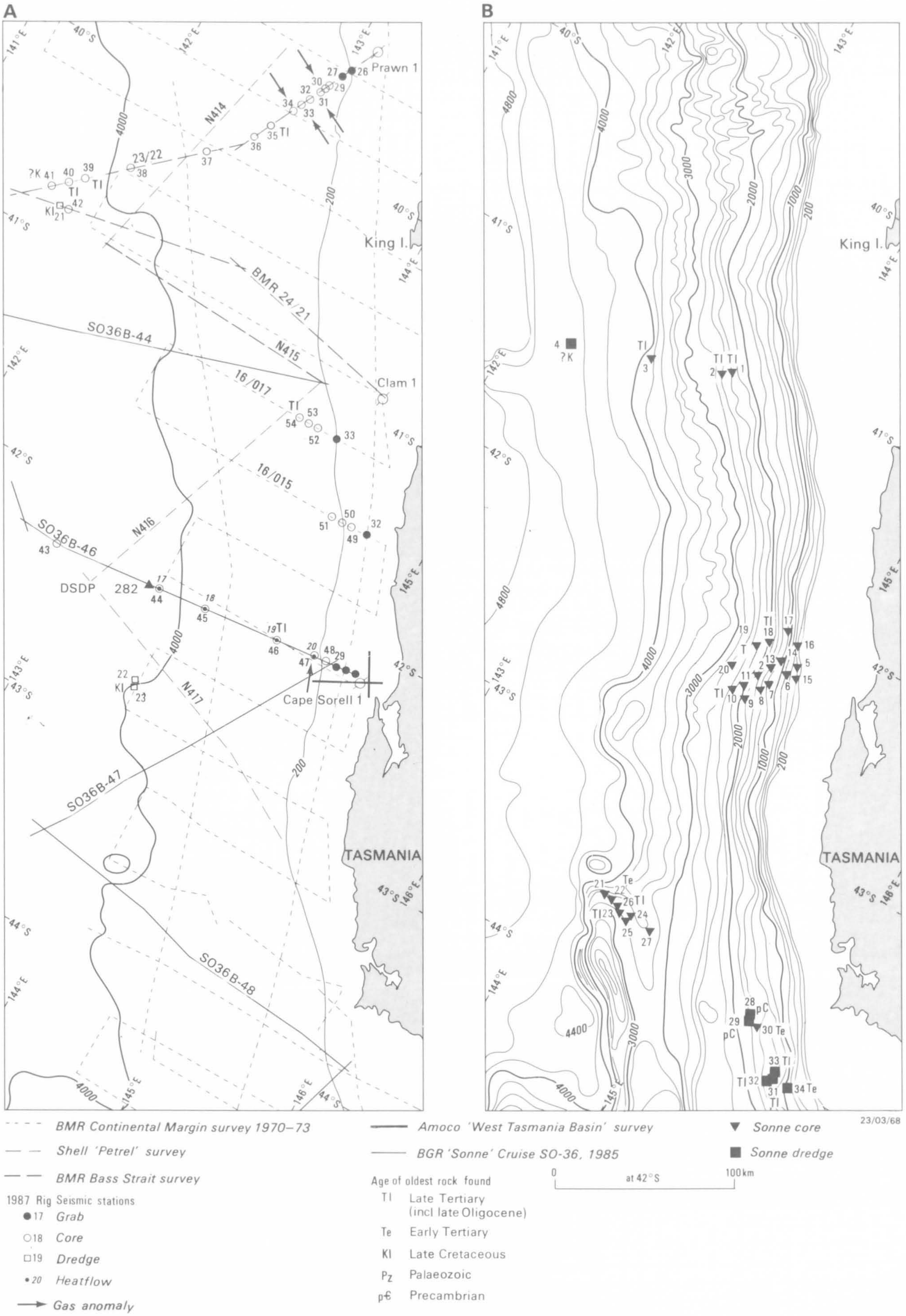


Fig. 2. Map of sampling and heatflow stations for 1985 Sonne and 1987 Rig Seismic west Tasmanian cruises, showing petroleum exploration wells, bathymetry, key deepwater seismic lines and major gas anomalies in surface sediments.

AB	D. Kane
AB	P. Birch
Cook	H. Dekker
Cook	G. Lemaire
Steward	M. Cumner
Steward/Seaman	J. O'Rourke

PREVIOUS STUDIES

N.F. Exon & C.S. Lee

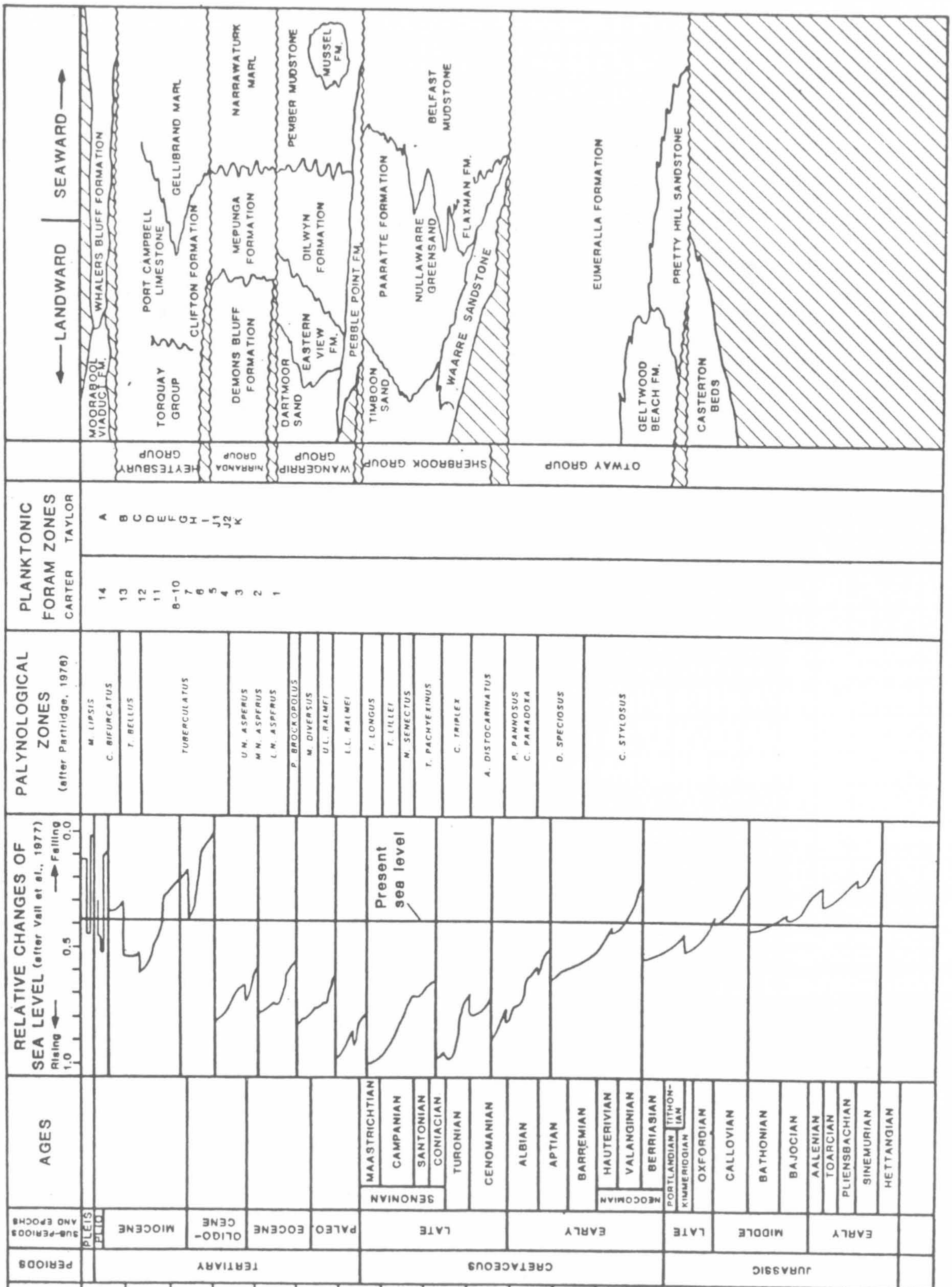
There has been a long history of outcrop geological studies, and of geophysical studies and petroleum drilling, in the Cretaceous-Tertiary Otway Basin. These are well covered in papers such as those of Wopfner & Douglas (1971), Ellenor (1976), Benedek & Douglas (1976), Kenley (1976), Abele & others (1976), Robertson & others (1978), and Megallaa (1986). A great deal of company reflection seismic work has been done on the continental shelf, and the results have been summarised by some of the above authors. Major syntheses by Megallaa (1986), Cockshell (1986), Gravestock & others (1986) and Williamson & others (1987), have helped establish the regional stratigraphy outlined in Figure 3.

The first regional seismic survey that included the entire offshore basin was the 1972 BMR Continental Margins Survey. This sparker survey extended from the shelf to the abyssal plain, with a line spacing of about 50 km, and was the basis of a report on the Australian southern margin by Willcox (1978).

In 1973, BMR recorded about 1000 km of low-energy reflection profiles over the west Tasmanian shelf from M.V. Sprightly. These profiles gave penetration of up to half a second (two-way time), and showed that gentle faulting, uplift and erosion occurred during the Late Miocene, and that Pliocene to Quaternary sediments unconformably overlie Miocene and older rocks (Jones & Holdgate, 1980). Much of the shelf consists of Miocene outcrop or subcrop below a veneer of younger sediments. Superficial sediments sampled on the same cruise showed that the inner shelf is covered by quartz sand with some shell debris, and the outer shelf by medium to coarse grained bryozoal sand and gravel (Jones & Davies, 1983). The shelf sands are mainly relict from times of lower sea level.

In 1973, Shell International Petroleum conducted a reconnaissance survey off southern Australia using the M.V. Petrel. This included nine lines from the shelf to the abyssal plain in the Otway Basin-West Tasmania region (Figs. 1,2 & 4). They were processed to a limited extent and showed 3 to 4 seconds (two-way time) of penetration. An interpretation by Bouef & Doust (1975) showed that this was a passive margin, with a thick wedge of sediments that was bounded by oceanic crust on the edge of the abyssal plain. Beneath the continental rise, block-faulted continental basement was recognised. They stated: 'The sedimentary wedge which overlies the block-faulted and collapsed continental basement is subdivided by unconformities into: (a) a continental Lower Cretaceous unit and a fluvio-deltaic unit of Upper Cretaceous-Danian age which are taken to represent rift valley stages of deposition controlled by extensional tectonics and (b) a post-breakup sequence of Tertiary units representing regional collapse and out-building of the shelf. The Upper Cretaceous sequence is missing along much of the continental edge where Tertiary sediments appear to rest directly on the Lower Cretaceous unit. Our interpretation suggests that a prolonged period of uplift took place along the axis of the rift valley prior to continental break-up. On the basis of palaeomagnetic data and biostratigraphic analysis the breakup phase started in the

Figure 3 : Regional stratigraphy of the Otway Basin. After Megallaa (1986)



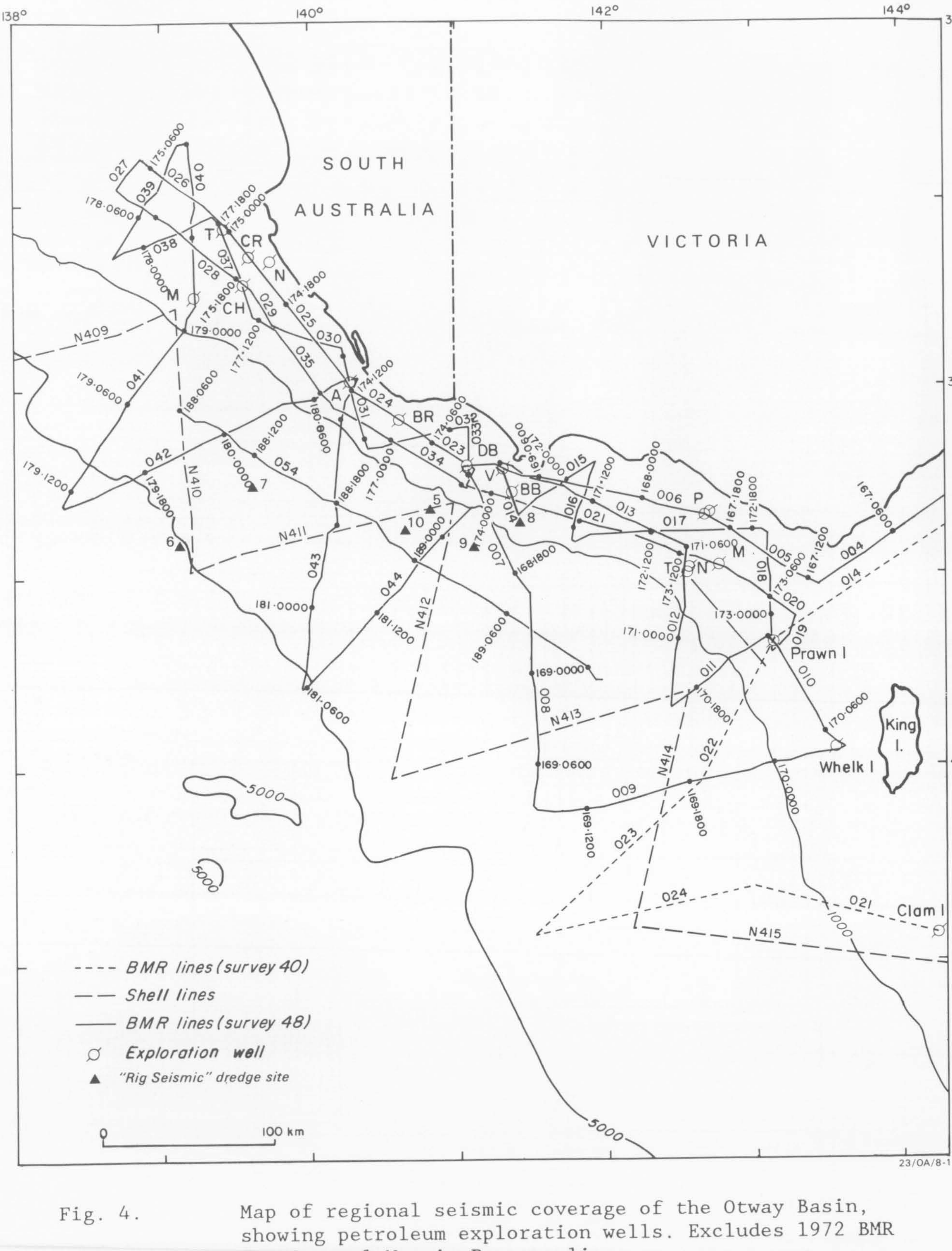


Fig. 4. Map of regional seismic coverage of the Otway Basin, showing petroleum exploration wells. Excludes 1972 BMR Continental Margin Program lines.

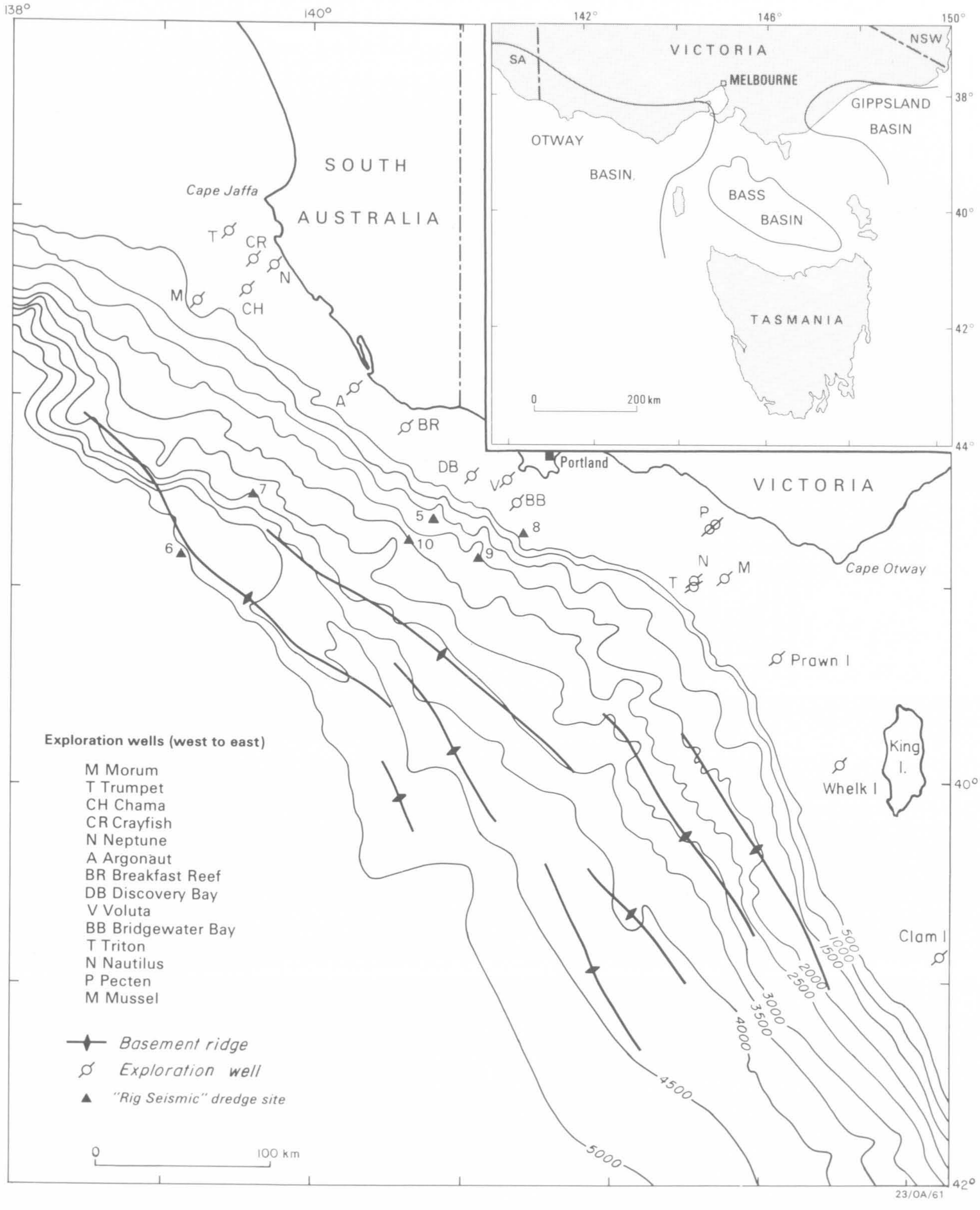


Fig. 5. Bathymetric map of the Otway Basin showing petroleum exploration wells, 1985 Rig Seismic dredge locations, and deepwater basement ridges.

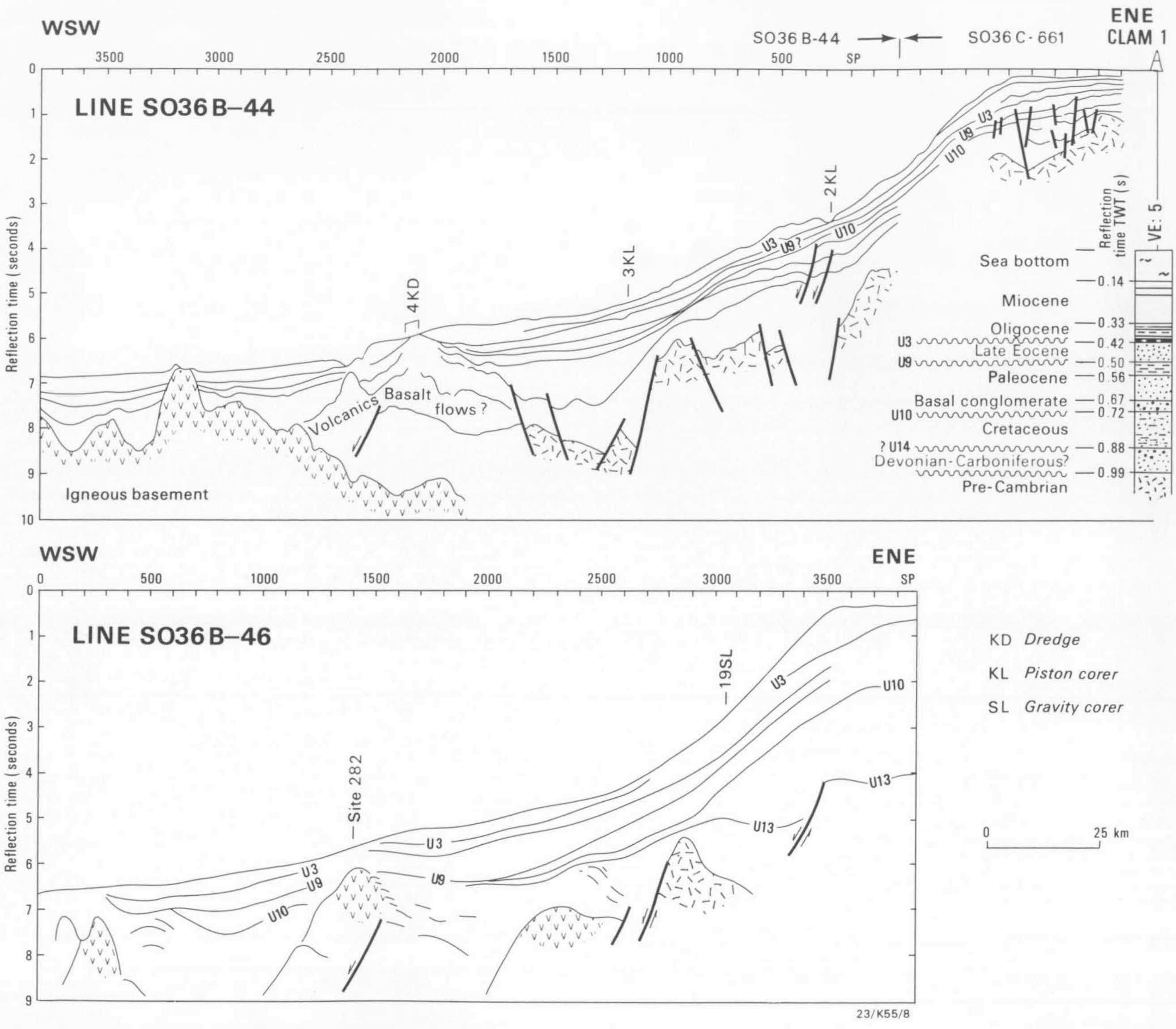


Fig. 6. Line drawings of Sonne seismic sections SO36/44 & 46 on the west Tasmanian margin, showing sample locations (see Table 1; Fig. 2). After Hinz & others (1986).

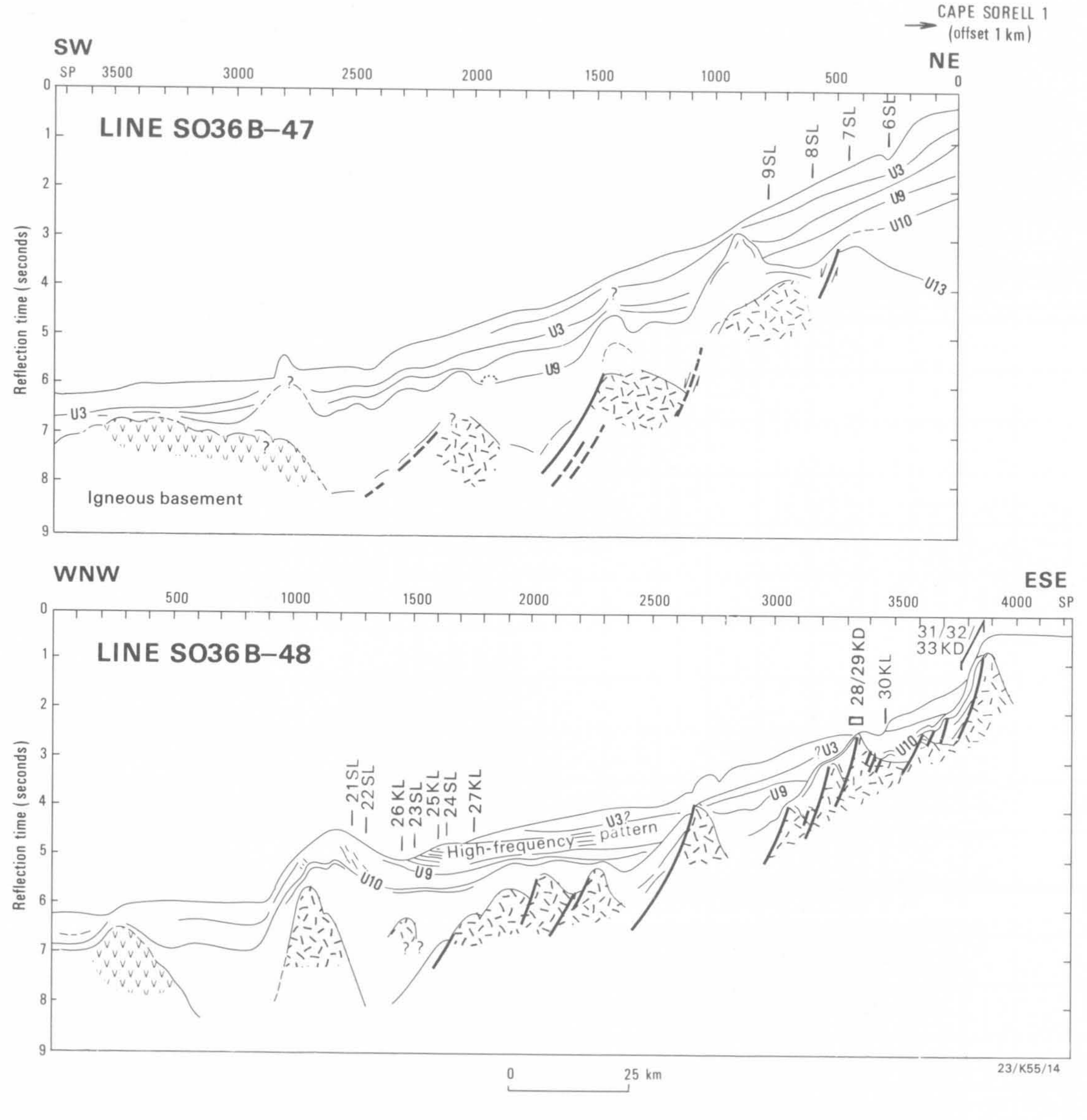
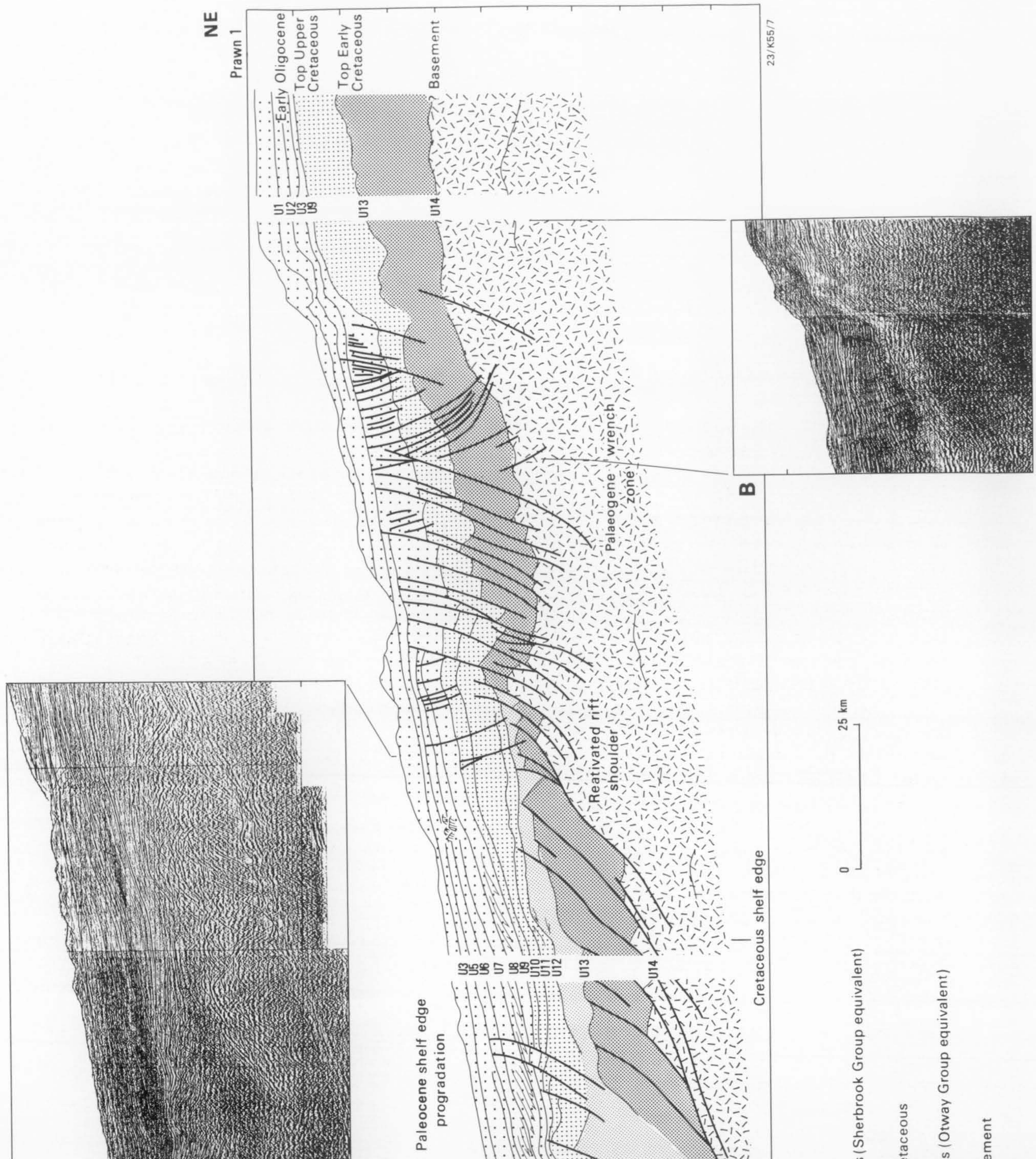


Fig. 7. Line drawings of Sonne seismic sections SO36/47 & 48 on the west Tasmanian margin, showing sample locations (see Table 1; Fig. 2). After Hinz & others (1986).

Fig. 8. Interpretation of BMR seismic profile 40-22/23, tied tentatively to Prawn No. 1 (see Table 1, Fig. 1). After J.B. Willcox in Hinz & others (1986).



Upper Paleocene.'

Bouef & Doust (1975) continued : 'From the continent outward several structural zones can commonly be recognised: (a) a zone of shallow basement with a thin Lower Cretaceous cover normally faulted and overlain by thin gently dipping Tertiary beds, (b) a zone of faulted and landwards tilted basement blocks and Lower Cretaceous sediments overlain (sometimes with clear unconformity) by thick Upper Cretaceous sediments, (c) a zone of thick, moderately deformed Tertiary sediments whose axis of deposition is generally offset to the south of the Upper Cretaceous basinal axis, (d) a zone of rotational faults and associated toe thrusts affecting the Cretaceous sediments and apparently related to the time of margin collapse, (e) an area of little disturbed Cretaceous and Tertiary sediments overlying continental basement. This zone extends into the "magnetic quiet zone" which is therefore believed to be, at least in part, a collapsed portion of the continental margin adjacent to oceanic crust.' This interpretation remains fundamentally correct today.

The following year, Denham & Brown (1976) reviewed wells and seismic data in the offshore area between King Island and the Victorian-South Australian border, most of them on the continental shelf. They regarded the Otway Basin as an intercratonic Late Cretaceous basin, and a marginal Tertiary to Recent basin. The northeast flank of the basin was formed by a series of down-to-basin faults, and increased movement on these faults and overall tilting gave a marginal basin in Tertiary time so that the section was a series of outbuilding sedimentary wedges. They recognised that the sequences present in the wells could be traced widely beneath the shelf and slope, and produced structure contour maps of three horizons, the deepest being the base of the Upper Cretaceous, which showed that there was widespread coast-parallel normal faulting in the Cretaceous sequence. Fault blocks generally dip landward.

In 1982, BMR contracted Geophysical Services International (GSI) to carry out a multichannel seismic survey of the Bass Basin (BMR Survey 40), with regional seismic lines extending on either side of King Island, into the Otway Basin and out to the abyssal plain (Figs 2, & 4).

In 1984-86 the South Australian Department of Mines & Energy undertook a review of the Otway Basin in South Australia and offshore (Cockshell, 1986; Gravestock & others 1986; Morton & Cockshell, 1987). All known company data were compiled and gamma ray and sonic logs for all wells were digitised. Recent high quality seismic data were also included to provide an up-to-date regional structural interpretation of the major horizons, and digitising of well logs clarified stratigraphic relationships.

In 1985, the West German Research Vessel Sonne carried out two BGR-BMR co-operative cruises on the Tasmanian margin (Sonne Cruises 36B & C), during which four regional multichannel seismic lines and several short tie lines (1000 km long in all) were recorded off west Tasmania, and 34 sampling stations occupied (Fig. 2). A detailed cruise report was provided by Hinz & others (1985). An interpretation of these seismic lines (Figs. 6 & 7), combined with those of a 1982 BMR line (Fig. 8), showed that up to 5 seconds (two-way time) of section was present and that up to 14 unconformities could be identified (Hinz & others, 1986). Sampling and well data indicated (Table 1) that unconformity U3 represented the regional Oligocene unconformity, U9 the basal Tertiary unconformity, and U12 the basal Late Cretaceous unconformity. The relatively thin Tertiary sequences consist essentially of Neogene carbonates and Palaeogene terrigenous sediments. The Late Cretaceous sequence appears to subcrop along the foot of the continental slope, along with continental basement which was sampled at

Unconform (Sequence)	Characteristics	Tectonic Significance	Facies Interpretation	Approx Thickness (m)	Proposed Age Identification: Stratigraphic	m.y.	Equivalent Mag Anom	Otway Basin Shelf Equivalent and Unconformities	Comment
	Low frequency, stratified and folded Floors Jurassic or Early Cretaceous rift beneath the lower continental slope	Pre-rift Tasman Geosyncline Crustal extension and first stage rifting at about U14 time	Varied metasediments and volcanics	Unknown	Palaeozoic and ? Precambrian				"Basement"
U14						? 140			
S(13–14)	Low frequency, stratified on rift shoulder		Continental–? fluvial, lacustrine	1000	Jurassic and Early Cretaceous		M Series	Casterton Beds and Otway Group Non-marine clastics and volcanogenic sediments	
	Contorted fill in first stage rift	Lower rift-fill	Alluvial fan and/or volcanics	3000 +					
U13						105			
S(12–13)	Bedded fill in first stage rift Now incorporated into tilted blocks beneath lower continental slope	Upper rift-fill, probably preceding marine transgression ? Development of shelf edge on U12	Fluvial-lacustrine possibly grading to marginal marine	0–?1000	"late" Early Cretaceous (? Albian)			Probably time equivalent to Eumeralla Formation (Otway Gp) Continental environments with volcanism	This sequence appears confined to the first stage rift
U12						95	34		
S(11–12)	Well stratified with onlap onto U12 U12/13 block-faulted beneath continental shelf	U12 (possibly U13) is main rift-onset unconformity in Otway Basin S(11–12) marine transgression	Marginal marine–marine (foram evidence from Ribis and Apthorpe, 1969)	0–?1000	Late Cretaceous (approx Cenomanian)		Slow spreading episode (Cande and Mutter, 1982)	Approximate Waarre Formation (Sherbrook Group) equivalent Shoreline facies	Wrenching and uplift of the tilted blocks beneath lower slope commenced
U11									
S(10–11)	Stratified sediment wedge with onlap onto U11 Basal channelling land ward of old shelf edge	U11 eustatic lowstand in ? Coniacian (Vail et al., 1977) S(10–11) basin transgr restricted by blocks below lower continental slope	Shallow marine (restricted basin)	0–1000 +	Late Cretaceous			Belfast Mudstone and Flaxman Formation (Sherbrook Group) Marginal marine–marine	1570 m Belfast Mudstone in Voluta 1
U10									
S(9–10)	Stratified sediment wedging out below lower slope Downlap onto U10	U9 and U10 relative falls in sea level U9–slowing or termination of movement of tilted blocks beneath lower slope	Shallow marine (regressive)	0–500 +	Late Cretaceous (approx Maastrichtian)			Curdies/Paaratte Formations (Sherbrook Group) Shoreline–continental	Slow spreading episode in southeast Indian Ocean has less influence on outer Otway Basin
U9						65	29		
S(8–9) U8 S(7–8) U7 S(6–7) U6 S(5–6)	S(5–6) to S(8–9) are distinctive, high frequency, downlapping sequences beneath lower continental slope Lower frequency, continuous, high amplitude beneath upper continental slope	A period of minimal subsidence in the outer Otway Basin due to contact between Australian and Antarctic plates in Tasmanian region Sedimentation influenced by elevated blocks beneath lower continental slope Outbuilding of fine clastics with minimal aggradation Unconformities largely reflect eustatic changes in sea level	Shelf clastics, grading into fine grained progradational wedges at palaeoshelf-edge (largely terrigenous)	200–1500	Paleocene—Middle Eocene		?	Age equivalent of the Wangerrip Group Shallow marine→shoreface→continental (regressive)	Sequences S(5–6) to S(8–9) are believed equivalent to depositional cycles TP1, TP2, TE1 and ?TE2 of Vail et al., (1977)
U5						42	18	? ?	
S(4–5) U4 S(3–4)	Stratified, onlapping S(3–4) extends across outer tilted blocks	Accelerated movement along Australian–Antarctic plate boundary Major wrenching and development of flower structures in southeast Otway Basin and western margin of Tasmania	Shallow marine (largely terrigenous)	0–800	Late Eocene—earliest Oligocene			Nirranda Group (transgressive) — shallow marine	? Minor volcanism at U5 time
U3						35	13		
S(2–3) U2 S(1–2) U1	Stratified, channelled, shelf-edge progradation	U3 is widespread Early Oligocene unconformity marking clearance of Australian and Antarctic plates and establishment of open marine conditions	Shelf – open marine (largely carbonate)	0–600	Late Oligocene and Neogene		Southeast Indian Ocean spreading	Heytesbury Group (transgressive) marine carbonates	Main episode of seafloor spreading

*For stratigraphy refer to BMR line 22/23 (Figure 3)

23/K55/15

Table 1: Correlation of seismic-stratigraphic sequences with unconformities and tectonic events in the southeast Otway Basin and the western Tasmanian margin (after Hinz & others, 1986).

three stations.

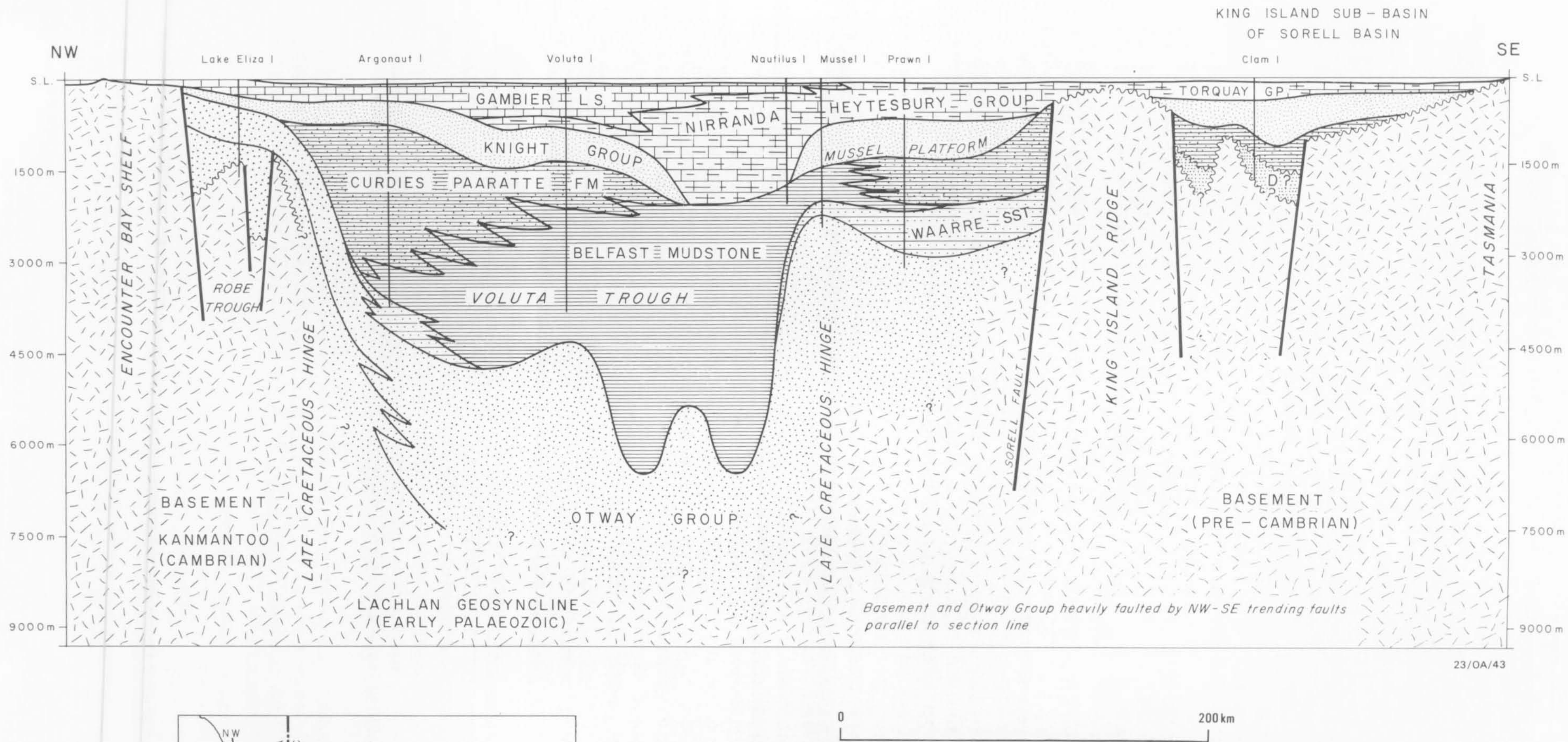
In mid-1985, the research vessel Rig Seismic carried out a regional study of areas offshore from northern Tasmania, and in Victorian and South Australian areas (BMR Survey 48), during which 3700 km of multichannel seismic data were gathered, including six regional lines which extended to the abyssal plain (Exon & others, 1987b). Teething problems with the geological winch confined sampling to six stations; the most interesting sampling result was the recovery of probably Palaeozoic metasediments from the outer margin on the edge of the abyssal plain. Tertiary samples indicated subsidence of 3500 m since the Middle Eocene. The geophysical data showed that detachment surfaces on which stretching had occurred, as recognised in the east on BMR 40/22-23 (Willcox & others, 1985), were also present in some profiles in the west (Williamson & others, 1987). A regional reassessment of available multichannel seismic profiles by Williamson & others (1987) has provided a series of structure contour maps of the region covered by the Rig Seismic cruise. These maps differ in detail from those prepared from company interpretations by Megallaa (1986), but show the same established picture of blocks bounded by coast-parallel faults and tilted landward. A summary of knowledge of the basin was published by BMR (1987).

Tectonic studies which have touched on the Otway Basin include that of Falvey (1974) who produced a model of this margin as a typical Atlantic margin, with breakup between Australia and Antarctica in the late Paleocene, in line with the interpretation of magnetic anomalies by Weissel & Hayes (1972), and that of Deighton & others (1976). Cande & Mutter (1982) revised the magnetic identification and concluded that margin formation commenced in the Santonian, with a period of slow spreading from 90 to 43 Ma, followed by more normal spreading rates until the present. Falvey & Mutter (1981) and Willcox (1982) included the Otway margin in general reviews of Australia's continental margins. Veevers (1985) has suggested that breakup started 95 Ma ago.

Geochemical and source-rock maturity studies commenced with work on coastal bitumen which was summarised by McKirdy & Horvath (1976). This study showed that bitumen from beaches along the western Otway Basin represents natural oil seepages, believed to be derived from submarine outcrops of Cretaceous freshwater and paralic rocks. More recent studies (McKirdy & others, 1986) show that the oils contain Botryococcane, indicating that they were derived from lacustrine green algae, apparently of Cretaceous age. Studies of the source-rock potential of core material from the Otway Basin (Jackson & others, 1983; Felton & Jackson, 1987) indicate that the best source rocks may be in the Late Cretaceous and possibly the early Tertiary sequences, and that maturity varies across the basin. Thermal geohistory studies by Williamson & others (1987) suggest that the Voluta Trough in the west may be an important area for the generation of hydrocarbons.

Leg 29 of DSDP drilled four partly cored holes in the Tasmanian region, including Site 282 on the west Tasmanian margin (Fig. 2A), which was some 310 m deep in 4202 m of water (Kennett & others 1974). Site 282 lies 160 km west of Cape Sorell on Sonne line 36B-46, which shows it to have been on a basement high (Fig. 6). The sequences drilled in it include much of the Cainozoic, but contain four major unconformities. The hole bottomed in pillow basalts of assumed middle Eocene age, which were overlain by Palaeogene siltstones and Neogene marls. Proposals for further drilling to resolve problems of breakup history under the Ocean Drilling Program have been made by Branson (1984) and Willcox & others (1985).

Organic-rich Late Eocene silty clays at DSDP Site 282 have considerable source rock potential (Hunt, 1975a; 1984). In Cape Sorell No. 1 (Amoco, 1982) extensive traces of oil were found in the latest



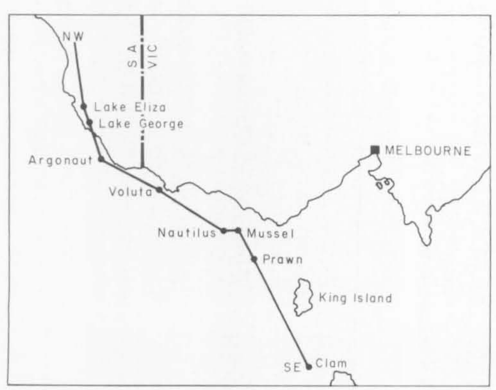


Fig. 9. Northwest-southeast cross-section through the Otway Basin. After Robertson & others (1978).

Cretaceous/earliest Paleocene. A shipboard study of 27 Sonne cores (Hinz & others, 1985) indicated that wet gas of thermogenic origin is abundant in surface sediments on the west Tasmanian margin, indicating the presence of mature source rocks.

Nineteen exploration wells have been drilled in the offshore Otway and west Tasmanian regions (Figs. 2 & 5). The results are discussed briefly under 'Petroleum Exploration'.

REGIONAL GEOLOGY

N.F. Exon & C.S. Lee

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 time before the breakup of East 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 terminations 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 WNW overall, and is extensively faulted, with major movements terminating mostly in the earliest Tertiary, but is relatively little folded. Structural trends in the basin are either WNW or NNE and most structures formed in the Cretaceous.

The Otway Basin straddles 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 is on land and its southwestern margin is at the base of the continental rise at about 4500 m water depth. A related sedimentary basin, the Sorell Basin, continues SSE down the west coast of Tasmania for 500 km, where it averages 100 km in width. Typical cross-sections are shown in Figures 6 & 7.

Palaeozoic metasediments crop out north of the Otway Basin in Victoria, and Proterozoic metamorphics crop out east of the Sorell Basin in Tasmania and King Island; both form 'economic basement' for petroleum exploration beneath the basins. The maximum sedimentary thickness is 10 km, and the sediments consist of four major sequences (Fig. 3): Early Cretaceous non-marine detrital sediments of the Otway Group; Late Cretaceous transgressive-regressive detrital sediments of the Sherbrook Group; Palaeocene-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.

It is generally believed that before breakup East Antarctica and/or the South Tasmania Rise (now south of Tasmania) adjoined the Otway and Sorell Basins. 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). The South Tasmania Rise and East 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 Hinz & others (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 and Sorell Basins. Most basinal sequences thin toward basement ridges at the foot of the continental rise; these ridges were probably topographic highs until breakup.

The Otway and Sorell Basins first formed in the latest Jurassic to earliest Cretaceous, in troughs caused by initial rifting. The oldest

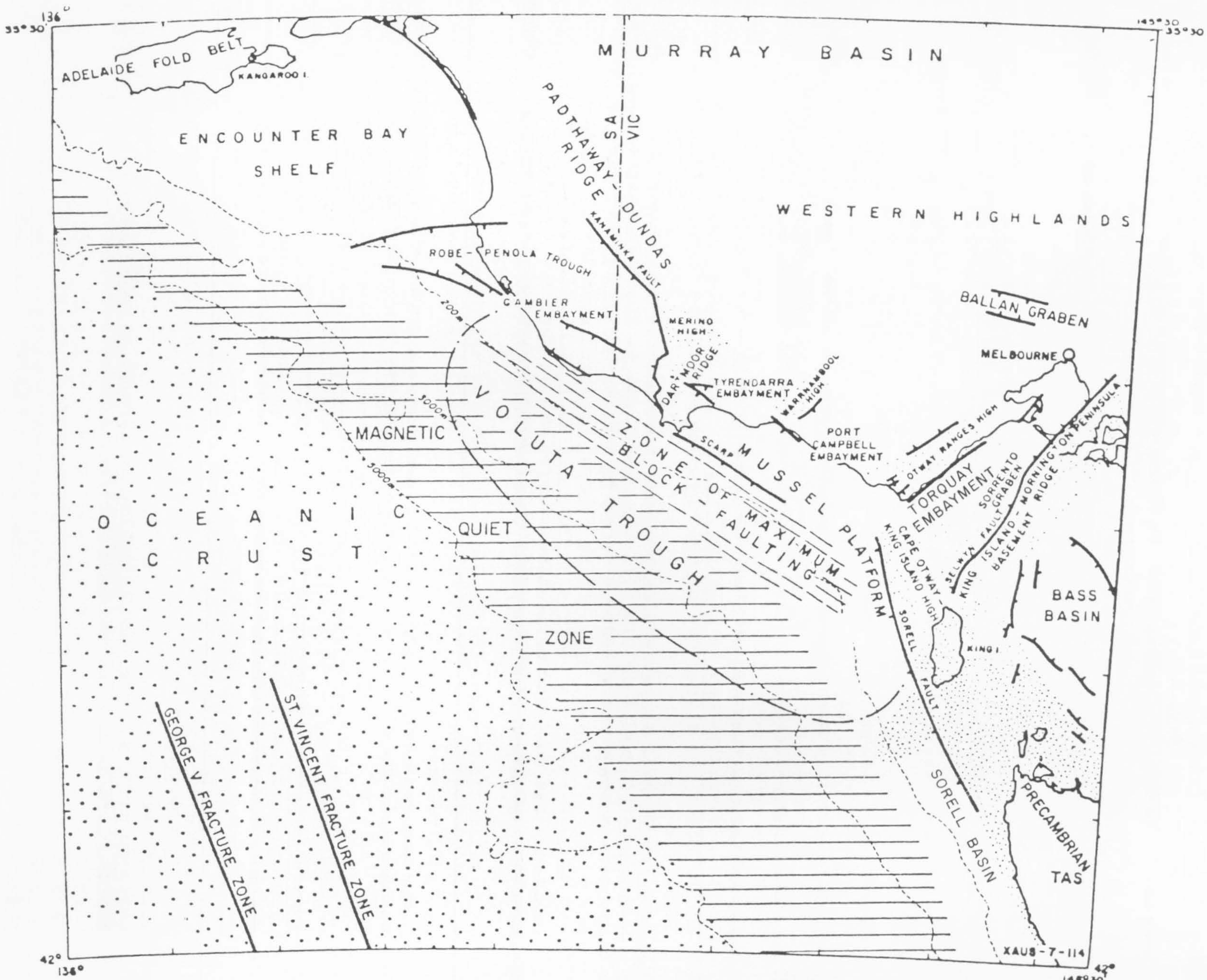


Fig. 10. Major structural elements of the Otway Basin. After Robertson & others (1978).

known sediments are of transitional Jurassic-Cretaceous age on floral and microfloral evidence (Dettmann & Douglas, 1976). Much of the Otway 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 Early Cretaceous Otway Group (Fig. 9), derived from contemporaneous volcanism (Gleadow & Duddy, 1981). Whether these sediments occur off western Tasmania in the Sorell Basin is not proven by drilling, but seismic interpretation suggests a thick sequence in the Strahan Sub-basin, seaward of Cape Sorell No.1, and elsewhere (Fig. 8).

In the Late Cretaceous, as rifting continued and then slow spreading started, the Otway Basin began to develop its present shape. In the east it terminated against the King Island-Mornington Peninsula Ridge (Fig. 10), the basin being separated from a smaller eastern portion, the Torquay Embayment, by the Otway Ranges High and Cape Otway-King Island High. The Torquay Embayment remained a non-marine sub-basin until Late Eocene times, being filled by 3000 m of Eastern View Formation coal measures. In the Sorell Basin more than 3200 m of Late Cretaceous sediments were drilled in Cape Sorell No. 1 (Amoco, 1982).

The western and southern parts of the Otway Basin were affected by a number of developing structures from early in the Late Cretaceous. Major NNE trending highs developed in the north (Fig. 10), where there are two Early Cretaceous troughs: the westerly trending Robe Trough, and the WNW trending Penola Trough adjoining it to the east. In the east the strike-slip Sorell Fault separated the non-depositional Cape Otway-King Island High from the Mussel Platform (Fig. 10), 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 subsided rapidly to form the WNW trending Voluta Trough (Fig. 10) as breakup occurred. East of the hinge line, WNW trending normal faults cut basement, the Otway Group and the early Late Cretaceous. The structure of the Sorell Basin on the Tasmanian margin is not well known, but it appears that a number of margin-parallelling strike-slip faults developed at about this time (Hinz & others, 1986).

Late Cretaceous transgressive-regressive detrital sediments of the Sherbrook Group were deposited widely in the basins as they sank, reaching a maximum thickness of 4000 m in the Voluta Trough (Figs. 9 & 10). 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 generally overlap all older basinal sequences on the landward side, but are not extensive beyond the present continental shelf. They are separated by a major Oligocene unconformity, U3 (Table 1), which coincides with a change from terrigenous to carbonate deposition. 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. It prograded southwestward across the Mussel Platform and into the Voluta Trough where it reaches a maximum thickness of 1000 m; similar prograding is evident in Eocene sequences on the Tasmanian margin (Hinz & others, 1986). As the margin continued to subside, normal marine conditions were slowly established and, outside the Torquay Embayment, thin sandstones and marls of the Nirranda Group were overlain by marine carbonates of the Late Oligocene and Miocene Heytesbury Group, which also prograded southwestward, more than keeping pace with subsidence on the shelf.

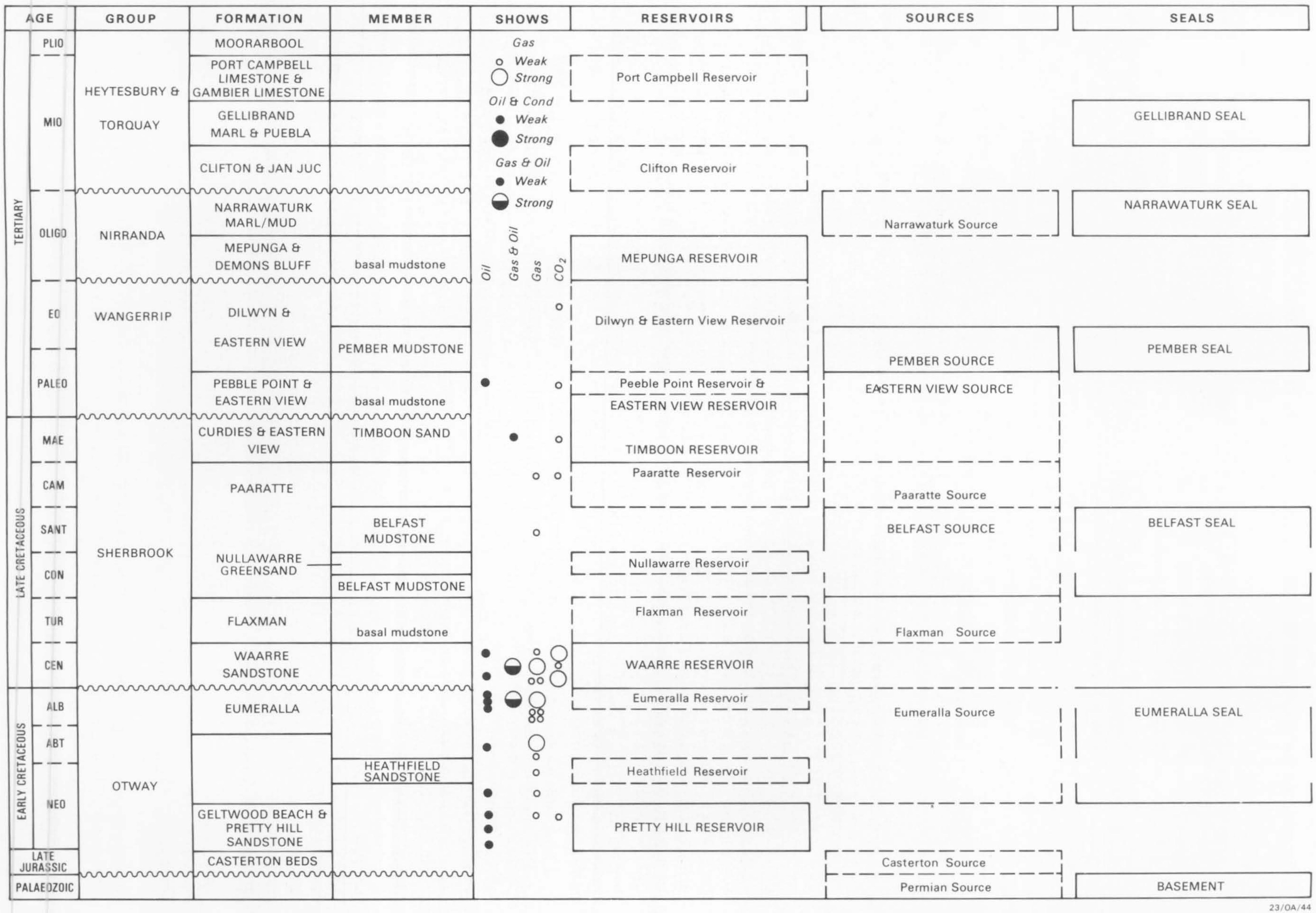


Fig. 11. Eastern Otway Basin stratigraphy related to hydrocarbon shows and to potential reservoirs, sources and seals.

INTRODUCTION

We here report the initial results of a 1987 geological cruise of R.V. Rig Seismic in the Otway Basin and in the Sorell Basin along the west Tasmanian margin. The cruise concentrated on geological sampling, but also carried out some measurements of the earth's heatflow. The aim of the work was to provide complementary information to that already existing, so that a full review of the geological framework and petroleum potential of the region could be carried out.

Earlier, and critically important, were two co-operative cruises in 1985 with the Bundesanstalt fuer Geowissenchaften und Rohstoffe (BGR) using R.V. Sonne (Hinz & others, 1985), and one BMR cruise using R.V. Rig Seismic (Exon & others, 1987b). The cruises provided 3700 km of regional multichannel seismic data in the Otway Basin, and 1000 km of similar data on the west Tasmanian margin. They also recovered 34 geological samples from the west Tasmanian margin and six from the Otway Basin.

The present cruise, BMR Cruise 67, was the first step in carrying out BMR Project 1C.09, a study of the geological development of the offshore Otway Basin and west Tasmanian margin. It was essentially a sampling cruise, with limited under-way geophysics between some stations. The vessel sailed from Adelaide on 15 January, called at Portland to repair some equipment on 29-30 January, and at King Island on 4 February to put ashore an injured crew member, and arrived in Sydney on 13 February. The field techniques included dredging and coring of older sequences, coring of younger sediments, heatflow measurements in younger sediments, and headspace analysis of gas in the surface sediments. Altogether 130 stations were occupied - 23 dredge, 54 core, 33 grab and 20 heatflow - in water depths of 50 to 5000 m (Figs. 1 and 2). A preliminary post-cruise report was provided by Exon & others (1987a).

A later cruise on the west Tasmanian margin, BMR Cruise 78, was reported on by Exon & others (1989), and its palynological results are discussed in this volume by M.K. Macphail (Appendix D).

Acknowledgements

The work benefited greatly from pre-cruise discussions with the late J. Branson (BMR); M. Megallaa and B. Thompson (Victorian Department of Industry, Technology and Resources); P.W. Baillie (Tasmanian Mines Department); R.W. Laws, D.I. Gravestock and C.D. Cockshell (South Australian Department of Mines and Energy; SADME); S.M. Yu (Gas & Fuel Corporation of Victoria); G. Cullen (BP Australia Ltd.). We thank SADME for the financial support they provided for the participation of D. McKirdy, and are grateful to the Geological Survey of Victoria for the report on foraminifera by C. Abele (Appendix C). The BMR technical support staff on the cruise were : J. Bedford, E. Chudyk, R. Curtis, P. Davies, J. Mowat, D. Pryce, H. Reynolds, G. Saunders, R. Schuler, T. Stone, J. Stratton, and P. Walker.

The enthusiasm and skill of the Rig Seismic crew was vital to the success of the cruise, especially when equipment started to fail. The ship's crew was:

Master	D. Harvey
Chief Officer	R. Hardinge
Second Officer	P. Mosley
Chief Engineer	S. Johnson
Second Engineer	P. Pittiglio/R. Thomas
Electrical Engineer	P. Jiear
EA/Seaman	K. Halliday
AB	N. Luscombe

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 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 on 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 mainly have tested structural traps. The majority of these are rollovers associated with the north-northwest trending fault system which dominates basin structure. 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 (1987) 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 80-60 Ma ago, permitting substantial hydrocarbon loss. The Late 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 Otway Group hydrocarbons would have been generated since fault trap development. The Late Cretaceous at Pecten No. 1A is still largely immature.

Prospectivity

Given the amount of structural disturbance in the basin up to 55 Ma ago, 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 that. 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 reservoirs sourced and sealed by Eumeralla Formation mudstones 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 Mudstone source may charge both Waarre and Tertiary reservoirs.

DREDGE SAMPLES

N.F. Exon, E.A. Felton, A. Stephenson, C. Wilson

Twenty-two dredge stations were occupied (Figs. 1, 2 & 3), 14 yielding hard rock material. Most stations also yielded Recent foram-nannofossil ooze in the pipe dredge. A summary of dredging results is presented in Table 2. Nannofossil ages were provided by S. Shafik (Appendix A), foraminiferal ages by C. Abele (Appendix C), and palynological ages by M.K. Macphail (Appendix D).

Methods and techniques

Dredging sites were located on the continental slope, except for DR20. Seismic lines, particularly those run on the 1985 BMR cruise 48, and echo-sounder profiles from that cruise, gave good control on site selection. Sites included slopes of 8^{o} or more, and canyons, particularly in the western part of the basin. One site (DR18) was occupied after a 600 m high topographic feature was noted on the echo-sounder profile during a transit.

On arrival at a proposed dredge site, an echo-sounder profile was run downslope to define the target. The ship was then stopped and wire run out until the amount of wire out equalled the water depth. The ship was then headed up the slope at 1-2 knots, and wire was paid out until its length exceeded the depth of water at the foot of the slope by 20-30%. Dredging continued to the top of the slope or a specified water depth. Tension on the wire was recorded on a chart recorder. On one occasion, the dredge had to be freed by reversing the ship's heading. One dredge was lost, at DR20, when the weak link, protecting the wire rope from excessive tension, gave way.

Equipment deployed was similar at all stations except DR01. A small pipe dredge was deployed ahead of a chain bag with a solid bridle. Weights were clamped to the wire rope several metres ahead of the pipe dredge. At DR01, a large chain bag with a toothed loading edge and a chain bridle was deployed, together with a pipe dredge. When retrieved, the pipe dredge was empty and the bag mesh was entangled with the loading teeth. This dredge bag was not used again during the trip.

Samples from the dredge were washed clean and sorted into groups of similar rock types. Each rock type present was give a number prefixed by the station number (e.g. DR07/1) and individual rocks from the sample given a letter suffix (DR07/1A, B, etc.). Mud from the pipe dredge was included in the listing. The proportion of each rock type present in the dredge haul was recorded, and the rocks described from hand specimen, using sawn faces where necessary. These descriptions have been improved following thin section examination of selected rocks (see Appendix E). Smear slides were prepared from weakly lithified specimens, and sedimentological and nannofossil descriptions made aboard ship.

Station data and results

Station DR01. This station was located at the base of the continental slope west of Beachport Terrace, on a ridge sloping down 10^{o} to the southwest. The ridge was interpreted from seismic evidence as either Otway Group or pre-Mesozoic basement. The dredge probably never touched bottom, due to a strong easterly drift and winch problems including loss of hydraulic pressure and a malfunctioning winch control panel.

Station DR02. The station was on the lower slope west of Beachport Terrace, in 4100-3700 m water depth. Slope angle was less than 10^{o} towards the southwest. The target was the Tertiary sequence.

Table 2 : Dredge Stations

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (hard rock)	Description or comments
DR01	37°49′	138°06′	5200	N409 67/002	None	Not on bottom
DR02	37°40.3′ 37°37.7′	138°16.8′ 138°19.6′	4100- 3800	N409 67/002	5 kg	L. Eocene & E. Oligocene grey sandy siltstone; grey Quaternary foram nanno ooze
DR03	38°14.6′ 38°14.0′	138°36.0′ 138°38.4′	4500- 4000	48/041 67/004	40 kg	Indurated Campanian (Late Cretaceous) marginal marine dark brown to grey siltstone in Fe oxide crust; plastic dark brown Early Eocene mud to silty claystone
DR04	38°26.7′ 38°24.3′	138°49.6′ 138°52.3′	4700- 4050	48/042 67/004	300 kg	Dark grey Campanian (Late Cretaceous) marginal marine laminated mudstone; mid grey siltstone in Fe oxide crust; pink Quaternary ooze
DR05	38°25.4′ 38°24.3′	139°54.7′ 138°55.8′	3900- 3850	48/042	200 kg	Dark grey Late Cretaceous siltstone, shale, claystone with ammonites including <u>Gaudryceras sp.</u>; pink Quaternary ooze
DR06	38°45.4′ 38°46.2′	139°08.9′ 139°09.0′	4660- 4450	N410 67/005	1 kg	Black Early Eocene restricted marine non-fissile mudstone, Mn crusts to 4 mm; grey Quaternary ooze
DR07	38°47.4′ 38°47.8′	139°12.4′ 139°12.1′	4450- 4200	N410 67/005	0.1 kg	Black Late Cretaceous? slate, brown mudstone, 2 mm Mn crust; light brown Quaternary ooze
DR08	39°01.2′ 39°02.7′	140°03.4′ 140°00.9′	4350- 4050	48/043	2 kg	Late Santonian/Early Campanian (Late Cretaceous) brown, restricted-open marine mudstone; brown Quaternary pelagic mud
DR09	39°26.9′	139°59.5′	4800	48/043	300 kg	Metaquartzite; quartz veined felsic volcanics; metashale; coarse felsic tuff; light brown Quaternary mud; rocks ?Palaeozoic or Mesozoic

Table 2 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (hard rock)	Description or comments
DR10	38°05.2′ 38°04.5′	139°45.2′ 139°46.4′	1950- 1700	48/042	200 kg	Fossiliferous calcareous clay, white (L. Oligoc) and grey (M. Eocene; L. Eocene-E. Oligocene); chert concretions; E-L. Oligocene bryozoal calcarenite; limonitic concretions in quartzose host; light brown mud
DR11	37°58.6′ 37°58.4′	139°49.0′ 139°49.5′	1400- 1200	16/085	-	Olive-grey Quaternary foram nanno ooze
DR12	37°46.3′ 37°46.7′	139°25.3′ 139°25.6′	1350- 1150	16/045	40 kg	E. Miocene chalk, L. Oligocene soft chalk, grey E-M. Oligocene and L. Oligocene chert or porcellanite, quartz-rich sandstone and sandy mudstone, grey sticky mud; pale grey foram nanno ooze
DR13	38°30.2′ 38°30.2′	140°52.0′ 140°53.7′	1020- 500	16/033	-	Green mud, soft and firm
DR14	38°50.0′ 38°49.8′	140°35.4′ 140°35.0′	3050- 2450	48/054	40 kg	White E. Oligocene, L. Oligocene & E-M. Miocene brown siltstone; grey ?Palaeozoic hard tuff and volcanic sandstone; minor quartz-granule conglomerate; grey ooze; white Miocene calcareous clay
DR15	38°58.3′ 38°56.8′	140°51.8′ 140°50.2′	3120- 2500	48/054	-	Grey and brown ooze
DR16	38°53.5′ 38°50.4′	141°29.2′ 141°29.0′	1450- 800	16/039	-	Light olive grey ooze
DR17	39°09.0′ 39°09.0′	141°51.1′ 141°53.0′	2270- 2060	16/029	-	Grey clay
DR18	39°12.9′ 39°11.8′	140°07.2′ 142°11.5′	1950- 1650	16/029	2 kg	White Middle Miocene chalk; brown L. Eocene-E. Oligocene and ?Miocene siltstone; grey mud-stone; white calcareous mud; olive-grey Quaternary ooze and mud

Table 2 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (hard rock)	Description or comments
DR19	$39^{\circ}29.2'$ $39^{\circ}29.5'$	$142^{\circ}13.4'$ $142^{\circ}16.2'$	2600- 2100	16/027	2 kg	White L. Oligocene chalk; brown mudstone; Quaternary grey ooze; and brownish grey ooze L. Oligocene)
DR20	$39^{\circ}05.8'$	$143^{\circ}19.9'$	66	16/029	-	Chain bag dredge broke off at weak link
DR21	$40^{\circ}50.3'$ $40^{\circ}49.5'$	$141^{\circ}46.0'$ $141^{\circ}49.0'$	4580- 4155	40/024	20 kg	Yellowish brown, f-m, well-sorted quartz lithic sandstone. Some Maastrichtian restricted - marginal marine clayey sandstone containing clay clasts and lenses
DR22	$42^{\circ}40.4'$ $42^{\circ}42.2'$	$143^{\circ}43.4'$ $143^{\circ}43.2'$	4200- 3900	16/008	1 kg	Brown and grey v.f. micaceous sandstone and siltstone; tough, dark grey Maastrichtian restricted-marginal marine mud; white and pale olive-brown foram nanno ooze
DR23	$42^{\circ}39.0'$ $42^{\circ}41.6'$	$143^{\circ}43.1'$ $143^{\circ}42.8'$	4257- 4000	16/008	-	Brown foram nanno ooze

Samples were recovered at 4100-3900 m from the pipe dredge only, and consisted of yellowish grey (Munsell colour 5Y7/2) foram/nannofossil ooze, dated from nannofossils as late Quaternary, and lithified light olive-grey sandy siltstone with some darker material (5Y5/2-10YR4/2), dated from nannofossils and foraminifera as Early Oligocene (Appendices A & C).

Station DR03. The station was on the lower slope south of Beachport Terrace, near the abyssal plain, in 4800-4100 m of water. The echo-sounder profile showed a slope of 10-12°, down to the southwest. About 40 kg of material was collected.

Sample type DR03/1 consists of a boulder of dark brownish grey indurated siltstone, with joints and fractures coated by secondary iron minerals. This boulder comprised half the 40 kg sample. Palynological examination (Appendix D) showed it to be Campanian in age and deposited in a marginal marine environment. DR03/2 is a dark brown mud with distinctive plastic texture, containing 'cores' of more indurated but still soft silty claystone with ferruginous coating. It comprises 50% of the sample. The dark brown mud lacks nannofossils but contains Early Eocene palynomorphs (Appendix D) and is probably from a marginal marine environment. Two fractions were present: DR03/2A is a plastic mud with more resistant 'core' material, DR03/2B. DR03/3 is moderately indurated ferruginous material (?boxstone in part) on soft silty claystone like DR03/2. It comprises less than 1% of the sample.

Station DR04. The target at station 4 was Early Cretaceous sediments interpreted from seismic data, at the base of the continental slope in 4800 m of water, on a 10° slope dipping southwest. A full bag (about 300 kg) of rocks was obtained from water depths of 4700-4050 m, together with pinkish ooze in the pipe dredge.

Sample type DR04/1 is dark grey to brown, soft to hard, pyritic mudstone with incipient to distinct cleavage. It is strongly fractured, with conchoidal fractures and ferruginous staining on fracture faces and cleavage planes. Indistinct lamination and occasional brecciated texture was noted on sawn faces. This rock type comprises about 90% of the haul. It is probably Late Cretaceous, from its lithological character.

Sample type DR04/2A is a medium grey-brown laminated mudstone; small ?burrows are seen to parallel the lamination on sawn surfaces. DR04/2B is like 2A, but hardened due to weathering/alteration; ferruginous crusts and boxworks surround central cores of mudstone. Palynological examination (Appendix D) showed DR04/2A to be of Campanian age and deposited in a marginal marine environment.

Sample type DR04/3 is calcareous mudstone with microkarst, ferruginous rinds and boxworks. On lithological grounds it is possibly Tertiary in age.

Sample type DR04/4 is coarse, poorly sorted, quartzose sandstone with rounded quartz grains set in a ferruginous quartz matrix. On lithological grounds it is probably Tertiary in age. DR04/5 is dark brown plastic mud with 'cores' to DR03/2. It is probably Late Cretaceous in age.

Sample type DR04/6 is a light brown Recent mud from the pipe dredge. DR04/7 consists of light brown siliceous flattened concretions (perhaps related to rock type 2A), and is probably Late Cretaceous in age.

Station DR05. This station was located near the base of the continental slope, in 3900 m of water, above station DR04. The target was presumed Early Cretaceous sediments. About 200 kg of material was recovered.

Sample type DR05/1A is medium to dark grey, moderately indurated mudstone, showing conchoidal fractures with limonite staining. It contains indistinct bedding laminae, with incipient fracture cleavage oblique to bedding. The sample type is similar to DR04/1. DR05/1B is similar to 1A, but with a black coating, possibly of manganese oxides. DR05/1C is like 1A but contains ammonites. Sample type DR05/1 made up 70% of the dredge haul. On lithological grounds it is probably Late Cretaceous. Dr T. Matsumoto of Kyushu University (pers. comm.) states that the fragmented ammonite remains probably belong to the genus Gaudryceras which is Aptian to Maastrichtian in age, and that unidentifiable remains of radiolaria and foraminifera are present in the sample.

Sample type DR05/2A consists of concretions developed in mudstone of type 1A, above. They are ferruginous skins with multiple concentric zones. DR05/2B is a weathered mudstone core from a concretion. The age of the core material would be the same as for DR05/1 above, but the age of concretion development is unknown. Concretionary material is about 25% of the haul.

Sample type DR05/3 is black, dark grey, grey brown, and light grey mud, derived in part from rock type 1A. The light grey material is probably Recent ooze. The age of the darker material is probably Late Cretaceous or Palaeogene. It comprises about 5% of the haul.

Station DR06. The station was located on the northern side of a ridge on the abyssal plain southwest of Argonaut No. 1 well, in 4800 m of water. Indurated brownish green, quartz-veined, silty mudstone was recovered from the south side of this ridge at station 048-DR06, during the 1985 Otway Basin cruise. Ten kilograms of material were recovered during the present cruise, in the pipe dredge only, from a depth of 4450 m.

Sample type DR06/A consists of small pieces of black, non-fissile mudstone, about 90% of all lithified material. Palynological examination (Appendix D) showed it to be of Early Eocene age, and probably deposited in a restricted marine environment. DR06/B consists of manganese crusts of unknown age, up to 4 mm thick. DR06/C is an olive-grey pelagic ooze with Quaternary nannofossils.

Station DR07. The target at this station was basement. The site was located in 4750 m of water on the same ridge as DR06, but further up the slope to the south. Recovery was about 5 kg and came from the pipe dredge only.

Sample type DR07A is light brown pelagic ooze with Quaternary nannofossils. DR07B consists of four pieces of black slate (to 4 mm diameter). DR07B/2 consists of four small, dark brown mudstone fragments. DR07/3 is one small, light brown mudstone. DR07B/4 is one manganese crust.

This material is similar to the range of rock types recovered at DR03. The mudstones are probably of Late Cretaceous age on lithological grounds; the black slate, if a true slate, is probably Palaeozoic.

Station DR08. The station was located on the northeastern side of a small ridge near the base of the continental slope south of Argonaut No. 1 well. The target was probable Early Cretaceous sediments. Recovery was 10 kg of pelagic ooze and dark brown mud, in the pipe dredge, from a water depth of 4351-4050 m. The pelagic ooze yielded Quaternary nannofossils. The brown mud contained fragments of soft, dark brown mudstone, similar to those described from DR03 and DR04. The age of the dark brown mud and mudstone is late Santonian to early Campanian on palynological grounds and it was deposited in a restricted to open marine environment (Appendix D).

Station DR09. The target at this location was basement, on the southeastern end of the topographic ridge dredged at DR06 and DR07. The water depth was 4800-4530 m. About 300 kg of hard rocks were recovered in the chain bag, and light brown ooze and some small rocks in the pipe dredge.

Pipe dredge material consisted of five sample types. Sample type DR09/1 is yellow-brown ooze with Quaternary nannofossils. DR09/2 is yellow-orange terrigenous clay, firm in texture but easily deformable. Its age is possibly Recent. DR09/3 consists of about 1 kg of rock fragments like the material in the chain bag. Fragments have manganese oxide coatings. DR09/4 consists of two small fragments of coarse quartz and feldspar, possibly pegmatite. DR09/9 is light brown ooze with Quaternary nannofossils.

Chain bag material consisted of five sample types. Sample type DR09/5 is light greenish grey, felsic, volcanic breccia, consisting of quartz and volcanic rock fragments set in a fine-grained siliceous groundmass. DR09/6 consists of coarse and fine-grained basic igneous rocks, greenish grey, fractured and quartz veined. Coarse varieties contain phenocrysts of plagioclase and ?pyroxene to 3 mm long, in altered greenish groundmass. These rocks comprise 75% of the hard rock sample. DR09/7 consists of fine-grained metaquartzite, pyritic in part, quartz-veined fine-grained siliceous felsic volcanic rock, and ?metashale. This material comprises 25% of the haul. DR09/8 is a spotted siliceous metavolcanic or metasedimentary rock, making up less than 1% of the haul.

This suite is tentatively assigned an early Palaeozoic or Precambrian (Adelaidean) age on lithological grounds. An early Mesozoic age (pre-Otway Group) is possible for part or all of the igneous rocks recovered: they may have been emplaced during the earliest stages of the Cretaceous rifting event which culminated in the separation of Australia and Antarctica.

Station DR10. Early Tertiary rocks were the target at this site, located on a 15^{o} slope down to the southwest, in 1950-1700 m of water. Two hundred kilograms of mixed carbonate rocks were obtained from the chain bag, and light brown ooze with fragments of rock from the pipe dredge.

Sample type DR10/1 consists of soft white (5Y8/1) fossiliferous calcareous claystone with poorly sorted, poorly rounded sand-sized quartz grains. Fossils are mainly bryozoan debris. The claystone is bioturbated, with burrows 2-7 mm in diameter, some with a manganese oxide lining. One sample yielded Late Oligocene coccoliths and another yielded late Early Oligocene foraminifera. This material comprised 30% of the dredge haul.

Sample type DR10/2 consists of chert concretions or nodules from both DR10/1 and DR10/3. DR10/2A contains Early to mid Oligocene nannofossils. DR10/2B contains Late Oligocene nannofossils and another sample contained Early Oligocene foraminifera. This material comprised 30% of the dredge haul.

Sample type DR10/3 is light brownish grey (2.5Y6/2) sparsely fossiliferous calcareous claystone, with minor poorly sorted, poorly rounded quartz sand grains, possibly bimodal. It contains minor mica and sparse borings of 2-4 mm diameter. This material comprises 25% of the dredge haul. DR10/3A contains Middle Eocene coccoliths and foraminifera. DR10/3B contains latest Eocene-Early Oligocene coccoliths and Late Eocene foraminifera. Sample DR10/3C is very fine soft sandstone with late Middle Eocene foraminifera.

Sample type DR10/4 is highly fossiliferous bryozoal calcarenite, with chert concretion. Fossils are 90% bryozoan and 10% molluscan debris along with worm-burrow fragments. Minor mica and well-rounded translucent to green quartz sand grains are present. One sample contains Late Oligocene coccoliths and another contains Early Oligocene foraminifera.

Sample type DR10/5 consists of brownish yellow (10YR2/1) limonitic concretions in a poorly sorted quartz sandstone host, with quartz grains similar to DR10/1 and 4. The concretions are manganese rich, and may result from cementation or lithification on the sea floor. This material comprises 5% of the haul and did not yield nannofossils. DR10/6 is a light brown ooze containing fragments of rock types as above.

Station DR11. This site, on the middle of the continental slope in 1400 m of water, west of Argonaut No. 1 well, had a target of early Tertiary rocks on a southwest-facing 10° slope. Only light olive-grey foram-nanno ooze was obtained in the pipe dredge. There was no recovery in the bag.

Station DR12. The station was located southwest of Beachport, the target being a canyon on the middle slope running southwestward. Water depths were 1350-1150 m. The south wall of the canyon was sampled for Late Cretaceous and Early Tertiary rocks. Five rock types were collected in the 50 kg sample, plus mud in the pipe dredge.

Sample type DR12/1 belongs to a sandy mudstone to ferruginous sandstone suite (25% of sample). The sandstone is fine to medium-grained, brown, and quartz rich. The sandy mudstone is dark grey, and is almost certainly a facies equivalent of the sandstone. Some rocks have cores of black sandy mudstone, surrounded by rims of ferruginous material 2-3 mm thick. This rock suite contains no nannofossils.

Sample type DR12/2 consists of white chalk, firm and bored (25% of sample). This sediment contains Early Miocene coccoliths, and grades to sample DR12/3, which consists of chert or porcellanite (30% of sample). Specimens range from pale grey to greenish grey in colour, and are bored. Some rocks consist of altered calcareous mudstone rather than chalk. All of lithotypes DR12/2 and DR12/3 apparently belong to one assemblage. However, DR12/3 contains coccoliths of both Early-mid Oligocene and Late Oligocene age, and foraminifera of early Oligocene age (in contrast to the early Miocene age determination of DR12/2).

Sample type DR12/4 is soft white chalk (10% of sample) dated by nannofossils as Late Oligocene. DR12/5 consists of brown to grey mudstone (10% of sample), dated by nannofossils as late Quaternary. Both lithotypes contain foraminiferal assemblages representing three age intervals : late Early Oligocene, Early Miocene and Quaternary. DR12/6 is light grey foram-nanno ooze recovered from the pipe dredge, of probable late Quaternary age.

In addition, the pipe dredge brought up colonial deepwater corals (some living), solitary corals, worms, paper-thin bivalves, and one deep-sea fish. The soft organisms and corals were forwarded to Wolfgang Zeidler of the South Australian Museum.

Station DR13. The station was located off Discovery Bay, west of Portland, the target being a canyon cut into possible Oligocene sediments, in water depths of from 1020 m to 500 m. No hard rock was recovered from the chain bag, but the pipe dredge contained two buckets of mud. No age determinations are available. Sample type DR13A consists of olive-grey, very soft foram-nanno ooze. DR13B consists of olive-grey firm mud and cohesive, sandy, foram-nanno ooze. It is probably bioturbated, as a worm was recovered from the sediment.

Station DR14. The station was located south of Port Macdonnell; the target was the western side of a south-southwest trending canyon in water depths of 3050-2450 m. Six rock types were recovered in the 40 kg chain bag sample, and 10 kg of ooze and clay in the pipe dredge.

Sample type DR 14/1 is white, bored and bioturbated fine-grained chalk, containing chert nodules, and with pale green weathering surfaces (?ferrous oxide). This comprised 70% of the sample, and contains two distinct types of boring: one of 1-2 cm diameter, and another of 1-3 cm diameter. The inside of the boring tubes was often lined with a coating of manganese oxide. Various samples contained

Late Oligocene and Early to Middle Miocene coccoliths, and Early Oligocene and Late Oligocene foraminifera.

Sample type DR14/2 consists of variably weathered (green ferrous oxide (like DR14/1), manganese dioxide or limonite) siltstone and claystone. This comprised 15% of the sample, and was often weathered to concretions with a 1 cm ferruginous layered rim enveloping a claystone core. No age has been determined. DR14/3 is one small piece of white foram-rich chalk, with some borings, containing some shelly fragments and Quaternary foraminifera.

Samples from DR14/4 form a grey, hard, tuff suite (10% of sample), varying from quartz-rich vitreous tuff to volcanogenic sandstone. This sample was further subdivided into sandy mudstone (A), quartz sandstone (B), and tuff (C).

Sample DR14/5 is a piece of hard, dense, dark-grey quartz arenite. It consists of quartz in a fine matrix containing pyrite. Sample DR14/6 is a piece of hard, grey conglomerate to quartz arenite, consisting of vein quartz pebbles in a quartzose matrix.

Soft material from the pipe dredge included DR14/7, pale grey foram-nanno ooze, and DR14/8, a white, soft calcareous clay, containing Miocene coccoliths.

Station DR15. The station was located south of Port Macdonnell, and the target was Oligocene or older rocks in a canyon with water depths of 3120-2500 m; the canyon appears to be associated with a major, near-vertical fault. No rocks were recovered in the chain bag, but 5 kg of grey and brown foram-nanno ooze was recovered from the pipe dredge.

Station DR16. The station was located south of Portland; the target was Eocene rocks on the upper continental slope in water depths of 1450-800 m. No rocks were recovered from the chain bag, but the pipe dredge contained 20 kg of light olive-grey foram-nanno ooze. This was cohesive and firm but unconsolidated, and had a minor silt fraction.

Station DR17. This station was located southwest of Portland, the target being Tertiary rocks forming a small scarp on the eastern side of an old, infilled canyon on the middle slope. Water depths ranged from 2270 to 2060 m. There was no recovery from the chain bag, and the pipe dredge recovered only a small amount of grey clay of presumed Holocene age.

Station DR18. This station was located southwest of Portland, the target being Oligocene and older rocks in the lower section of a canyon on the middle slope. Water depths ranged from 1950 m to 1650 m. There was no recovery from the chain bag, but the pipe dredge recovered 15 kg of sample, including 2 kg of lithified material.

Sample type DR18/1 consists of a small amount (less than 1% of sample) of moderately lithified, foram-bearing white Middle Miocene chalk. DR18/2 consists of soft, white calcareous semi-lithified mud (ca. 50% of sample), containing Middle Miocene nannoplankton. DR18/3 consists of pale brown, non-calcareous, weakly lithified siltstone (ca. 50% of sample), dated as Late Eocene to Early Oligocene on nannoplankton, and Late Eocene on foraminifera.

Sample type DR18/4 consists of unconsolidated, light olive-grey foram-nanno ooze, containing late Quaternary nannofossils intermixed with soft, olive-grey calcareous mud. DR18/5 is one piece of dark grey lithified mudstone (less than 1% of sample). DR16/8, a palaeontological subset of DR18/4, contained late Quaternary nannofossils, along with a few mid Tertiary ones.

Station DR19. This station was located southwest of Nautilus A-1 well, on the middle slope. The target was pre-Oligocene rocks on a fault scarp and canyon wall, in water depths of 2625 m to 2250 m. No rocks were recovered from the chain bag, but 2 kg of sediment was recovered from the pipe dredge.

Sample type DR19/1 consists of off-white, semi-consolidated chalk, probably a composite sample. It contains Late Oligocene nannofossils and foraminifera. Sample type DR19/2 consists of a few small pebbles of apparently non-calcareous, pale brown, finely bedded mudstone, containing late Quaternary nannofossils. DR19/3 consists of plastic, pale grey, foram-nanno ooze. DR19/4 is soft, pale brownish grey, foram-nanno ooze, containing reworked Late Oligocene nannofossils.

Station DR20. This station was located southwest of Cape Otway, on a basalt high between Cape Otway and King Island (Gill & Segnit, 1986). The target was in 66 m of water. The chain bag dredge became ensnared and broke off at the designed weak link, so there was no recovery of sample. However, basalt was recovered by grab (GS24).

Station DR21. This station was located west of King Island, the target being a ridge of presumed Cretaceous sediment near the abyssal plain, in 4580-4155 m of water. The western side of this ridge, which was dredged, appears to be associated with a major normal fault. About 20 kg of rock was recovered from the chain bag. Both lithotypes recovered are highly leached and weathered, and contain no visible fossils.

Sample type DR21/1 is massive, moderate yellowish brown quartz lithic sandstone (80% of sample). It is well-sorted, medium-grained, weakly lithified, micaceous, and feldspathic. Two populations of garnets are present. It contains 2-3 mm diameter borings, and 1-2 mm thick manganiferous crusts. The mica consists of 1 mm flakes of muscovite. Bedding exists, but is indistinct. DR21/2 is well-bedded, thinly bedded, fine-grained, micaceous quartz-lithic sandstone with mud clasts, and makes up 20% of the sample. It contains dark yellowish brown 1-2 mm manganiferous crusts, particularly in 1 cm diameter borings. It contains clay lenses with bedding draped over some of them, and abundant carbonaceous debris. Palynological examination (Appendix D) showed it to be of Maastrichtian age and deposited in a restricted to marginal marine environment.

Station DR22. This station was located southwest of Cape Sorell; the target was presumed Early Cretaceous sediments on the lower continental slope, in 4200-3909 m of water. No rocks were recovered from the chain bag, but 1 kg of sample was recovered from the dredge mouth, and from within ooze in the pipe dredge.

Sample type DR22/1 consists of small pieces of brown and grey siltstone, and very fine-grained micaceous sandstone (5% of semi-lithified and lithified sample). DR22/2 consists of tough, dark grey mud, recovered from the chain dredge lip (80% of semi-lithified and lithified sample). It contains Maastrichtian palynomorphs and was deposited in a restricted to marginal marine environment (Appendix D). DR22/3 consists of white, sticky foram-nanno ooze (20% of semi-lithified and lithified sample). DR22/4 consists of pale olive-brown nanno-foram ooze (samples DR22/1 and DR22/3 were contained within this ooze).

Station DR23. This station was located southwest of Cape Sorell, in water depths of 4275-4000 m. The target was presumed Early Cretaceous sediments, in a ridge just above the abyssal plain. This ridge was that sampled in DR22. DR22 sampled the western (oceanward) side of the ridge; DR23 sampled the eastern (landward) side. There was no recovery from the chain bag, but some 5 kg of ooze was recovered from the pipe dredge. DR23 consists of brown, oxidised, recent fine-grained foram-nanno ooze. The ooze was sieved, but no rock fragments were present.

GRAVITY CORES

C. Wilson, N.F. Exon, E.A. Felton, A. Stephenson

Objectives

Fifty-four gravity cores (Figs. 1 and 2) were taken with the objectives of sampling unconsolidated Quaternary and Tertiary sediments, and older more consolidated sequences where possible. Cores were split aboard ship for initial lithological description, nannofossil study (see Shafik, Appendixes A and B), and geochemical analysis (see McKirdy & Heggie, this volume). Foraminiferal studies were carried out after the cruise by C. Abele (Appendix C). Palynological examination of key samples was provided by M.K. Macphail (Appendix D). Conductivity experiments were undertaken on selected cores for calculation of heat flow values (see Lee, this volume). Post-cruise grainsize and carbonate analyses have been added to three typical core logs to give a general impression of the range of these parameters. Position, water depth, core length and a brief description are given in Table 3. A key to all the figures showing core logs is given in Figure 12.

Sampling method and description

Unconsolidated sediment was recovered using a gravity corer consisting of a 1200 kg weight, and 3-5 m core barrels using 65 mm liners. Penetration into semi-consolidated or consolidated sediment proved difficult, often resulting in poor penetration and bent core barrels. However, these sediments were usually pre-Quaternary so that, even with limited recovery, the data collected were extremely important. In some cases the core liner was fitted with a flapper valve to trap bottom waters for geochemical analysis.

Cores were divided into one-metre lengths using a hand saw, and then split lengthwise using a frame mounted power saw. Cores were labelled with a cruise number (67), a site number (i.e. GC08), a section interval measured in centimetres from the top of the core (i.e. 100-134 cm), and a core letter designating the sequence of the sections (CC designated core catcher). In addition, yellow tape was secured around the lower half of each section. Cores were stored in their liners in plastic bags at a temperature of 4°C.

Cored material was described by lithological unit, following the sediment classification of the DSDP (Fig. 12), and colour variations were matched against a Munsell colour chart. The position of samples for nannofossil, geochemical and smear slide studies were recorded in the log.

Presentation of data

A twofold approach was used in interpretation and presentation of the data. Cores from the same general region (i.e. along the same or related seismic profiles) were arranged sequentially according to depth. Wherever possible, units were correlated to give geological sections along a depth profile, allowing general trends to be observed and interpreted.

Some problems with this approach naturally arise, primarily from the different styles of interpretation by the various shipboard geologists who described the cores. Cross-sections were thus constructed with some artistic licence. Obvious lithologies, such as the surface oxidised layer, proved easy to separate. However, the oozes were difficult to correlate because variations in colour and lithology were often slight. The distinction of units was limited to a simple twofold division, based primarily on colour. The lighter-coloured bands (generally grey/greenish grey) were separated

Table 3: Gravity Core Stations

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm)	Description or comments
GC01	37°10.2′	138°35.8′	425	16/049 67/001	220	80 cm greenish grey foram nanno ooze, over greenish grey fine sandy and silty muds
GC02	37°23.9′	138°34.7′	1270	16/049	54	Greenish grey foram nanno ooze
GC03	37°33.0′	138°35.0′	1476	16/049	310	Olive-grey to greenish grey foram nanno ooze
GC04	37°35.0′	138°35.0′	1526	16/049	184	130 cm greenish grey foram nanno ooze, over bluish grey claystone; ashy horizon 144-147 cm
GC05	37°45.5′	138°34.9′	2235	16/049	80	Olive-grey foram nanno ooze, over L. Eocene semilithified mud
GC06	39°30.8′	139°57.7′	4590	48/043	263	Olive-grey foram nanno mud; minor calcareous turbidites; ashy horizon 111-112 cm
GC07	39°20.1′	139°59.2′	4120	48/043	287	Banded olive-grey foram nanno ooze and mud; ashy horizon 66-68 cm
GC08	39°02.2′	140°02.9′	3980	48/043	294	Olive-grey and greenish grey foram nanno ooze and mud; ashy horizon 34 cm
GC09A	38°57.1′	140°06.6′	3615	48/043	203	Olive-grey foram and greenish grey nanno ooze and mud; minor calcareous turbidites; ashy horizon 27 cm; Middle Eocene restricted marine firm brown mud in core catcher
GC10	38°51.7′	140°06.1′	3332	48/043	374	Light olive-grey foram nanno ooze; minor turbidite; ashy horizon 25 cm
GC11	38°45.0′	140°07.4′	3214	48/043	308	Greenish grey and grey foram nanno ooze and mud; thin calcareous turbidites; ashy horizon 30 cm
GC12	38°42.6′	140°07.1′	3150	48/043	10	Peaty, open-marine siltstone, Middle Eocene; corer tipped over, young material washed out
GC12A	38°42.6′	140°07.1′	3133	48/043	306	Olive-grey and greenish grey foram nanno ooze; ashy horizon 35 cm

Table 3 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm)	Description or comments
GC13	38°27.9'	140°10.0'	2525	48/043	364	Olive-grey foram nanno ooze; minor calcareous turbidites
GC14	38°25.4'	140°09.0'	2250	48/043	357	Olive-grey and greenish grey foram nanno ooze; one minor calcareous turbidite
GC15	38°22.9'	140°10.6'	1964	48/043	291	Olive-grey and greenish grey foram nanno ooze; one minor calcareous turbidite
GC16	38°20.0'	140°10.9'	1650	48/043	196	Olive-grey and greenish grey foram nanno ooze
GC17	38°17.2'	140°11.1'	1490	48/043	326	Olive-grey and greenish grey foram nanno ooze; one minor calcareous turbidite
GC18	38°11.6'	140°11.5'	1035	48/043	233	Olive-grey foram nanno ooze
GC19	38°07.2'	140°13.0'	345	48/043	176	Olive-grey bryozoal sand to 28 cm; olive-grey mud below
GC20	38°05.0'	140°14.36'	166	48/043	-	No recovery; ?bottom contact
GC20A	38°05.2'	140°14.4'	166	48/043	-	No recovery; bent pipe suggests sand
GC21	37°59.4'	140°03.6'	315	48/042	232	Olive-grey shelly muddy foram sand
GC22	38°02.3'	139°58.0'	1003	48/042	319	Olive-grey foram nanno ooze; one minor calcareous turbidite
GC23	38°03.2'	139°55.9'	1146	48/042	277	Olive-grey foram nanno ooze; minor calcareous turbidite
GC24	38°35.1'	141°09.6'	392	48/007	184	Olive-grey sandy calcareous ooze
GC25	39°36.5'	141°10.5'	450	48/007	184	Olive-grey sandy calcareous ooze
GC26	38°37.9'	141°11.1'	469	48/007	224	Olive-grey sandy calcareous ooze, thin coarse bioclastic bed 114-117 cm

Table 3 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm)	Description or comments
GC27	38°38.9′	141°11.5′	506	48/007	225	Olive-grey foram nanno ooze, minor coarse bioclastic bed 188-192 mm
GC28	38°40.1′	141°12.5′	545	48/007	248	Olive-grey foram nanno ooze, minor coarse bioclastic bed 178-190 cm
GC29	39°34.0′	142°59.0′	240	40/022	364	71 cm olive-grey shelly carbonate ooze over olive shelly mud
GC30	39°35.0′	142°57.4′	558	40/022	145	28 cm olive-grey sandy calcareous ooze over greenish grey clay
GC31	39°36.0′	142°57.0′	829	40/22	296	Sandy olive foram nanno ooze over olive-grey calcareous ooze
GC32	39°40.1′	142°54.7′	1244	40/22	93	Olive-grey muddy foram nanno ooze
GC33	39°45.5′	142°52.0′	1433	40/22	270	Olive-grey and greenish grey foram nanno ooze
GC34	39°47.7′	142°48.8′	1630	40/22	287	Light-olive-grey and greenish grey foram nanno ooze, with two calcareous sand turbidites
GC35	39°54.8′	142°44.2′	2280	40/22	144	Light-olive-grey foram nanno ooze, containing E-M Miocene mudstone slump
GC36	40°00.9′	142°40.1′	2182	40/22	259	Grey and greenish grey foram nanno ooze; L. Pliocene at base
GC37	40°14.1′	142°25.2′	3090	40/23	275	Greenish grey foram nanno ooze, with three carbonate sand turbidites.
GC38	40°27.9′	142°04.9′	3850	40/23	194	Greenish grey foram nanno ooze, with two carbonate sand turbidites
GC39	40°37.9′	141°50.1′	4300	40/23	135	Olive-grey foram nanno ooze, with one sand turbidite, over L. Oligocene green clay

Table 3 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm)	Description or comments
GC40	40°41.5′	141°46.4′	4370	40/23	62	Grey foram nanno ooze over E. Miocene olive-brown calcareous clay
GC41	40°43.8′	141°42.4′	4645	40/23	190	Two thick calcareous turbidite sequences, above multi-coloured pre-Quaternary clays
GC42	40°49.6′	141°48.8′	4161	40/23	84	Light grey foram nanno ooze, over yellow to reddish mottled pre-Quaternary gypsiferous clay (soil profile)
GC43B	42°17.8′	142°51.7′	4830	SO36/46	2	Light olive-grey v.c. gritty bryozoal sand
GC44	42°14.8′	142°31.6′	4103	SO36/46	146	Greenish grey foram nanno ooze, with four calcareous sand turbidites; ?ash horizon 40 cm
GC45	42°13.6′	142°52.5′	3715	SO36/46	360	Grey and greenish grey foram nanno ooze, L. Pliocene at base
GC46	42°12.1′	144°24.8′	2360	SO36/46	176	93 cm greenish grey foram nanno ooze, over 7 cm calcareous sand turbidite, over soft light greenish grey chalk
GC47	42°10.6′	144°40.9′	765	SO36/46	134	Grey foram nanno ooze, with four carbonate sand turbidites
GC48	42°10.8′	144°44.3′	377	SO36/46	190	Olive-grey mixed c. bryozoal sand and foram nanno ooze
GC49	41°31.4′	144°20.3′	838	16/015	294	Olive-grey bryozoal sand, foram sand and foram nanno ooze
GC50A	41°30.5′	144°17.4′	1081	16/015	169	Olive-grey and greenish grey foram nanno ooze
GC51	41°31.2′	144°13.1′	1557	16/015	127	Greenish grey foram nanno ooze
GC52	41°10.9′	143°57.5′	1145	16/017	175	Olive foram nanno ooze

Table 3 (contd.)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm)	Description or comments
GC53	41°10.9′	143°55.4′	1367	16/017	166	Olive-grey foram nanno ooze
GC54	41°10.9′	143°50.2′	1634	16/017	97	Olive-grey foram nanno ooze, over L. Oligocene hard greyish olive mudstone

from the darker bands (olive to dark greenish grey).

Cores illustrated show either a typical profile, some typical feature, or an anomalous feature of particular interest.

Western Beachport Terrace

Five cores across the western Beachport Terrace, GC01-05 on BMR seismic profile 16/49, provide a cross-section from outer shelf to mid slope (Figs. 2 & 13).

The outer shelf sample (GC01) is dominated by bioturbated greenish grey, calcareous silty muds and fine sands. Detrital mica grains are common. Moving southwards downslope, the sand and silt fraction is rapidly lost, and the cores become dominated by calcareous oozes. There is an associated change from the intensely bioturbated, unbedded sediments of the upper slope to the banded units of the lower slope. Typically the lower slope profiles show an alternation between lighter greenish grey and darker olive green units. Lithological variation is slight.

GC04 contains an atypical claystone (Fig. 14). The upper 130 cm is dominated by muddy foram/nanno oozes, showing typical colour banding. Variation is slight and preservation of the banding is due largely to limited bioturbation. This sequence overlies an anomalous olive grey claystone containing a possible ash band. The claystone is taken to represent a terrigenous-dominated period of sedimentation, contrasting with a non-terrigenous pelagic carbonate phase, represented by the foram/nanno oozes.

GC05, a light yellowish brown nanno/foram ooze, overlies a Late Eocene, olive-grey mud.

Western Otway Basin

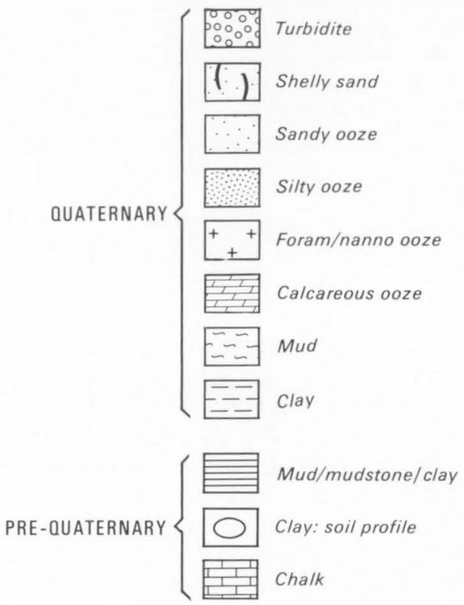
The western Otway Basin region, off Mount Gambier, is represented by samples GC06-GC19 along BMR seismic profile 48/43, and GC20-GC22 along profile 48/42. The resultant geological section (Fig. 15), records the transition from the outer shelf (GC19, 21) to the abyssal plain (GC06).

The shelf samples are dominated by extensively bioturbated skeletal sands containing bryozoa, foraminifera and pelecypods. Rapid deposition and bioturbation have destroyed most internal structure, resulting in thick homogeneous, olive grey units (Fig. 16). Apart from a higher than normal gravel fraction and a lower than normal mud fraction near the surface, there is little variation in grainsize down the core. In general it contains about 5% gravel, 60% sand, 10% coarse silt and 25% mud. The carbonate fraction remains remarkably constant at 70-75%.

Southward, down the slope, the sand fraction is rapidly lost and foram/nanno oozes dominate. This lithological change is accompanied by a change from intensely bioturbated units to those displaying _Zoophycos_-type and unidentified burrows, which gives the sediment a mottled appearance. Bioturbation is lacking in the deepest cores (GC06-08), and internal banding is present. Lithological variation between the bands is slight (the darker bands appear to contain slightly more clay than the lighter bands), and its recognition is primarily on alternation of colour. In the deepest cores, banding is cyclic and may represent climatic or other long term cycles.

A thin turbidite unit occurs at a similar depth in several cores and a tentative correlation has been made (Fig. 15). The turbidite is apparently a chronostratigraphic unit. It is overlain by increasingly less sediment in deeper-water cores, reflecting slower rates of sedimentation towards the abyssal plain. Its absence in GC07 and GC08, and the presence of four 'turbidite' events in GC06 from the base of the slope, suggests that GC06 has a different source area for part of

LITHOLOGICAL SYMBOL



SYMBOL

Y	*Yellow, oxidised surface, Munsell colours* 5Y7/3, 5Y7/2, 5Y6/3 2·5Y7/2, 2·5Y6/4, 2·5Y6/2 10YR8/6, 10YR7/3, 10YR6/4
G	*Grey, Munsell colours* 5Y7/2, 5Y7/1, 5Y6/2, 5Y6/1, 5Y5/1 5GY7/2, 5GY7/1, 5GY6/1
O	*Olive, Munsell colours* 5Y5/4, 5Y5/3, 5Y5/2 5Y4/4, 5Y4/3, 5Y4/2, 5Y4/1 5GY5/1, 5GY4/1
v v v v	*Volcanic ash layer*
M	MIOCENE
LM	LOWER MIOCENE
LO	LOWER OLIGOCENE
LE	LOWER EOCENE

23/OA/80

Fig. 12. Key to all core logs.

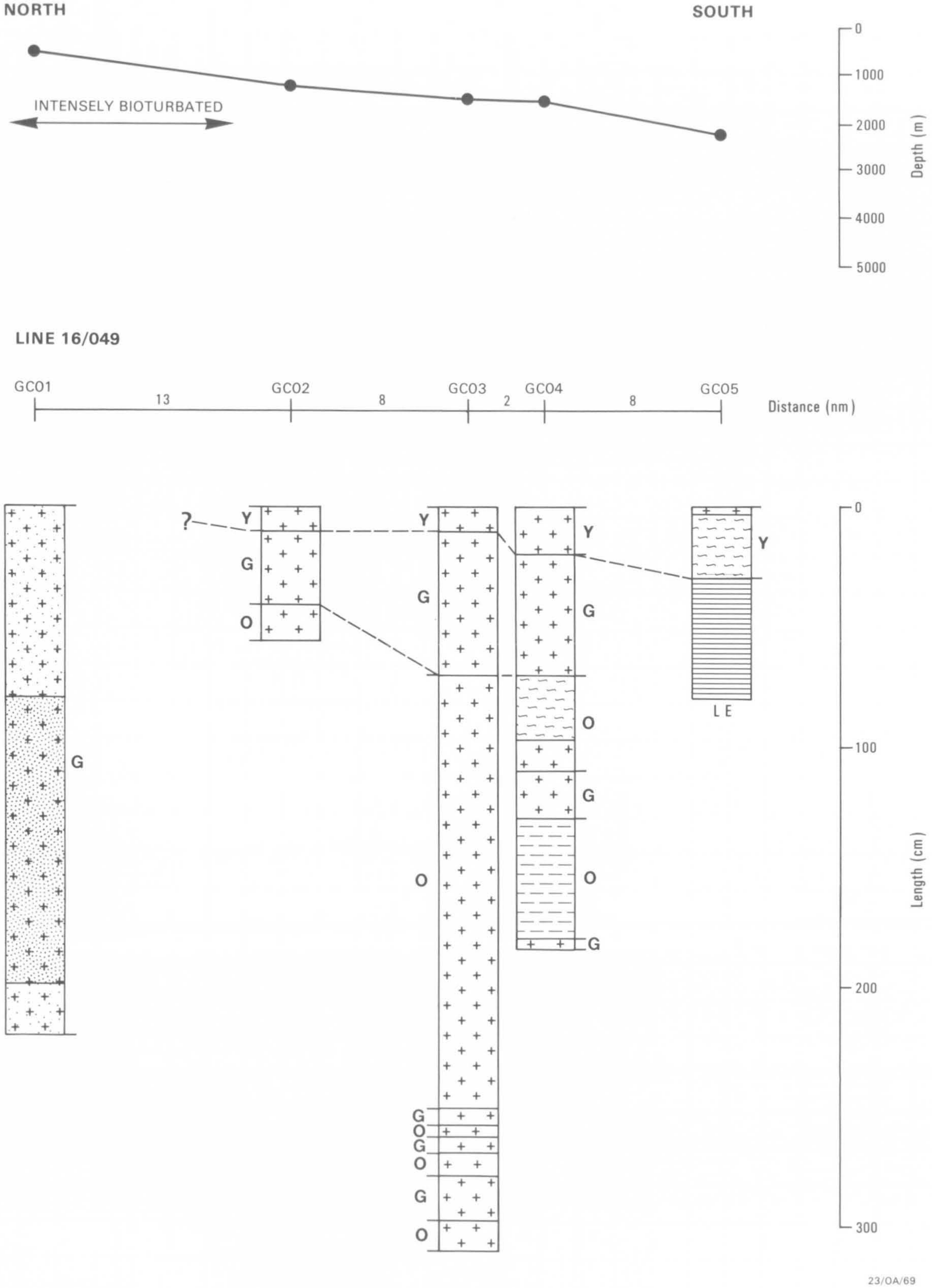


Fig. 13. Cores GC01-5, on BMR seismic line 16/49, west of Beachport. Location on Figure 1. Refer to Figure 12 for key.

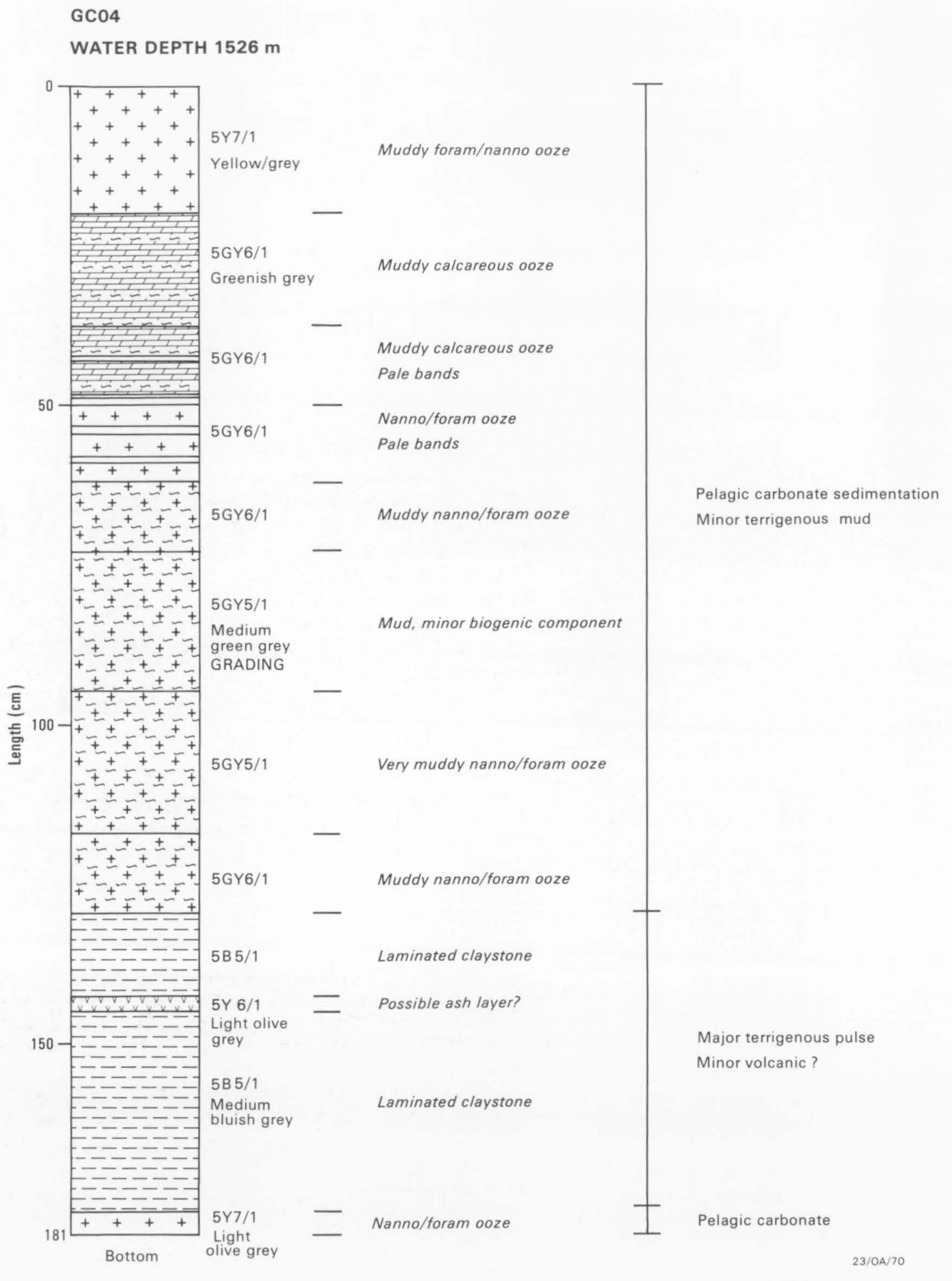


Fig. 14. Detail of Core GC04 on upper slope, west of Beachport.

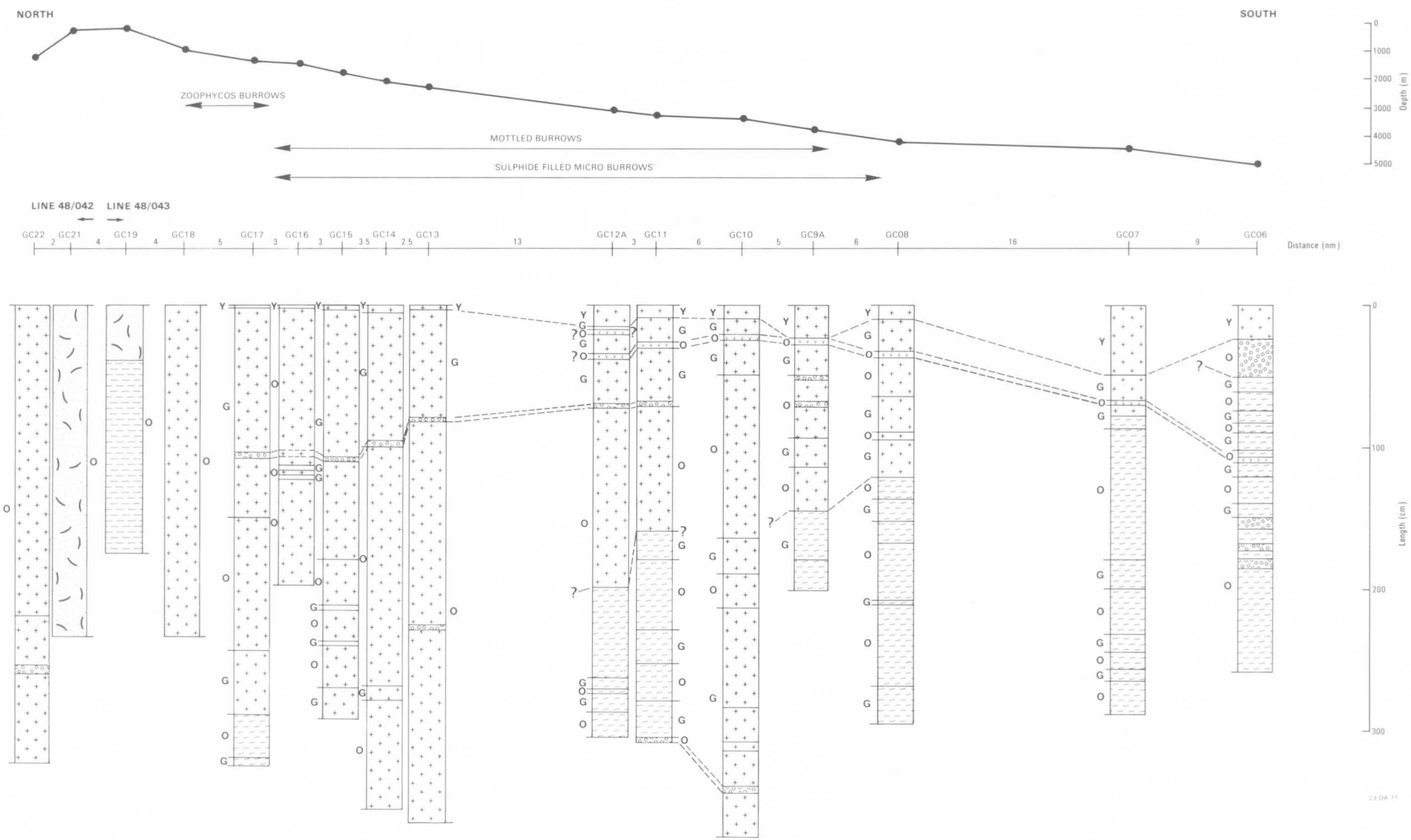


Fig. 15. Cores GC06-22 on BMR seismic lines 48/42 and 48/43, from shelf to abyssal plain south of Beachport.

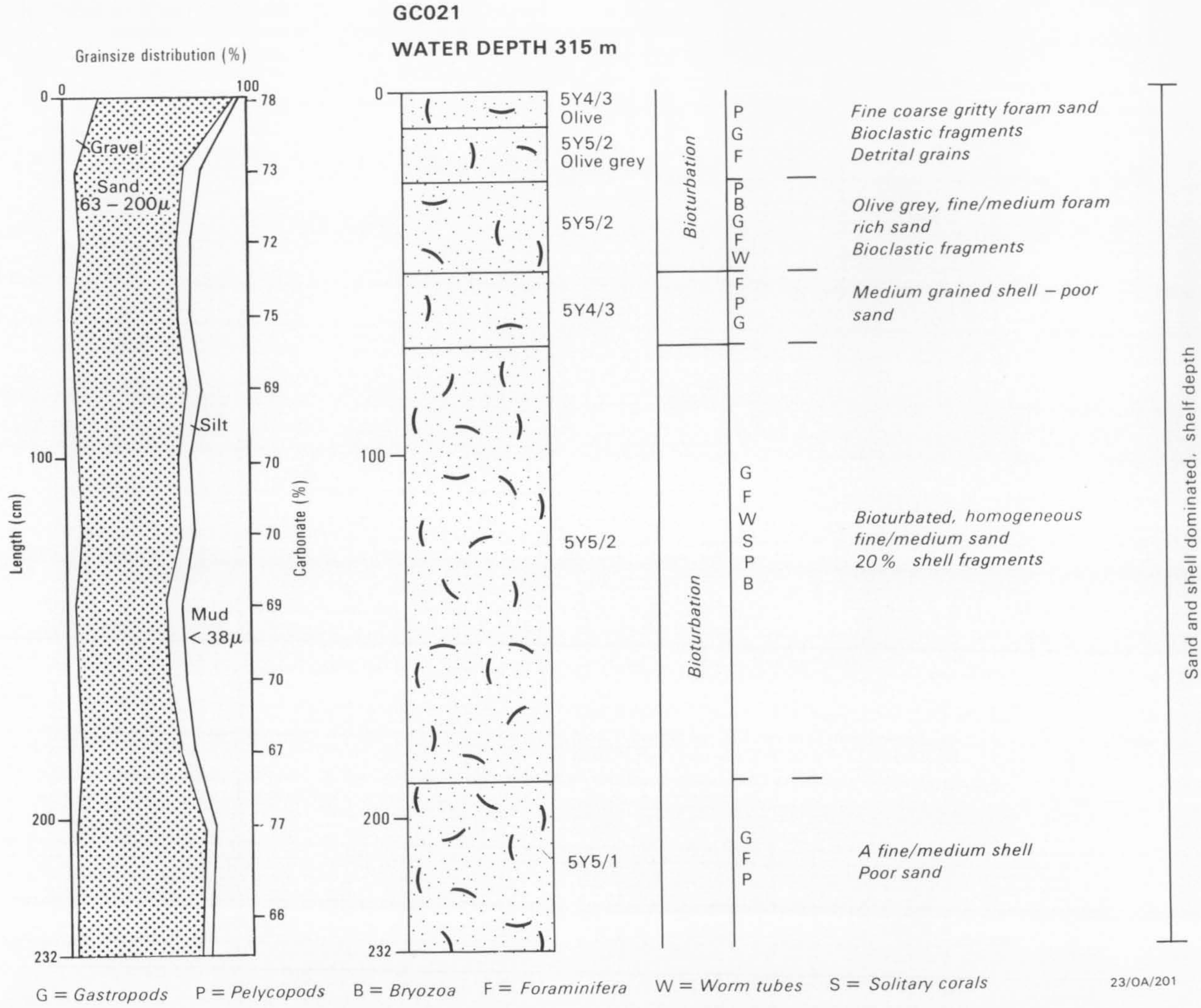


Fig. 16. Detail of homogeneous outer shelf core GC21, from south of Beachport.

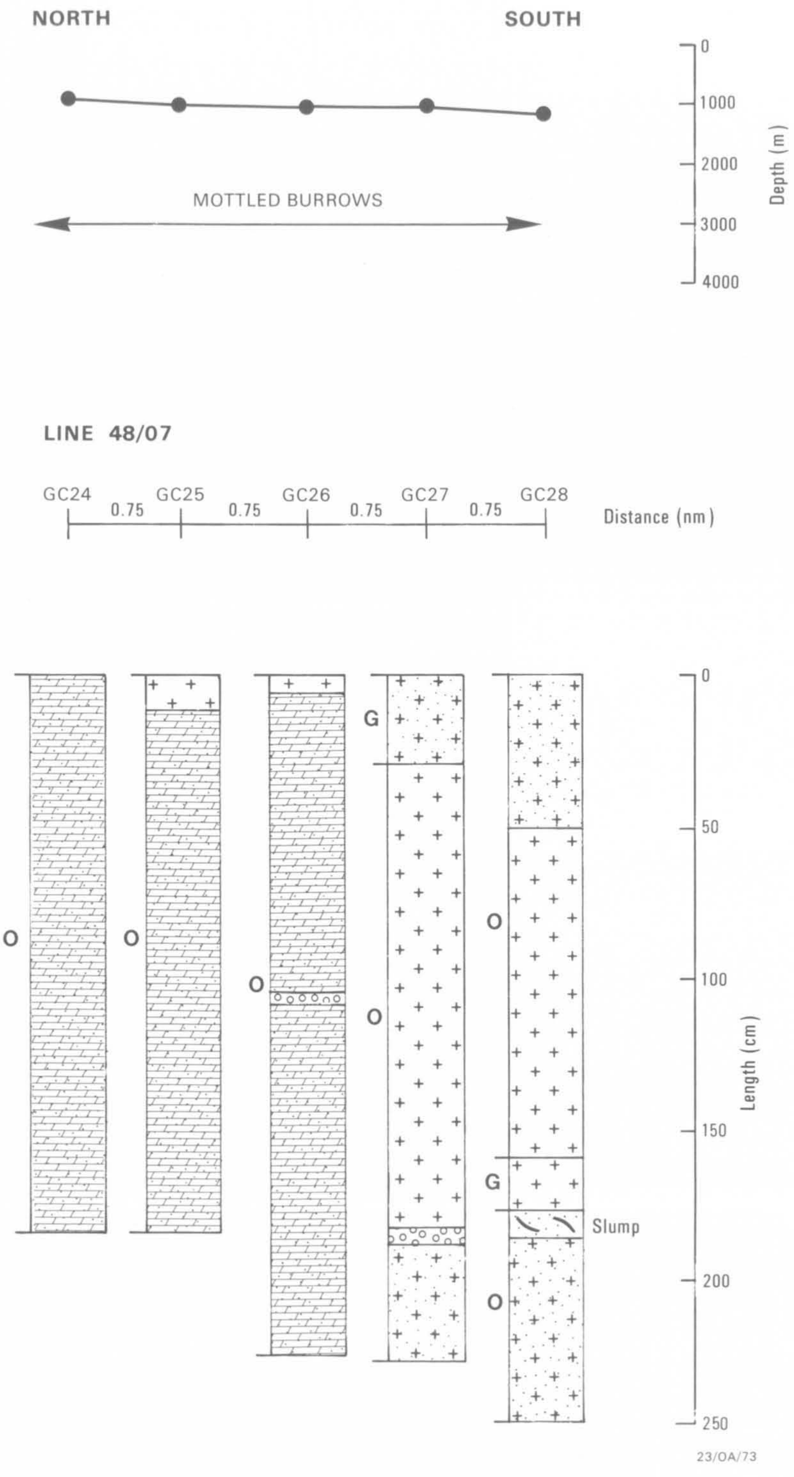


Fig.17. Upper slope cores GC24-28 on BMR seismic line 48/07 south of Portland.

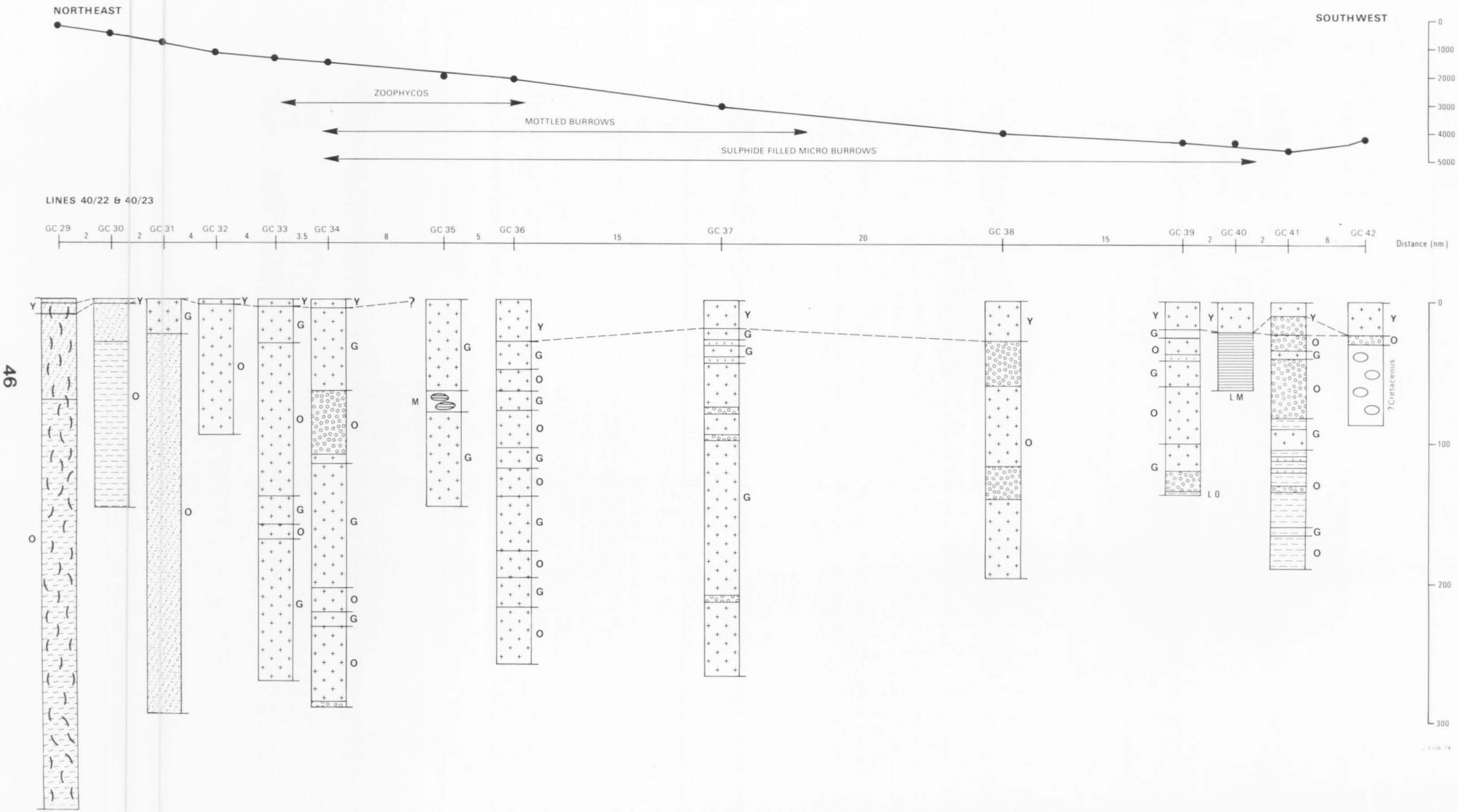


Fig. 18. Cores GC29-42 on BMR seismic lines 40/22 and 40/23, from shelf to continental rise off King Island.

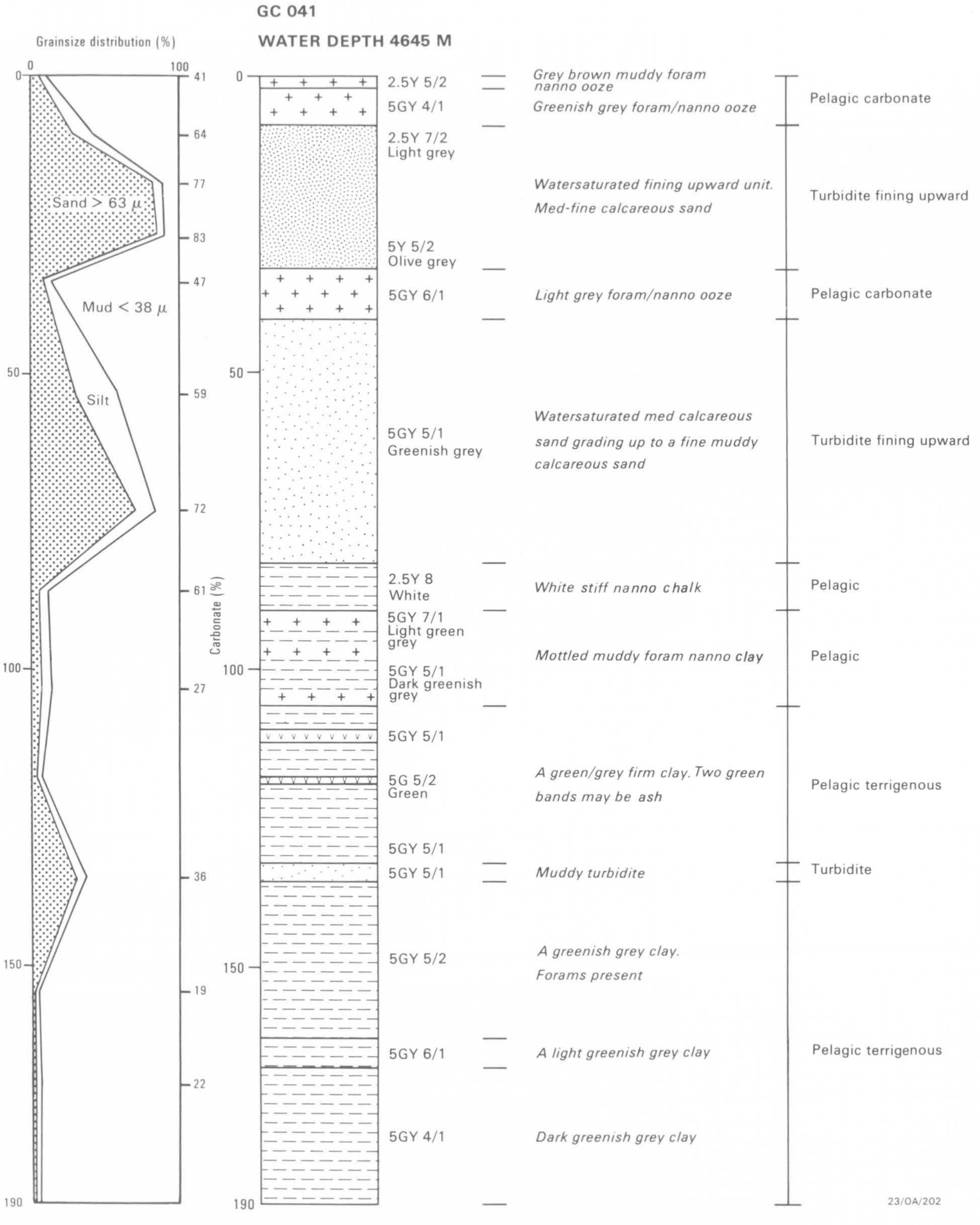


Fig. 19. Detail of core GC41 from continental rise west of King Island, showing unusual lithological variation. Location on Figure 2.

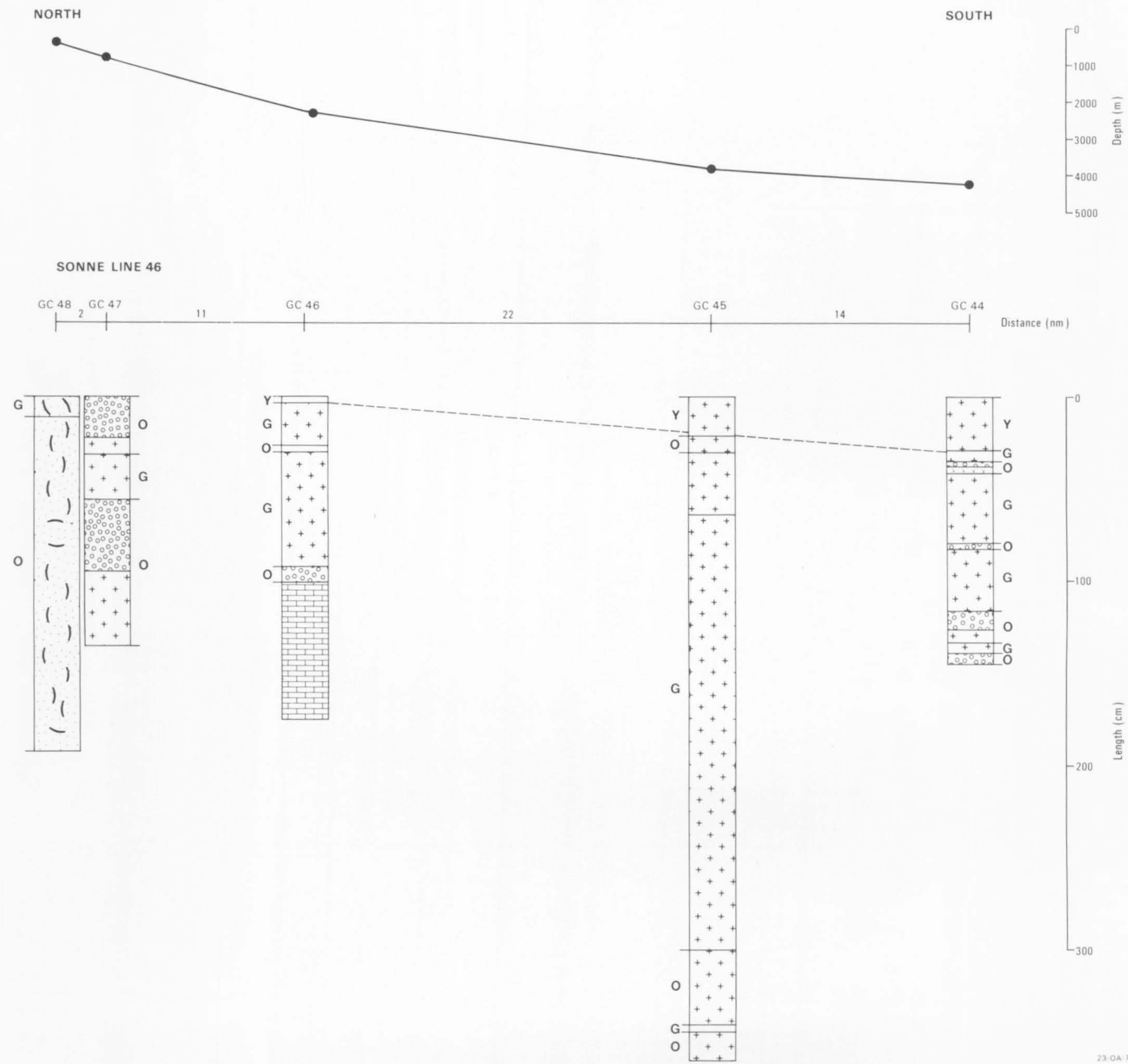


Fig. 20. Cores GC44-48 on Sonne seismic line SO36/46 west of Cape Sorell, from shelf to continental rise.

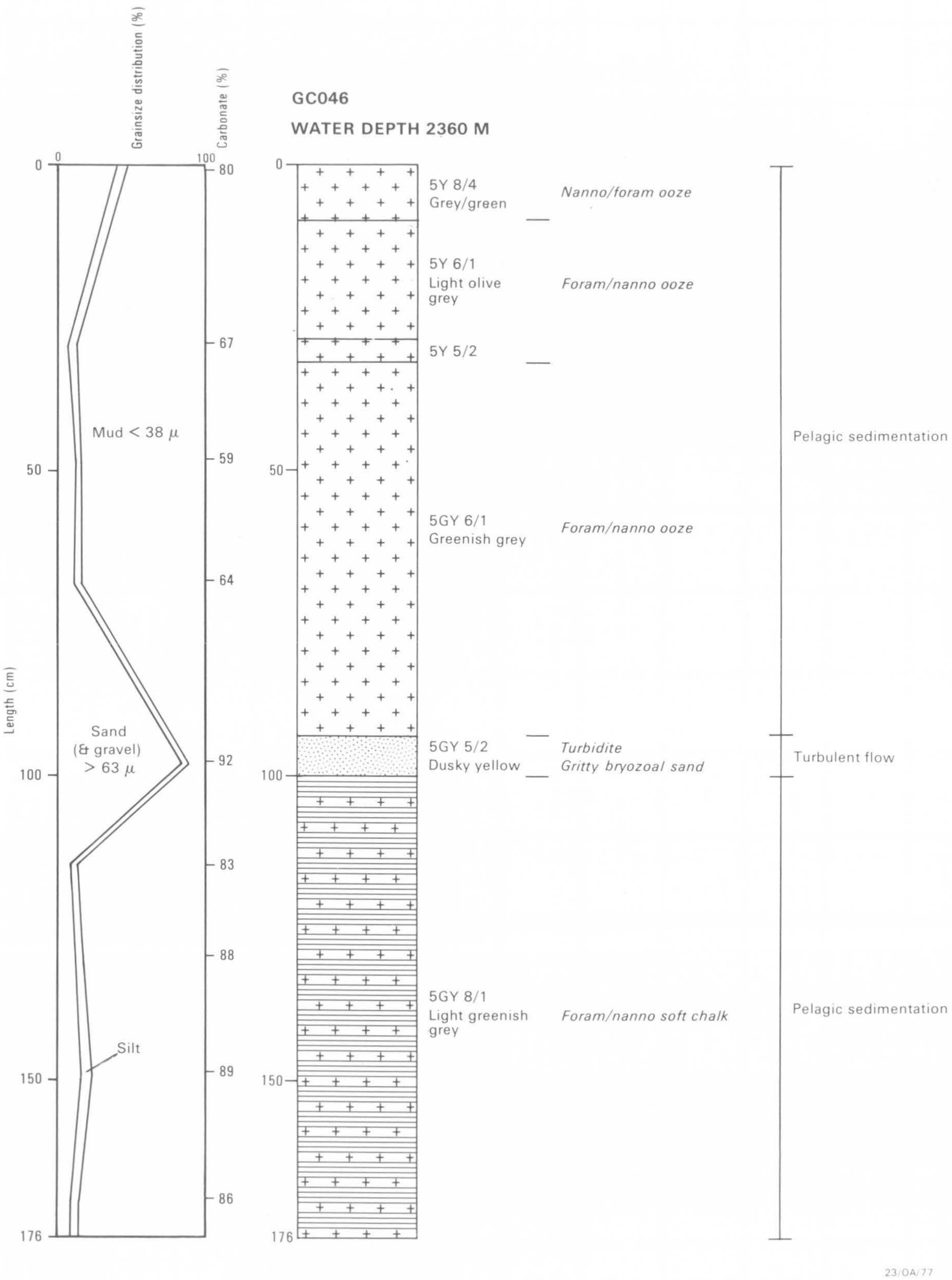


Fig. 21. Detail of Core GC46 from the mid-slope west of Cape Sorell.

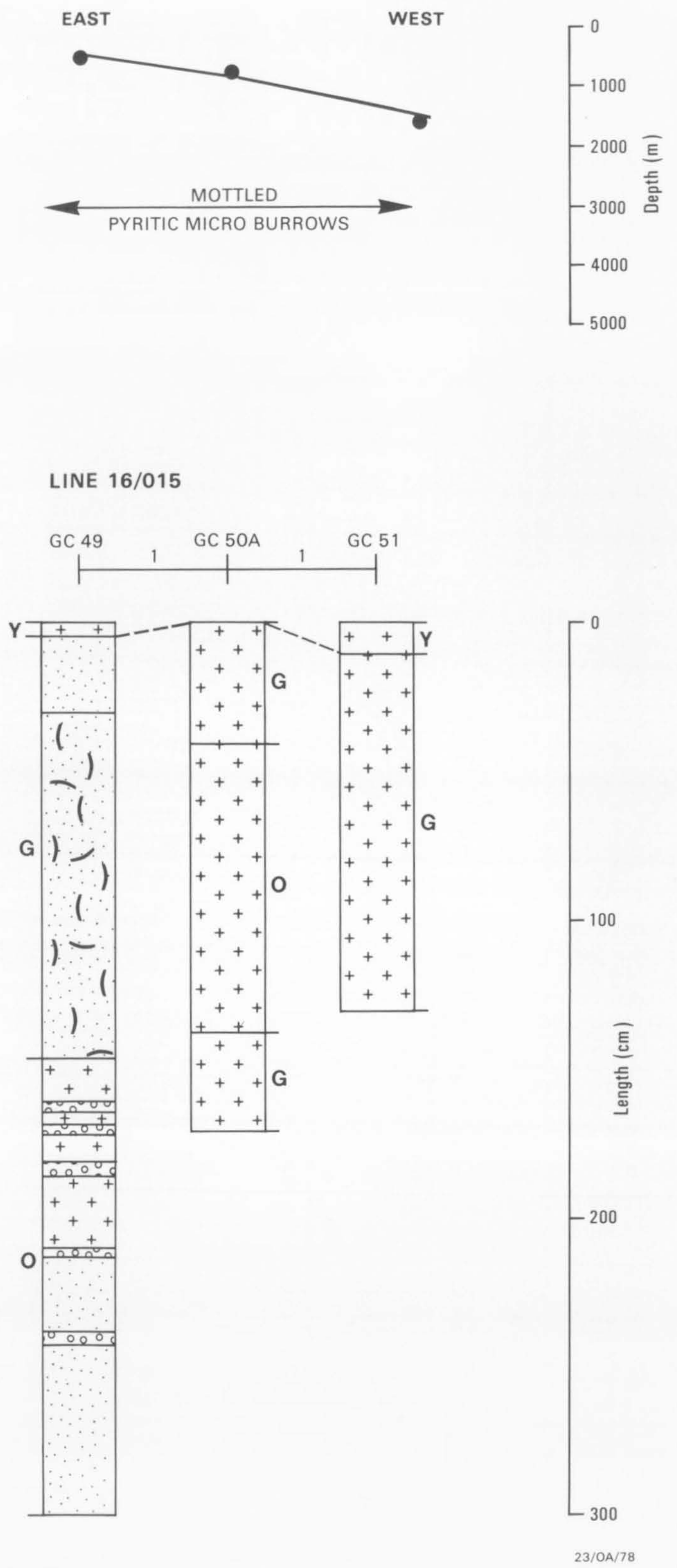


Fig. 22. Cores GC49-51 on BMR seismic line 16/15 on outer shelf and upper slope off northwest Tasmania.

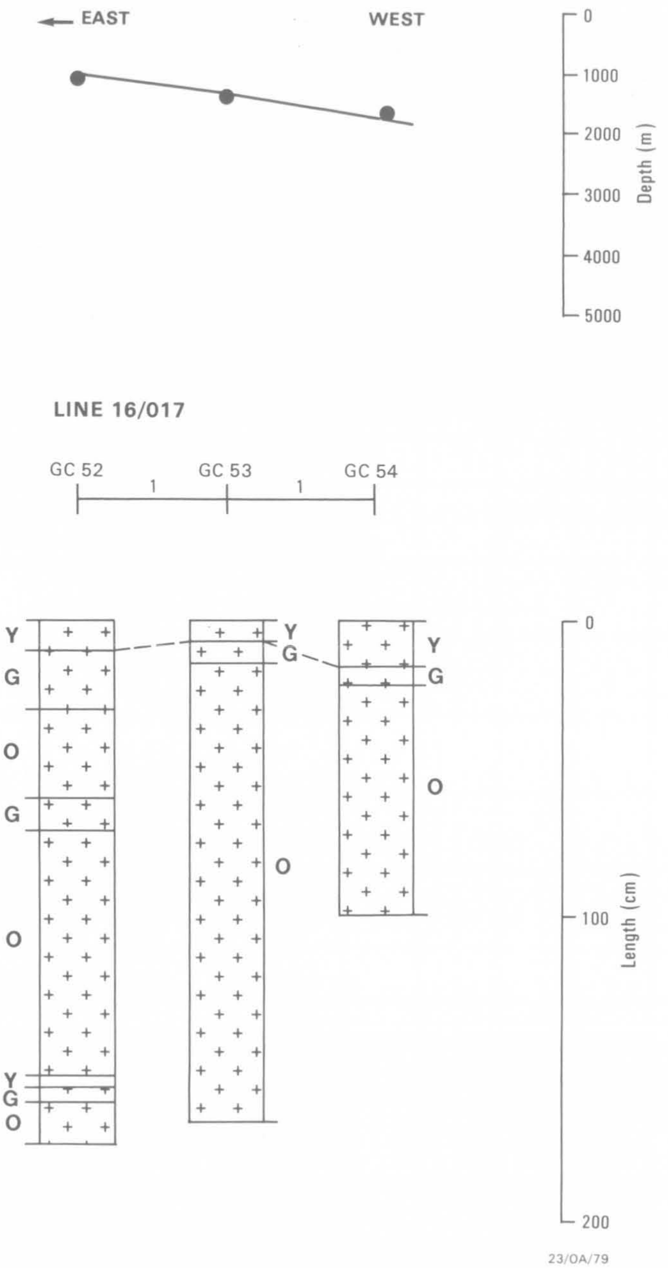


Fig. 23. Cores GC52-54 on BMR seismic line 16/17 on upper slope off northwest Tasmania. GC54 is Late Oligocene at base.

its sediment.

A thin brown or green horizon, present in the upper parts of cores GC06-12A, may represent a volcanic ash horizon and is thus potentially dateable.

An oxidised surface layer appears first at a water depth of 1490 m (GC19), and increases in thickness downslope. Its absence above 1500 m may relate to presence of an oxygen-minimum zone.

The lower sections of GC06-GC08, GC12A and GC13, are dominated by olive and greenish grey muds. Such muds become more important in the deeper cores. It is suggested that the muds may represent a phase of sedimentation dominated by terrigenous material, in contrast to the overlying phase dominated by carbonate, or may relate to leaching of carbonate below the CCD.

The base of GC09A (203-213 cm) consists of firm, brown middle Eocene restricted marine mud (Appendix D). GC12 recovered 10 cm of open marine peaty siltstone, of Middle Eocene age (Appendix D).

Mid Otway Basin

This region off Portland is represented by GC24-GC28, along the seismic line 48/07. All cores are from the region of the outer shelf (Fig. 17). Sedimentation is dominated by fine sandy oozes and bioturbation is extensive so internal banding is rare. GC24 and GC25 contain a homogenous unit almost two metres thick. There is no surface oxidised layer, suggesting that all the cores, which are in water depths of 400-550 m, lie within the oxygen-minimum zone.

Eastern Otway Basin

The eastern Otway Basin off King Island is represented by GC29-GC41 along BMR seismic profile 40/22-23, and GC42 along profile 40/24. The geological section (Fig. 18) shows a transition from outer shelf to abyssal plain.

The shallowest core (GC29) records a relatively high-energy style of sedimentation dominated by olive grey shelly muds and oozes. The shelly component is typically shelf-derived bryozoal, coral, pelecypod, and gastropod fragments up to 1 cm in diameter, which together make up 20-30 percent of the sediment. The shelly material rapidly decreases downslope, and GC30-GC31 are typically olive and olive-grey fine sands and fine sandy calcareous oozes. These cores are extensively bioturbated, the result being thick homogeneous units. Further downslope (GC32-42) pelagic foram/nanno oozes dominate. Below about 1000 m, the bioturbators change to <u>Zoophycos</u> and the generators of mottled and small sulphide burrows, and this change is accompanied by an increase in the internal banding of the deeper cores. Compositional variation between bands, as with other sections, generally is not perceptible and banding is an alternation of olive-green and light greenish grey oozes. However, GC41 is unusual in that its banding shows obvious lithological variation (see Fig. 18); greenish grey pelagic clays alternate with foraminifera/nannofossil oozes and the alternation may be climatically controlled.

The volcanic ash layer recognised in profile 48/43 is generally absent, except for two thin bands close to the top of GC27 and at an approximate depth of 110 cm in GC41. The oxidised surface layer thickens downslope into deeper water, and its absence in GC31 probably relates to the position of the oxygen-minimum zone.

GC30 (Fig. 18) has an upper, olive-grey, sandy calcareous ooze, which passes sharply downwards into a firm, dark, greenish grey clay. This contrasts with the carbonate-dominated sedimentation of surrounding cores, and represents a terrigenous-dominated phase. The clay is burrowed at its upper surface.

GC35 (Fig. 18) contains a 20 cm thick unit of medium grey ooze in which grey, calcareous, Early-Middle Miocene mudstone clasts were found. Glauconitic siltstone pebbles up to 3 mm long suggest an original shelf origin for them.

GC39 (Fig. 18) has an upper, banded, greenish grey and olive grey foram/nanno ooze, overlying a coarse sand containing rounded basalt granules. This unit in turn overlies a stiff green clay of Late Oligocene age. It seems likely that erosion of the slope exposed Miocene clays to Quaternary sedimentation.

GC41 (Fig. 19) consists of two thick calcareous turbidite units which overlie well bedded, multicoloured, possibly pre-Quaternary clays. The two turbidite units consist of 70-80% sand at their bases and fine upwards, passing into foram/nanno oozes with less than 10% sand fraction. The carbonate percentage is greater in the sandy lower parts of the turbidites (70-80%), which were clearly derived from carbonate shelf sands, than in the mixed upper parts or the overlying oozes (40-50%). This indicates that the pelagic sediments have a high clayey terrigenous content. The more consolidated sediments beneath 83 cm are chalky at the top, but the carbonate content is low below 90 cm. Most are clays with more than 90% mud fraction, although there is one muddy turbidite within them with 28% sand and 36% carbonate.

In GC42 (Fig. 18), a light grey, soft foram/nanno ooze, overlies a yellow to reddish, mottled gypsiferous soil profile. The presence of a soil profile in over 4000 m of water has important implications for the subsidence of the margin.

West Tasmanian region

Three profiles were successfully cored off west Tasmania.

The first profile, including cores 44-48, lies along the Sonne seismic profile 46 west of Cape Sorell. Figure 20 represents a section from mid shelf (GC48), to lower slope (GC44). GC48, at a water depth of 377 m, consists entirely of an olive-grey, shelly sand, so extensively bioturbated that it forms one thick (190 cm) homogeneous unit. Pelecypod, coral and bryozoal fragments are the dominant components of the shelf fraction.

The shell and sand components rapidly disappear downslope, and the cores become dominated by foram/nanno oozes. Calcareous turbidite units up to 20cm thick are present, but are not correlatable. The deepest cores are only slightly bioturbated and internal banding becomes more important. Lithological variation is slight, and banding consists of an alternation of light greenish grey and darker olive-green units. A weakly developed glass layer is present below a thin, calcareous turbidite in GC44. The surface yellow-brown, oxidised layer, as with other profiles, thickens downslope to reach a maximum of 30 cm in GC44.

GC46 (see Fig. 21) consists of 93 cm of greenish grey, foram/nanno ooze, overlying a thin bryozoal sand turbidite, which in turn overlies a light greenish grey chalk. The ooze is relatively coarse grained near the surface, but generally contains more than 80% mud; carbonate percentage is highest near the surface but is generally 60-65%. The turbidite is more than 80% sand and around 90% carbonate and clearly was derived from the shelf. The foram/nanno chalks at the base are more than 75% mud and 80-90% carbonate and are clearly pelagic sediments with little terrigenous content.

The second profile includes GC49-GC51, and is stationed along BMR seismic profile 16/015 west of Sandy Cape. The geological section, (Fig. 22), shows the transition from outer shelf to mid slope. The outer shelf sample, GC49, consists of skeletal bryozoal sands and olive grey sandy oozes, typical of other outer shelf samples. It is extensively bioturbated and thick homogenous units dominate the core. The sand/shell fraction disappears rapidly downslope and greenish grey foram/nanno oozes dominate.

The third profile includes cores GC52-GC54, along BMR seismic profile 16/017 off Bluff Hill Point. The cores are typical of the middle and upper slope region and are characteristically banded grey and olive-grey oozes (see Fig. 23).

Summary and conclusion

Pre-Quaternary units. Pre-Quaternary sediments were recovered from several cores. Eocene sediment (GC5 and GC12) reflects a terrigenous-dominated phase of sedimentation. The peaty siltstone recovered from GC12 is inferred to be part of a mid Eocene to mid Oligocene unit recorded in DSDP hole 280/282, and Sonne cores SO36/22SL and SO36/30KL. Olive-brown, calcareous clay of Oligocene age may be part of the same formation. Miocene sediments are represented by multicoloured clays (GC41), and slumped, glauconitic mudstone clasts (GC35).

Quaternary. Quaternary sediments, dominated by calcareous sands and foram/nanno oozes, were deposited throughout the area. From plotted geological cross-sections, trends in shelf-to-abyssal-plain sedimentation have been established and a model of sedimentation along this margin is proposed.

Trend from shelf to abyssal plain. 1) In-situ lithology changes rapidly downslope, from outer shelf shelly sands and sandy oozes with more than 70% carbonate, to slope foram/nanno oozes with about 60-65% carbonate, and finally to rise and abyssal plain oozes with less than 50% carbonate. The sand fraction declines in parallel: about 60% in shelf sands, 10-15% in mid slope oozes, and less than 10% in rise oozes. 2) Calcareous turbidites, generally absent on the shelf, are found in slope and abyssal plain cores. The coarser fraction of these turbidites contains 70-80% carbonate and is derived from the shelly shelf sands. A thin turbidite is tentatively correlated between cores along profile 48/043 (Fig. 15), and is overlain by a decreasing amount of sediment downslope, suggesting slower rates of deposition towards the abyssal plain. 3) A yellow-brown surface-oxidised layer, generally absent in the outer shelf cores, increases in thickness downslope. Its presence is related to oxygen-enriched cold bottom waters. 4) A thin green or brown band present in many cores is probably a volcanic ash layer and is thus potentially dateable. 5) Cores from the shelf consist of thick bioturbated, homogeneous units. Internal banding becomes more important downslope, as bioturbation decreases. Lithological variation between bands is generally slight (except in GC4), and is recognised by the alternation of light greenish grey and darker olive-green colours. The banding is probably cyclic and may be climatically related. 6) The style of bioturbation changes with water depth. Outer shelf cores are extensively bioturbated and preserve little internal structure. Below about 1000 m, bioturbation decreases and internal banding becomes increasingly preserved. Sediments are generally mottled, and contain infilled horizontal Zoophycos and other burrows. Zoophycos seems restricted to 1000-2500 m. Below about 4000 m mottling is absent, and the only evidence of bioturbation is the presence of small (1 mm diameter), sulphide-filled burrows.

Model of sedimentation. Shelf areas are characterised by relatively high-energy deposits: shelly bryozoal sands and fine sandy oozes. These sediments are dominantly calcareous, and most likely sourced by a middle to outer shelf 'carbonate factory', dominated by bryozoa, pelecypods, gastropods and benthic foraminifera. There is extensive bioturbation by a relatively large infauna giving thick homogeneous units. Shelf sands periodically move downslope as turbidity currents, but their contribution to overall slope and abyssal plain sedimentation is generally slight.

Slope and abyssal areas are dominated by pelagic and hemipelagic carbonates, typically olive-grey and greenish grey, foraminiferal and nannofossil oozes. Terrigenous clays and muds, sourced from coastal areas, are present only in small amounts. Variations in the terrigenous component appear to be cyclic, and may be climatically controlled. Bioturbation decreases downslope, and the cores are typically banded.

Recent volcanic eruptions, possibly in the Mount Gambier region, deposited fine ash layers over the area of sedimentation sampled on this cruise.

GRAB SAMPLES

N.F. Exon, E.A. Felton, C. Wilson, A. Stephenson

It was important to have shelf samples, as part of the profiles from shelf to deep water, in the search for thermogenic gas, and to a minor extent in the search for phosphate.

It had been hoped that the 7 m vibrocorer could be used at key shelf stations, but it proved too difficult to deploy. The gravity corer was used on the outer shelf at station GC20, where the water depth was 166 m, but did not penetrate sandy bottom. However, this corer was successfully deployed in water depths of more than 300 m, where sands were generally fine-grained or muddy. The dredge was used at one shelf station but was too cumbersome for widespread use in shallow water.

Because of the lack of reasonable alternatives, the van Veen grab was deployed at almost all shelf stations, from the hydrographic winch. It was successful at virtually all stations, only failing where there was hard outcrop at the sea bed. Altogether it was used at 33 stations, in water depths of 34 to 450 m, with the bulk of stations in depths of 60 to 200 m (Table 4). Their locations are shown in Figures 1 and 2, and a brief description of natural groups of samples follows.

Nine grab samples (GS2A-10) were taken in shallow water (20-204 m) on seismic profiles 48/042 and 48/043, south and southwest of Lake Bonney near Argonaut No. 1 well off South Australia. Those in the shallowest water (5 & 6) showed that there was rocky bottom - probably Miocene limestone - covered in kelp and sponges. Beyond this, in water depths of 67 to 123 m, was coarse brownish bryozoal sand and grit (3, 4, 7, 8, 9), containing varied but subordinate quantities of sponges, gastropods, pelecypods, algae, echinoids, solitary corals, and encrusting serpulids. Quartz and rock fragments were virtually absent. The two deepest samples (2A, 10) are somewhat finer grained and consist of abraded fragments of the same organisms, with a smaller proportion of bryozoa.

Nine samples (GS15-23) were taken in water depths of 50 to 100 m south of Port Macdonnell, in an area where propane anomalies had been recorded in the water column and gas plumes identified by sidescan sonar in 1980 (Shoreline Exploration Company, 1983). The shallowest stations (22, 23), in water less than 75 m deep, recovered very little sediment and were probably situated on hard bottom. One contained abundant sponges and other organisms, and a little relatively fine-grained sand consisting of abraded shell and bryozoal material. The others contained either coarse bryozoal sand or grit, or well-sorted, medium to coarse grained carbonate sand dominated by fragments of bryozoa and shells.

Four samples (GS11-14) were taken off Portland in the search for a possible shale diapir and a gas anomaly, both identified on seismic sections provided by Phillips Petroleum Company. Water depths were 45

Table 4: Grab stations

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm or weight)	Description or comments
GS01	$37^{\circ}05.00'$	$138^{\circ}34.8'$	118	16/049	15 cm	Yellow-grey v.c. gritty carbonate sand
GS2A	$38^{\circ}04.7'$	$140^{\circ}13.5'$	163	48/043	10 cm	Brownish c. calcareous sand
GS03	$38^{\circ}02.1'$	$140^{\circ}16.0'$	123	48/043	5 cm	Brownish c. bryozoal sand
GS04	$37^{\circ}59.1'$	$140^{\circ}17.7'$	69	48/043	20 cm	Brownish bryozoal grit
GS05	$37^{\circ}57.0'$	$140^{\circ}20.3'$	27	48/043	1 cm	Lithified sand, kelp, sponges = rocky bottom
GS06	$37^{\circ}58.4'$	$140^{\circ}19.4'$	20	48/043	-	Kelp only = rocky bottom
GS07	$37^{\circ}55.7'$	$140^{\circ}14.0'$	67	48/042	10 cm	Brownish c. bryozoal sand
GS08	$37^{\circ}56.5'$	$140^{\circ}08.8'$	88	48/042	1 cm	Brownish c. bryozoal sand
GS09	$37^{\circ}56.4'$	$140^{\circ}8.6'$	100	48/042	20 cm	Brownish bryozoal grit
GS10	$37^{\circ}58.2'$	$140^{\circ}05.3'$	204	48/042	10 cm	Olive-brown f-c. carbonate sand
GS11	$38^{\circ}27.05'$	$141^{\circ}33.74'$	45	OP80/51	1 cm	Brown gritty bryozoal sand, abundant sponges
GS12	$38^{\circ}28.23'$	$141^{\circ}33.58'$	60	OP80/53	1 cm	Brown c. bryozoal sand, abundant sponges
GS13	$38^{\circ}28.30'$	$141^{\circ}32.68'$	60	OP80/53	1 cm	Brown gritty bryozoal sand, abundant sponges
GS14	$38^{\circ}28.62'$	$141^{\circ}32.40'$	70	OP80/53	1 cm	Brown gritty bryozoal sand, abundant sponges
GS15	$38^{\circ}13.58'$	$140^{\circ}37.96'$	100		20 cm	Light grey bryozoal grit
GS16	$38^{\circ}13.5'$	$140^{\circ}43.04'$	95		30 cm	Light-olive-grey carbonate sand
GS17	$38^{\circ}13.5'$	$140^{\circ}43.9'$	94		30 cm	Light brownish grey bryozoal grit
GS18	$38^{\circ}13.75'$	$140^{\circ}42.6'$	95		30 cm	Light brown c-v.c. carbonate sand, well sorted
GS19	$38^{\circ}13.45'$	$140^{\circ}43.2'$	94		30 cm	" " " " " " "

Table 4 (contd)

Station	Latitude	Longitude	Water depth (m)	Seismic profile	Recovery (cm or weight)	Description or comments
GS20	38°13.50′	140°43.5′	97		20 cm	Light brown, well sorted m. carbonate sand
GS21	38°13.8′	140°43.5′	89		15 cm	Light grey f-m carbonate sand
GS22	38°13.4′	140°47.3′	50		-	Probably hard bottom, two attempts
GS23	38°13.3′	140°49.5′	74		1 cm	Light brown f-m carbonate sand, abundant sponges
GS24	39°05.84′	143°19.9′	34	16/029	100g	Black, fresh basalt
GS25	39°06.3′	143°19.1′	38	16/029	10g	Weathered basalt
GS26	39°30.0′	143°01.0′	110	40/22	200g	Light brown c. bryozoal sand
GS27	39°32.0′	143°00.0′	180	40/22	5kg	Light brown m-c calcareous sand
GS28	40°02.0′	143°13.2′	450		500g	Yellow m. calcareous sand
GS29	42°10.0′	144°50.1′	156	Sonne 46	5kg	Light brown muddy, m-c bryozoal sand
GS30	42°09.0′	144°55.0′	134	Sonne 46	500g	Ferruginous light brown ?phosphatic shelly concretions
GS30A	42°08.9′	144°55.0′	135	Sonne 46	5kg	Light brown f-m. calcareous sand
GS31	42°08.0′	145°01.0′	100	Sonne 46	8kg	Yellowish brown v.c. bryozoal sand and gravel
GS32	41°30.8′	144°25.1′	294	6/015	6kg	Pale olive m-c bryozoal sand
GS33	41°10.6′	144°08.1′	203	16/017	30kg	Olive-brown muddy m-v.c. bryozoal sand

NB: For sands f = fine, m = medium, c = coarse, v c = very coarse.

to 70 m, and small quantities of sediment and abundant sponges suggest hard bottom. The sediment is coarse to gritty bryozoal sand containing forams, echinoid spines, large bivalves, encrusting serpulids and algal crusts.

Two samples (GS24, 25) were taken from a submerged volcano off Cape Otway (Gill & Segnit, 1986), and consist of fresh and weathered basalt.

Nine stations (GS26-33) were located off King Island and western Tasmania in water depths of 110 to 450 m. Those in shallower water (26, 31) recovered coarse brown bryozoal sands with some corals and pelecypods. The other samples are largely medium to coarse grained carbonate sands, with bryozoa generally dominant, and minor pelecypods, forams, brachiopods, and solitary corals. Several contain considerable mud, and one (30) contains ferruginous and possibly phosphatic concretions.

Overall, the shelf sands could be readily matched with the sands in turbidites in deep water, which are predominantly of bryozoal origin.

HEATFLOW

C.S. Lee, C. Penney

Objectives

The objectives of the heatflow study in the Otway/Tasmania cruise were to examine the present-day heatflow distribution along this complex rifted continental margin, and to apply the results to establish the maturation geohistory of the various stratigraphic sequences and relate it to the deep crustal structure. Two heatflow transects were carried out - along seismic profile BMR48/43 on the offshore Otway margin and SO36/46 on the west Tasmanian margin.

Thermal gradient measurement

Thermal gradient measurements were attempted at 20 stations (Figs. 1 and 2) during the Otway/Tasmania cruise by using the Nichiyu Giken NTS-11 heatflow instrument. This instrument contains an electronic package which can be utilised for up to 15 hours of continuous measurement, eight thermistors which are evenly spaced on a 3-m expendable lance, and a personal computer system for data handing and processing. A more detailed description of the NTS-11 heatflow instrument can be found in the 1985 BMR heatflow cruise report (Choi & others, 1987).

During the survey, we used two different types of thermistor lance. One was the conventional 4-cm diameter lance, which was subject to bending in the middle and was difficult to straighten back to a re-useable condition. The other, a new design by BMR technical officer Peter Walker, has three vanes mounted on the lance, which protect the thermistors during deployment and increase the weight and hence penetration. The new lance bent less, and removing this bending, at a designed weak point, was much easier than for the conventional lance. The improvements enabled the pogo technique of heatflow measurement to be tried for the first time on a BMR cruise.

The heatflow probe penetrated at least two to three times at each station (station-pogoing) except at station 2. These multiple penetrations have shown the data to be repeatable and thus have increased our confidence in the data (Table 5). An attempt at profile-pogoing with the heatflow probe was made at stations 12-16 along a 15-km profile, with a slow ship speed of 2 knots. This attempt was not successful, due to the number of reliable thermistors being reduced eventually to two, and tilts being as high as 40°. A careful

Table 5: Preliminary heatflow results of the Otway/Tasmania cruise

STATION	LAT.	LONG.	WATER DEPTH (M)	NO. OF SENSORS WHICH PENETRATED	THERMAL GRADIENT ($^{\circ}C/Km$)	CORE NO.	CONDUCTIVITY (W/m.K)	HEATFLOW (mW/m^2)
ALONG SEISMIC LINE BMR 48/43								
HF/02	$39^{\circ}27.8$	$139^{\circ}58.7$	4905	7	96.0	GC/06	0.73	67.20
HF/03	$39^{\circ}18.3$	$139^{\circ}58.9$	4090	7	59.0	GC/07	0.73	43.07
HF/04	$39^{\circ}12.3$	$139^{\circ}59.3$	4330	7	56.0	GC/07	0.73	40.88
HF/05	$39^{\circ}08.4$	$140^{\circ}00.4$	4333	7	55.0	GC/08	0.73	40.15
HF/06	$39^{\circ}02.2$	$140^{\circ}02.6$	4010	7	77.5	GC/08	0.73	56.58
HF/07	$38^{\circ}51.0$	$140^{\circ}06.0$	3307	7	83.0	GC/10	0.79	65.57
HF/08	$38^{\circ}39.6$	$140^{\circ}07.5$	2691	7	28.5	GC/13	0.82	23.37
				7	37.0	GC/13	0.82	30.34
HF/09	$38^{\circ}33.4$	$140^{\circ}07.7$	2623	7	58.0	GC/13	0.82	47.56
HF/10	$38^{\circ}27.7$	$140^{\circ}10.2$	2463	6	84.5	GC/13	0.82	69.29
ALONG SEISMIC LINE SONNE 36/46								
HF/17	$42^{\circ}14.0$	$143^{\circ}32.0$	4100	7	54.5	GC/44	0.76	41.42
				5	44.	GC/44	0.76	33.44
HF/18	$42^{\circ}14.0$	$143^{\circ}53.0$	3720	6	38.5	GC/45	0.82	31.57
				6	44.5	GC/45	0.82	36.49
HF/19	$42^{\circ}12.0$	$144^{\circ}25.0$	2340	5	25.5	GC/46	0.83	21.17

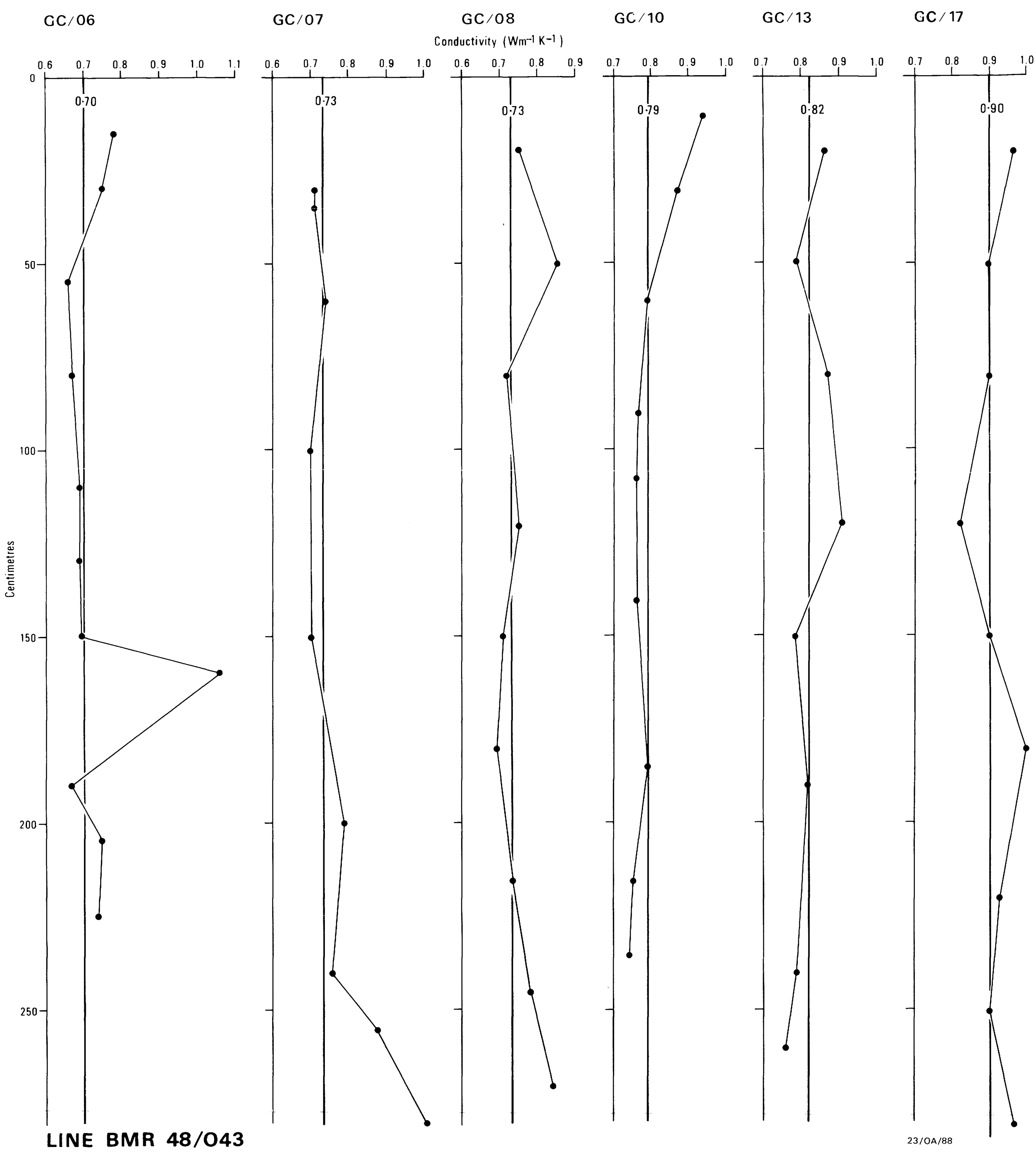
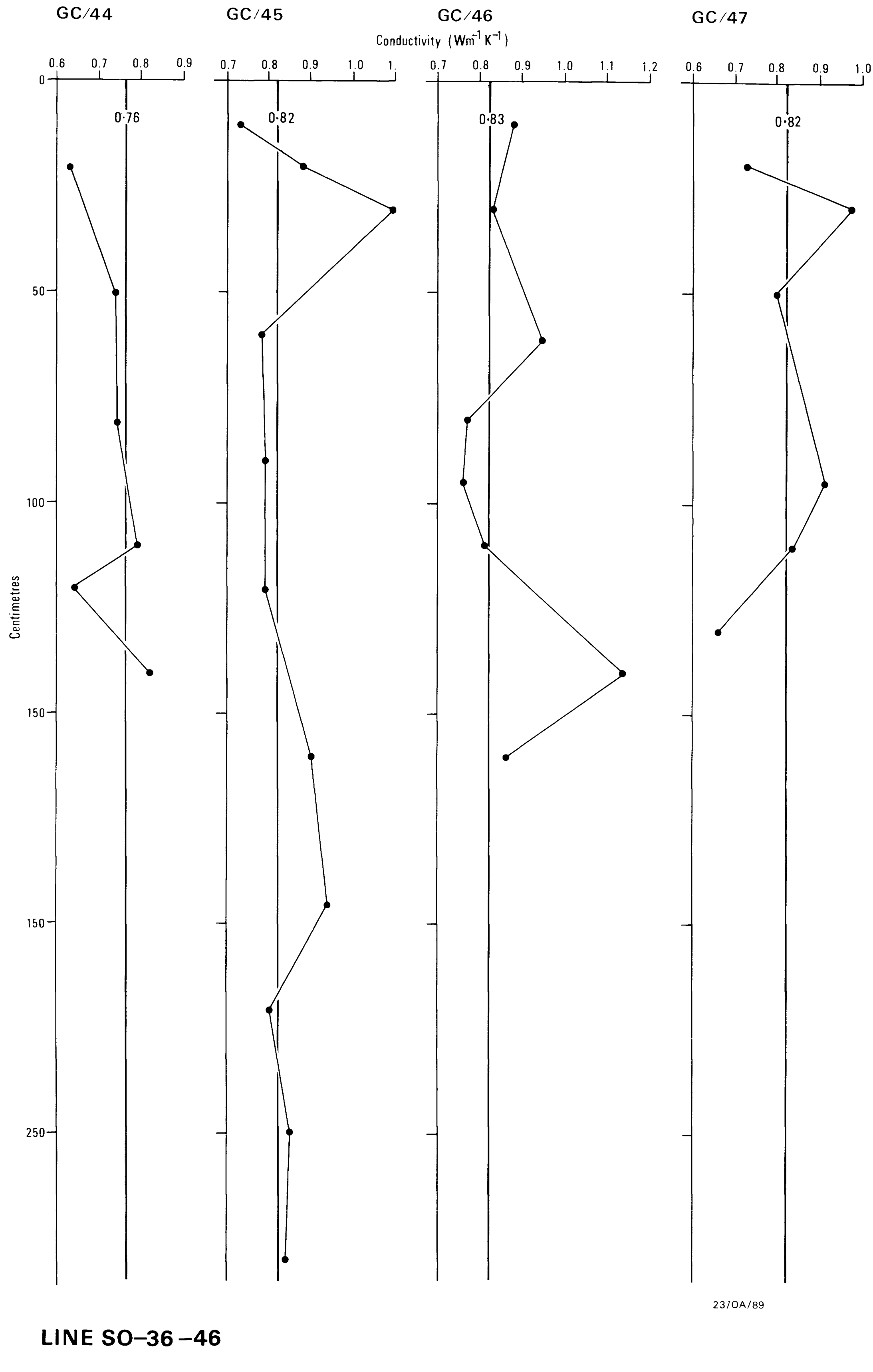


Fig. 24. Conductivity measurements of sediment cores along seismic line BMR 48/43.



LINE SO-36-46

Fig. 25. Conductivity measurements of sediment cores along seismic line SO36/46.

treatment of this dataset may still give useful information.

Station 20 was in relatively shallow water (795 m), where the fluctuation of bottom water temperature may cause fluctuations in temperature in the sediment. Until we have a substantial shallow water dataset, gathered over a long period of time, it is difficult to quantify this type of error. Station 1 failed owing to a faulty battery unit.

Thermal conductivity measurement

The thermal conductivities of the sediments were determined by needle-probe measurements (von Herzen & Maxwell, 1959) on ten gravity cores ranging from 1.5 to 3 m long (Figs. 24 and 25). Most of the cores used for conductivity measurement were either on a station where a gravity core was also taken, or on the same structure and within a distance of less than 20 km, thus ensuring relevant values. A measurement was made in every representative lithology, after cores had been equilibrated at room temperature for at least 24 hours.

The conductivity measurements showed relatively little variation and were in the range of 0.70-1.05 W/m/^{o}K. High values of 1.00 W/m/^{o}K and above were obtained from some very coarse quartz-rich turbidite sands, and also from compacted and apparently much older sediments, such as Palaeogene peaty siltstone. In general, the mean conductivity values increase from 0.73 W/m/^{o}K in deep water to 0.90 W/m/^{o}K in shallow water. The variations are thought to be related to sediment type, porosity and grainsize.

Results

The primary shipboard heatflow values were simply calculated from the product of measured thermal gradients and sediment conductivities (Table 5). These values should ideally be corrected for environmental factors like topography, structure, sedimentation rate, and the glacial effect on the equilibrium of conductive heat flux (von Herzen,1973). Although we have not applied these corrections, they usually increase the final values by 10-15% (Ben-Avraham & von Herzen, 1987). The primary heatflow results can be summarised as follows:

1. The heatflow measured averages 40 mW/m^2 throughout the continental margin. This is consistent with the Late Cretaceous age of continental breakup between Australia and Antarctica (Falvey & Mutter, 1981; Cande & Mutter, 1982). Some high values of 70 mW/m^2, particularly in the the Otway margin's mid-slope, are probably related to Tertiary tectonic activity in the region, like that reflected in the zone of more dense normal faulting in BMR seismic profile 48/43.

2. Comparison of two transects (BMR 48/43 and SO36/46) has shown that the average heatflow in the Otway margin (48.4 mW/m^2) is generally higher than that in the Tasmanian margin (32.8 mW/m^2). The difference may be caused by different sedimentation rates and tectonic settings.

3. Assuming the 'oil window' lies between 80^{o}C and 120^{o}C, the temperature gradient measurements from this study suggest that mature source rocks would be buried 2-4 km beneath the seafloor. Future studies will include the combined analysis of the actual heatflow measurements, the estimated heatflow values from offshore wells, and other relevant geological and geophysical data; these will help us better understand the thermal maturation history of the Otway/Tasmania continental margin.

HYDROCARBON GAS IN SEAFLOOR SEDIMENTS

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INTRODUCTION

Background

Hydrocarbon gases (C1-C4) and volatile hydrocarbons of higher molecular weight (C5-C7) are common in young marine sediments (Claypool & Kvenvolden, 1983; Hunt, 1975b). These naturally occurring hydrocarbons have two possible origins:

1) biogenic, i.e. produced in situ by bacterial activity
2) thermogenic, i.e. arising from non-biological processes whereby petroleum is formed when organic-rich sediments attain burial temperatures of 80-150°C.

In both cases methane is invariably the dominant component. Background concentrations are in the range 0.01-10 microlitres of gas/litre of wet sediment (micro L/L).

Thermogenic (petroleum-related) gas can be distinguished from biogenic (microbially-derived) gas on the basis of the relative abundance of its C1-C4 components (e.g. C1/C2+C3, C2/C2:1, C3/C3:1, *i*C4/*n*-C4) and the isotopic composition of its methane (delta 13C, delta D) (Bernard & others, 1976; Reed & Kaplan, 1977; Kvenvolden & Redden, 1980; Kvenvolden & others, 1981; Claypool & Kvenvolden, 1983).

Anomalous concentrations of thermogenic C1-C5 hydrocarbons in the upper 1-3 m of fine-grained sediment on the continental shelf and slope are direct evidence of submarine seeps. Seeps or vents in turn signify the existence of active source rocks or discrete petroleum accumulations, at depths up to 5 km below the seafloor. Hydrocarbon seepage is favoured in areas where the continental margin is strongly faulted (Kvenvolden & others, 1981) or intruded by diapirs (Anderson & others, 1983).

Previous studies

In view of its tectonic style, recent earthquake activity and thickness of sediment, the offshore Otway Basin and western Tasmanian margin were identified by Wilson & others (1974) as areas of moderate potential for submarine oil seepage. This assessment is supported by the weathered bitumen and fresh waxy crude oil which are regularly washed ashore along the coastlines of southeast South Australia and western Victoria (Sprigg & Woolley, 1963; McKirdy & Horvath, 1976; McKirdy & others, 1986).

A large oil slick, which polluted beaches along a 70 km stretch of coastline on southern Kangaroo Island in December 1986, can be linked with seismic activity in the western Voluta Trough (McKirdy & Cox, 1987). Twenty-four days prior to the stranding of the oil an earthquake (magnitude = 2.2 on Richter scale) with an epicentre located approximately 75 km southwest of Kingston, SA, was recorded on the SADME seismic array.

A 1600 km survey, using a seaborne gas sniffer and sidescan sonar, identified plumes of thermogenic gas in the water column 16 km due south of Port Macdonnell (Shoreline Exploration Co., 1983). These plumes were notable for their unusually high propane/methane ratios (C3/C1 = 0.03-3, mean = 1).

Likewise, C1-C5 hydrocarbons (up to 1 ppm by weight) were obtained from 27 piston and gravity cores of fine-grained sediment on the

Table 6. Gas Data, offshore South Australia
(co-ordinates in Table 3)

Core	Depth in core (m)	Water depth (m)	Total C_1-C_4 ppm h'space	Total C_1-C_4 ppm sediment	Wet gas (%)	$\frac{C_1}{C_2+C_3}$	$\frac{C_2}{C_{2:1}}$	$\frac{C_3}{C_{3:1}}$	$\frac{i\text{-}C_4}{n\text{-}C_4}$	$\frac{i\text{-}C_5}{n\text{-}C_5}$
Seismic profile 48/43										
9A	133-153	3615	3.009	1.595	0.98	115	0.246	1.15	-	0.77
	173-193		3.394	1.799	0.86	151	0.108	0.577	0.67	0.97
10	286-306	3332	1.025	0.543	3.7	40.6	0.163	0.710	0.50	1.16
	325-345		1.307	0.693	4.5	28.4	0.160	1.02	0.50	0.89
11	210-230	3214	2.531	1.341	2.6	48.6	0.224	1.12	0.36	0.80
	250-270		2.552	1.353	2.1	66.1	0.206	1.08	0.46	1.03
12A	210-230	3133	1.052	0.558	4.1	29.9	0.221	1.20	0.39	0.58
	260-280		1.446	0.766	2.8	40.6	0.303	1.10	0.50	0.56
13	210-230	2525	40.490	21.460	1.2	90.8	4.34	5.55	0.30	0.48
	270-290		65.289	34.603	0.95	109	6.64	3.74	0.50	0.47
14	270-290	2250	3.662	1.941	4.4	25.0	0.673	3.06	0.35	0.62
	310-330		2.932	1.554	3.4	33.4	0.433	2.07	0.46	0.40
15	170-190	1964	4.049	2.146	2.8	44.9	0.435	1.62	0.24	0.68
	240-260		5.146	2.727	1.7	70.6	0.404	1.60	0.26	0.81
16	70-90	1650	1.618	0.858	5.1	22.3	0.262	1.25	0.36	0.74
	140-160		3.439	1.823	2.5	49.7	0.295	1.46	0.40	0.67
17	210-230	1490	3.998	2.119	1.9	65.1	0.338	1.62	0.29	0.85
	270-290		4.753	2.519	3.9	30.8	0.500	1.86	0.32	0.61
18	210-230	1035	188.795	100.061	0.35	380	1.41	7.43	0.55	0.51
	270-290		921.582	488.438	0.26	545	1.07	10.30	0.73	0.66
19	30-50	345	2.435	1.291	6.9	16.0	0.848	2.68	0.30	0.49
	70-90		4.503	1.387	4.3	26.4	0.968	3.32	0.29	0.63

Table 6 (contd)

Core	Depth in core (m)	Water depth (m)	Total C_1-C_4 ppm h'space	Total C_1-C_4 ppm sediment	Wet gas (%)	$\frac{C_1}{C_2+C_3}$	$\frac{C_2}{C_{2:1}}$	$\frac{C_3}{C_{3:1}}$	$\frac{i\text{-}C_4}{n\text{-}C_4}$	$\frac{i\text{-}C_5}{n\text{-}C_5}$
Seismic profile 48/42										
21	110-135	315	2.632	1.395	4.1	31.3	0.508	2.10	0.54	0.67
	165-190		2.165	1.147	3.6	36.8	0.751	2.69	0.58	0.32
22	210-230	1003	19.328	10.244	2.3	48.1	0.946	3.70	0.30	0.54
	260-280		40.427	21.426	0.96	116	1.02	3.59	0.29	0.57
23	170-190	1146	71.091	37.678	1.1	100	0.916	3.16	0.24	0.52
	218-238		81.046	42.954	0.30	357	3.41	4.95	0.35	0.10

Table 7. Gas Data, offshore Victoria
(co-ordinates in Table 3)

Core	Depth in core (m)	Water depth (m)	Total C_1-C_4 ppm h'space	ppm sediment	Wet gas (%)	$\frac{C_1}{C_2+C_3}$	$\frac{C_2}{C_{2:1}}$	$\frac{C_3}{C_{3:1}}$	$\frac{i\text{-}C_4}{n\text{-}C_4}$	$\frac{i\text{-}C_5}{n\text{-}C_5}$
Seismic profile 48/007										
24	110-130	392	2.962	1.570	5.9	18.0	0.635	2.53	0.34	0.35
	151-171		4.772	2.529	4.1	27.6	0.737	3.23	0.36	0.48
25	114-134	450	5.571	2.953	6.1	18.5	1.12	3.90	0.35	0.72
	154-174		7.296	3.867	2.5	46.0	0.772	3.52	0.36	0.61
26	157-177	469	5.570	2.952	3.3	34.2	0.668	2.90	0.32	0.71
	197-217		6.708	3.555	4.6	23.9	1.21	3.87	0.35	0.60
27	159-179	506	4.660	2.470	2.6	44.1	0.641	2.11	0.43	0.81
	197-217		4.982	2.640	2.5	52.6	0.608	2.25	0.35	0.52
28	159-179	545	5.470	2.899	2.1	54.7	0.753	2.85	0.31	0.41
	219-239		3.521	1.866	3.4	33.3	0.626	2.30	0.35	0.55
Seismic profile 40/22										
29	0-20	240	1.325	0.702	4.7	27.2	0.151	0.752	0.32	0.65
	100-120		2.170	1.150	7.5	14.8	0.811	2.14	0.33	0.59
	200-220		1.647	0.873	7.6	15.1	0.510	2.26	0.32	0.86
	332-352		1.218	0.645	16.3	6.08	0.375	2.61	0.35	0.76
30	65-85	558	2.025	1.073	9.9	10.1	1.70	3.69	0.24	0.86
	105-125		3.275	1.736	5.6	19.7	1.43	3.81	0.40	0.90
31	224-244	829	6.280	3.328	3.1	36.1	0.947	4.00	0.31	0.80
	264-284		8.459	4.483	3.1	34.8	1.54	4.43	0.34	0.62
32	22-42	1244	1.031	0.546	8.6	12.9	0.227	1.12	0.42	0.70
	62-82		2.732	1.448	3.4	34.7	0.269	1.41	0.50	0.72
33	196-216	1433	4.106	2.176	5.1	21.3	0.762	2.70	0.30	0.80
	236-256		4.276	2.266	3.8	28.7	0.809	3.28	0.46	0.85

Table 7 (contd)

Core	Depth in core (m)	Water depth (m)	Total C_1-C_4 ppm h'space	Total C_1-C_4 ppm sediment	Wet gas (%)	$\frac{C_1}{C_2+C_3}$	$\frac{C_2}{C_{2:1}}$	$\frac{C_3}{C_{3:1}}$	$\frac{i\text{-}C_4}{n\text{-}C_4}$	$\frac{i\text{-}C_5}{n\text{-}C_5}$
34	200-222	1630	17.251	9.143	2.1	51.1	1.51	4.14	0.36	0.51
	241-262		18.175	9.633	1.3	86.4	1.40	3.35	0.32	0.58
35	69-89	2280	0.820	0.435	6.2	19.0	0.405	1.13	0.79	-
	109-129		0.874	0.463	6.7	17.3	0.230	0.997	0.62	0.84
36	150-170	2182	0.255	0.135	14.4	7.7	0.328	0.958	0.42	0.65
	200-220		0.313	0.166	11.5	10.0	0.303	0.914	0.43	0.28
<u>Seismic profile 40/23</u>										
37	170-190	3090	1.464	0.776	3.5	34.0	0.206	1.40	0.33	0.77
	220-250		1.616	0.856	4.1	30.2	0.184	1.12	0.39	0.72
38	120-140	3850	1.276	0.676	12.4	8.47	0.525	1.97	0.30	0.55
	150-170		0.456	0.242	3.3	38.6	-	0.578	-	0.98
39	82-102	4300	0.280	0.148	7.2	15.9	1.17	0.587	-	0.63
40	32-52	4370	0.159	0.843	12.3	10.0	0.454	1.56	0.75	1.00
41	108-128	4645	1.853	0.982	1.1	157	0.165	0.546	0.50	0.59
	148-168		1.664	0.882	1.2	108	0.100	0.683	-	0.71

Table 8. Gas data, offshore west Tasmania
(co-ordinates in Table 3)

Core	Depth in core (m)	Water depth (m)	Total C_1-C_4 ppm h'space	ppm sediment	Wet gas (%)	$\frac{C_1}{C_2+C_3}$	$\frac{C_2}{C_{2:1}}$	$\frac{C_3}{C_{3:1}}$	$\frac{i\text{-}C_4}{n\text{-}C_4}$	$\frac{i\text{-}C_5}{n\text{-}C_5}$
Seismic profile SO36/46										
44	70-90	4103	0.481	0.255	10.3	11.2	0.200	1.31	0.44	-
	120-140		0.750	0.387	14.7	7.12	0.360	1.59	0.40	0.68
45	230-250	3715	3.215	1.704	1.2	176	0.060	1.89	0.70	0.40
	310-330		5.434	2.880	0.67	195	0.166	1.07	0.50	0.3
46	70-90	2360	2.037	1.080	4.0	29.1	0.684	1.99	0.38	0.41
	143-168		2.623	1.390	2.5	46.9	0.699	2.60	0.46	1.27
47	70-90	765	2.868	1.520	4.6	24.2	1.07	2.46	0.31	0.63
	110-130		4.019	2.130	4.4	24.8	1.50	3.14	0.26	0.59
48	113-133	377	0.285	0.151	26.9	3.14	1.08	2.75	0.28	1.03
	160-180		0.650	0.344	12.7	8.32	0.924	2.51	0.24	1.12
Seismic profile 16/15										
49	174-194	838	5.810	3.079	1.5	75.0	1.72	3.91	0.36	0.44
	224-244		0.997	0.528	6.5	19.7	0.373	1.01	0.55	0.90
	264-284		1.668	0.884	4.6	24.8	1.59	1.46	0.62	0.86
50A	76-96	1081	2.094	1.110	3.4	33.6	0.632	2.39	0.44	0.61
	116-136		1.242	0.658	10.3	10.2	1.52	3.81	0.36	0.49
51	37-57	1557	1.182	0.626	3.6	36.3	0.262	1.21	0.57	0.75
	77- 97		3.820	2.025	2.6	46.6	0.733	2.93	0.50	0.68
Seismic profile 16/17										
52	70-90	1145	0.740	0.392	16.2	6.33	0.732	2.21	0.40	1.03
	130-150		1.413	0.749	10.9	9.80	0.844	2.60	0.35	0.76
53	70-90	1367	1.321	0.700	3.9	49.6	0.395	1.42	0.37	0.44
	123-143		1.623	0.860	8.8	11.9	1.25	3.72	0.42	0.70
54	20-40	1634	0.161	0.085	26.9	3.30	0.284	0.956	0.38	0.65
	60-80		0.285	0.151	21.9	4.72	0.366	1.40	0.36	0.56

continental slope, in two areas immediately west of Clam No.1 and Cape Sorell No.1 off western Tasmania (Whiticar & others, 1985). Sediment was degassed using an in vacuo acid digestion technique. A thermogenic origin was attributed to these hydrocarbons on the basis of their extremely low Bernard Parameter values (C1/C2+C3 = 1.3-6.7).

Aims of present study

The previous studies made it clear that the offshore Otway Basin and West Tasmanian margin are ideal targets for a regional reconnaissance survey aimed at defining areas of anomalously high thermogenic gas. Accordingly, a major objective of the present cruise was to routinely analyse all gravity cores for C1-C5 hydrocarbons, using a headspace gas sampling technique and shipboard gas chromatography.

In the final outcome, cores from 43 sites located along eight different seismic profiles of the continental margin between southeastern South Australia and western Tasmania (Figs. 1 and 2) were successfully analysed. Selected grab and dredge samples also were analysed, but with less than satisfactory results. The results have been discussed by Heggie & others (1988).

ANALYTICAL METHODS

Sampling of cores

Upon removal from the core barrel the plastic core liner (65 mm I.D.) containing up to 3.5 m of wet sediment was cut into 1 m lengths and then sectioned longitudinally. Twenty-centimetre lengths of half core (usually two per core, Tables 6-8) were immediately removed from the anoxic section of the core and placed in metal cans (1.137 litre capacity) each of which had a septum-covered hole in its base. Degassed (i.e. freshly boiled) deionised water was added to the can until a 175 mL headspace remained. The headspace was purged with high-purity helium via two syringe needles inserted through the septum. The can was then shaken mechanically for 10 minutes to release gases originally dissolved in the pore water into the headspace (Kvenvolden & Redden, 1980). Finally, the can was placed in a water bath at 70^{o}C for 30 minutes to desorb any gas still bound to mineral surfaces. Upon cooling to ambient temperature (20^{o}C), a 5 mL aliquot of the headspace gas mixture was withdrawn with a syringe and injected into the gas chromatograph.

The principal sediment type analysed was grey calcareous nannofossil ooze of Quaternary age. The grab samples analysed were unconsolidated bryozoal grits and sands. The latter yielded very low concentrations of gas (C1-C4 <1 micro L/L) and displayed evidence of preferential loss of methane.

Gas chromatography

The headspace gas was analysed by shipboard gas chromatography, using the following instrumental parameters:

Gas chromatograph:	Varian Vista 6000 fitted with flame ionisation detector
Column:	1.8 m x 3.2 mm I.D. copper column packed with activated alumina (80-100 mesh)
Injector temperature:	50^{o}C
Detector temperature:	25^{o}C

Carrier gas:	He at 35 mL/min.
Detector range:	10^{-12}
Column temperature:	50-250°C at 20°C/min.
Quantification:	Peak areas were measured with a Varian Spectra Physics 4270 Integrator and calibrated against a standard mixture of 100 ppm (by volume) of each of methane, ethane, propane, *n*-butane, *n*-pentane and *n*-hexane in nitrogen.

Concentrations of C1-C4 hydrocarbons, determined initially as ppm (by volume) of headspace, are reported here as micro L/L of wet sediment (Tables 6, 7, 8). The lower detection limit of the method is about 0.005 micro L/L. Regular procedural blanks revealed small background levels of methane (C1), isopentane (*i*-C5) and normal pentane (*n*-C5), for which appropriate corrections were made.

INITIAL SHIPBOARD RESULTS

Gravity core hydrocarbon data

Analytical data on 87 core samples are summarised here as follows:

State	Seismic Profile	Core	Table
South Australia	BMR 48/043	9A-19	6
	BMR 48/042	21-23	6
Victoria	BMR 48/007	24-28	7
	BMR 40/022	29-36	7
	BMR 40/023	37-41	7
Tasmania	SO 36/46	44-48	8
	BMR 16/015	49-51	8
	BMR 16/017	52-54	8

Recognition of thermogenic hydrocarbons

Several compositional parameters were used to distinguish light hydrocarbons of mainly thermogenic origin from solely biogenic gas:

1)	C1/C2+C3	< 500	(Bernard & others, 1976)
2)	C2/C2:1	> 1	(Kvenvolden & others, 1981)
3)	C3/C3:1	> 3	(this study)
4)	*i*-C4/*n*-C4	< 1	(Monnier & others, 1983; Alexander & others, 1983).
5)	*i*-C5/*n*-C5	< 4	(Hunt, 1984)

Parameters (1)-(3) are based on the fact that contemporary bacterial activity in marine sediments produces mainly methane, resulting in very high C1/C2+C3 ratios (>1000), and minor but significant amounts of ethene (C2:1) and propene (C3:1) which are not components of thermogenic gas.

Parameters (4) and (5) are maturity indicators. The values specified correspond to the principal phase of thermogenic hydrocarbon generation (vitrinite reflectance, VR = 0.6-1.35%).

Hydrocarbon anomalies

Application of these criteria to the hydrocarbon data in Tables 6-8 led to the recognition of anomalous concentrations of thermogenic gas at a minimum of eleven localities (Tables 9, 10, 11; Figs.1, 2).

Throughout the study area hydrocarbon gas concentrations were generally in the range 0.1-2.5 micro L C1-C4/L of wet sediment. Background concentrations were highest on the upper slope along BMR seismic line 48/07, south-southeast of Discovery Bay No. 1 on the northern flank of the Voluta Trough (Tables 7 and 10). The lowest background C1-C4 values were recorded in the eastern Otway Basin along BMR seismic lines 40/22 and 23, southwest of Prawn No. 1 on the Mussel Platform, and along BMR 16/15 and 17 which traverse the upper slope south of Clam No. 1 at the northern end of the West Tasmanian margin (Tables 7, 10 and 11).

Major thermogenic anomalies were identified at four sea-bottom localities off South Australia (Table 9), five off Victoria (Table 10) and two off Tasmania (Table 11; Figs. 1 and 2). These sites in water depths of 450-2500 m appear to be active submarine gas seeps. Most of the seeps lie above major faults. The contrast between anomaly and background is greatest in the western Voluta Trough where C1-C4 concentrations up to 488 micro L/L were recorded (Table 9) and faulting offsets the seafloor.

The faults associated with major anomalies are fracture zones which appear to be acting as conduits for petroleum-related gas migrating upwards from deeply buried Cretaceous source rocks. The gas comprising these anomalies is very dry and probably of late catagenic origin. The wetness of the gas seeps (C2-C4 as a percentage of C1-C4) varies across the study area as follows:

western Voluta Trough	0.3-2.3%	(mean = 0.93%)
north flank of Voluta Trough	2.5-6.1%	(mean = 4.4%)
eastern Voluta Trough	1.3-9.9%	(mean = 4.2%)
west Tasmanian margin	1.5-4.4%	(mean = 3.0%)

The absence of gas anomalies at other core sites located above faults suggests either that not all faults facilitate hydrocarbon escape to the seafloor or that they are not on hydrocarbon migration paths.

Two hydrocarbon anomalies in the eastern Otway Basin (core sites 25 and 34: Table 10) are not directly related to faulting, but lie above large horst blocks which display seismic evidence of possible anticlinal closures at the top of the Sherbrook Group. Such anomalies may indicate hydrocarbon accumulations at depth in Cretaceous reservoir sands and therefore are of particular significance for petroleum exploration.

Table 9. Hydrocarbon anomalies, offshore South Australia

Seismic profile	Gravity core	Water depth (m)	Depth in core (cm)	C_1-C_4 alkanes (micro L/L)	anomaly/background*
BMR 48/43	13	2525	210-230	21.5	14.0
			270-290	34.6	22.6
	18	1035	210-230	100	65.4
			270-290	488	319
BMR 48/42	22	1003	210-230	10.2	6.67
			260-280	21.4	14.0
	23	1146	170-190	37.7	24.6
			218-328	43.0	28.1

*Mean background (micro-L C_1-C_4/L wet sediment) = 1.53 (n = 20)

Table 10. Hydrocarbon anomalies, offshore Victoria

Seismic profile	Gravity core	Water depth (m)	Depth in core (cm)	C_1-C_4 alkanes (micro L/L)	anomaly/background*
BMR 48/07	25	450	114-134	2.95	1.22
			154-174	3.87	1.60
	26	469	197-217	3.56	1.47
BMR 40/22	30	558	65-85	1.07	1.31
			105-125	1.74	2.12
	31	829	224-244	3.33	4.06
			264-284	4.48	5.47
	34	1630	200-222	9.14	11.2
			242-262	9.63	11.7

*Mean background (micro L C_1-C_4/L wet sediment) =

2.42 in BMR 48/07, n = 7)
0.82 in BMR 40/22 & 23 (n = 20)

Table 11. Hydrocarbon anomalies, offshore Tasmania

Seismic Profile	Gravity core	Water depth (m)	Depth in core (cm)	C_1-C_4 alkanes micro L/L	anomaly/background*
SO36/46	47	765	110-130	2.13	1.97
BMR 16/15	49	838	174-194	3.08	4.22

*Mean background (micro L C_1-C_4/L wet sediment) =

1.08 in SO36/46 (n = 9)
0.73 in BMR 16/15 & 17 (n = 12)

SEDIMENT AND POREWATER GEOCHEMISTRY

D.T. Heggie

INTRODUCTION

The objectives of the sediment and porewater geochemistry program were:

1. To document the 'redox' nature of continental-margin sediments, in order to contribute to an understanding of the sediment hydrocarbon gas data (see McKirdy & Heggie, this volume).
2. To examine the processes that control organic carbon preservation in continental-margin sediments, particularly within the oxygen-minimum zone.
3. To test if (and how) organic carbon preservation in margin sediments controls manganese and other trace-metal sediment inventories. This work examines trace-metal contents and distributions as potential palaeoceanographic tracers.
4. To determine how early diagenesis exerts a control on the chemical composition of the sediments.
5. To determine the relative importance of terrigenous inputs, the _in-situ_ production of organic carbon, and regional oceanography as controls on surface-sediment distribution and composition.

Methods

To achieve these objectives, eleven gravity cores were processed aboard the ship to separate sediment pore fluids from the sediment matrix. The cores processed are summarised in Table 12 and shown in Figures 26 & 27. The protocol for handling sediment cores was as follows (Fig. 28) :

1. The core was split in the geology lab and one half, after description, archived.
2. The remaining half core was inspected, and usually 10-16 samples, in 3-cm slices, were taken from the top 2 m of the core and loaded into centrifuge tubes.
3. Selected samples (1 cm) were taken in 10 cm^3 syringes for ^{35}S isotope studies of sulphate reduction rates, and stored at _in-situ_ temperatures of 30°C for subsequent analysis at BMR.
4. Sediment samples were centrifuged at 14000 rpm for 5 mins, at 3°C, in a gimbal-mounted Sonvall RC-5 superspeed refrigerated centrifuge.

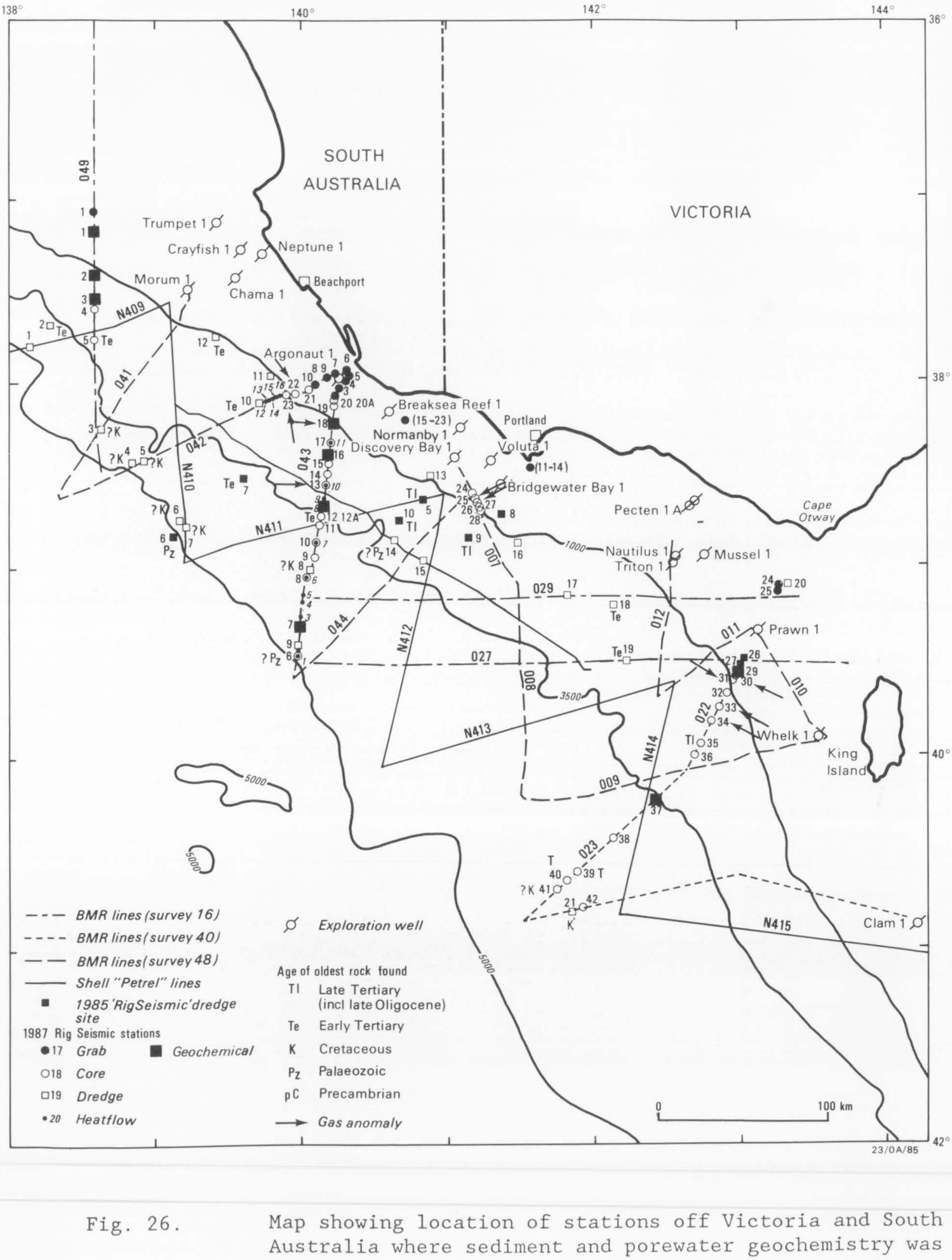
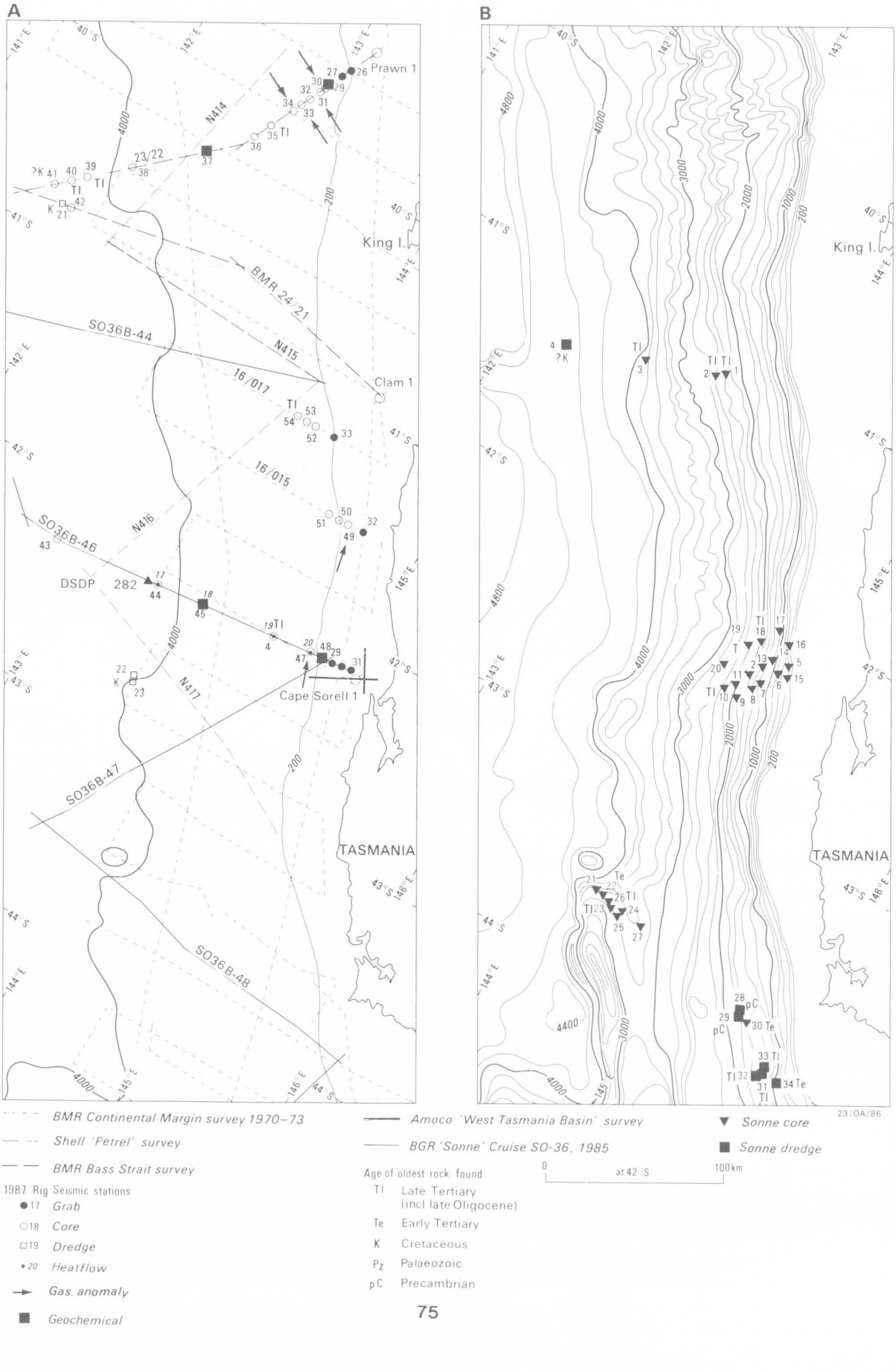


Fig. 26. Map showing location of stations off Victoria and South Australia where sediment and porewater geochemistry was studied.

Fig. 27. Map showing location of stations off Tasmania where sediment and porewater geochemistry was studied.



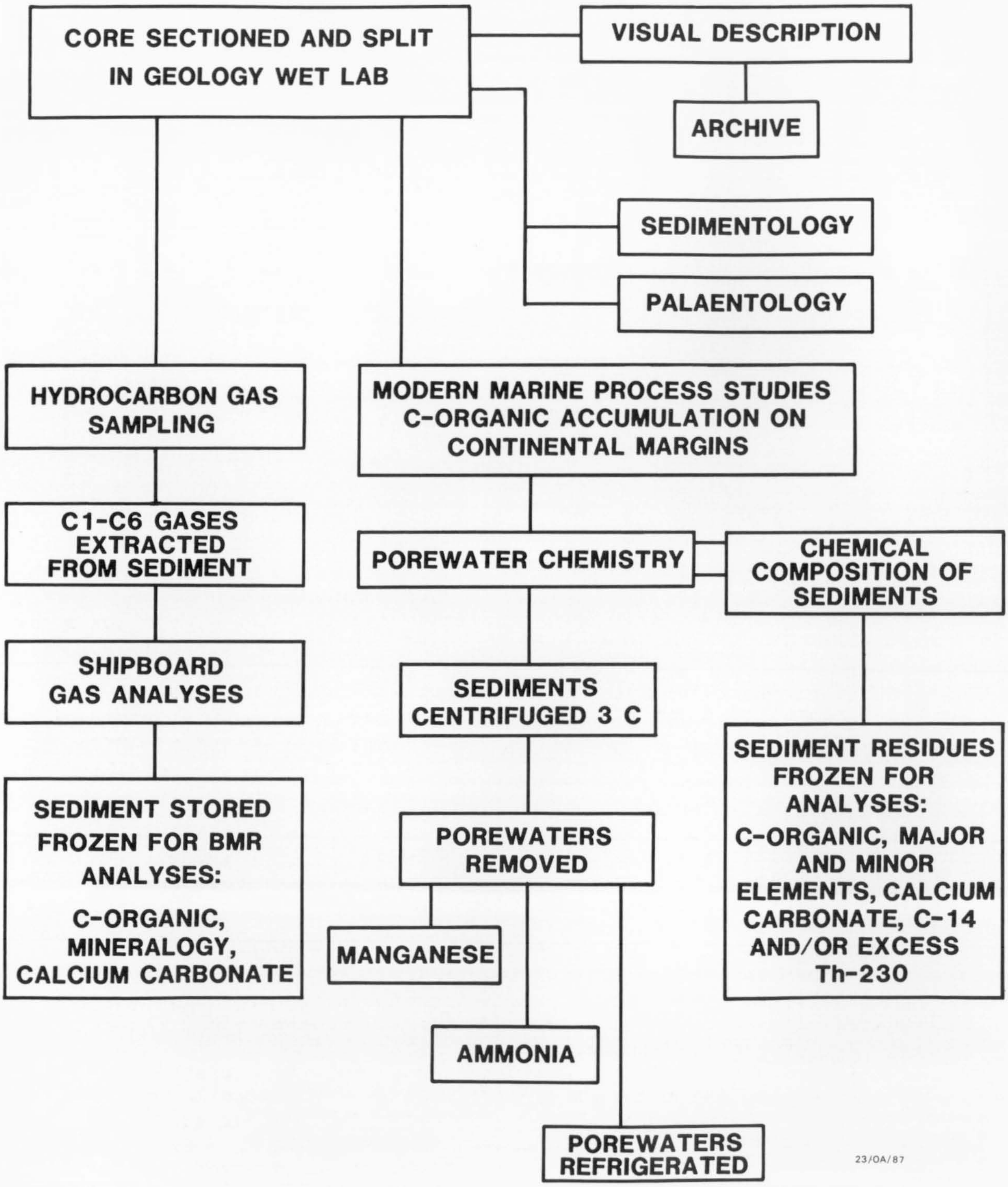


Fig. 28. Schematic diagram of geochemical sampling.

5. Porewaters were syphoned from the sediments and aliquotted to sample vials.
6. All porewaters were analysed aboard ship for ammonia and manganese.
7. Remaining porewaters were stored refrigerated for subsequent analysis.
8. All centrifuge sediment plugs were stored frozen for subsequent determinations of major and trace elements, organic carbon contents, and sedimentation rate determinations via ^{14}C or ^{230}Th methods.

Table 12. Cores processed for porewater geochemistry

Station	Lat.	Long.	Water depth (m)	Seismic line	Recovery (cm)
GC01	37°10.2′	138°35.8′	425	16/049	220
GC02	37°23.9′	138°34.2′	1270	16/049	54
GC03	37°33.0′	138°35.0′	1476	16/049	310
GC07	39°20.1′	139°59.2′	4120	48/043	287
GC12A	38°42.6′	140°07.1′	3133	48/043	306
GC16	38°20.0′	140°10.9′	1650	48/043	196
GC18	38°11.6′	140°11.5′	1035	48/043	233
GC29	39°34.0′	142°59.0′	240	40/22	364
GC37	40°14.1′	142°25.2	3090	40/23	275
GC45	42°13.6′	142°52.5′	3715	SO36/46	360
GC48	42°10.8′	144°44.3′	377	SO36/46	190

RESULTS AND DISCUSSION

The manganese and ammonia data collected from the eleven cores are summarised in Figures 29-32, and tabulated in Exon & others (1987a).

Organic carbon preservation in continental margin sediments

Manganese and ammonia measured at sea are used as indicators of the onset of organic carbon oxidation processes in marine sediments. Manganese in oxic sediments resides primarily as Mn IV in oxyhydroxide phases. Porewater Mn concentrations in oxic sediments are indistinguishable from overlying bottom-water concentrations and are undetectable when measured colorimetrically, being <0.1 micromol/litre of interstitial water (micromol/L). When Mn oxides dissolve, reduced Mn II is released to porewaters. The depth at which porewater Mn concentrations begin to rise rapidly above bottom-water concentrations is used as one indicator of the approximate depth of oxygen penetration into the sediments, which defines the 'oxic' sediment zone.

Ammonia is produced during anaerobic oxidation of organic matter by sulphate reduction. The depth at which porewater ammonia begins to rise rapidly indicates the onset of sulphate reduction and the upper limit of 'anoxic' sediments.

All data from the four transects show consistent trends in the depth distributions of manganese and ammonia across the continental margin. Data from cores collected in water depths near 4000 m indicate that the top few (<20) centimetres of the sediments are 'oxic' (GC07, GC45). As water depth decreases, the depth at which ammonia concentrations begin to rise rapidly in porewater is closer to the sediment/seawater interface. Ammonia concentrations increase with increasing depth, indicating extensive sulphate reduction shallow in the sediments. The highest ammonia concentrations were found in GC18

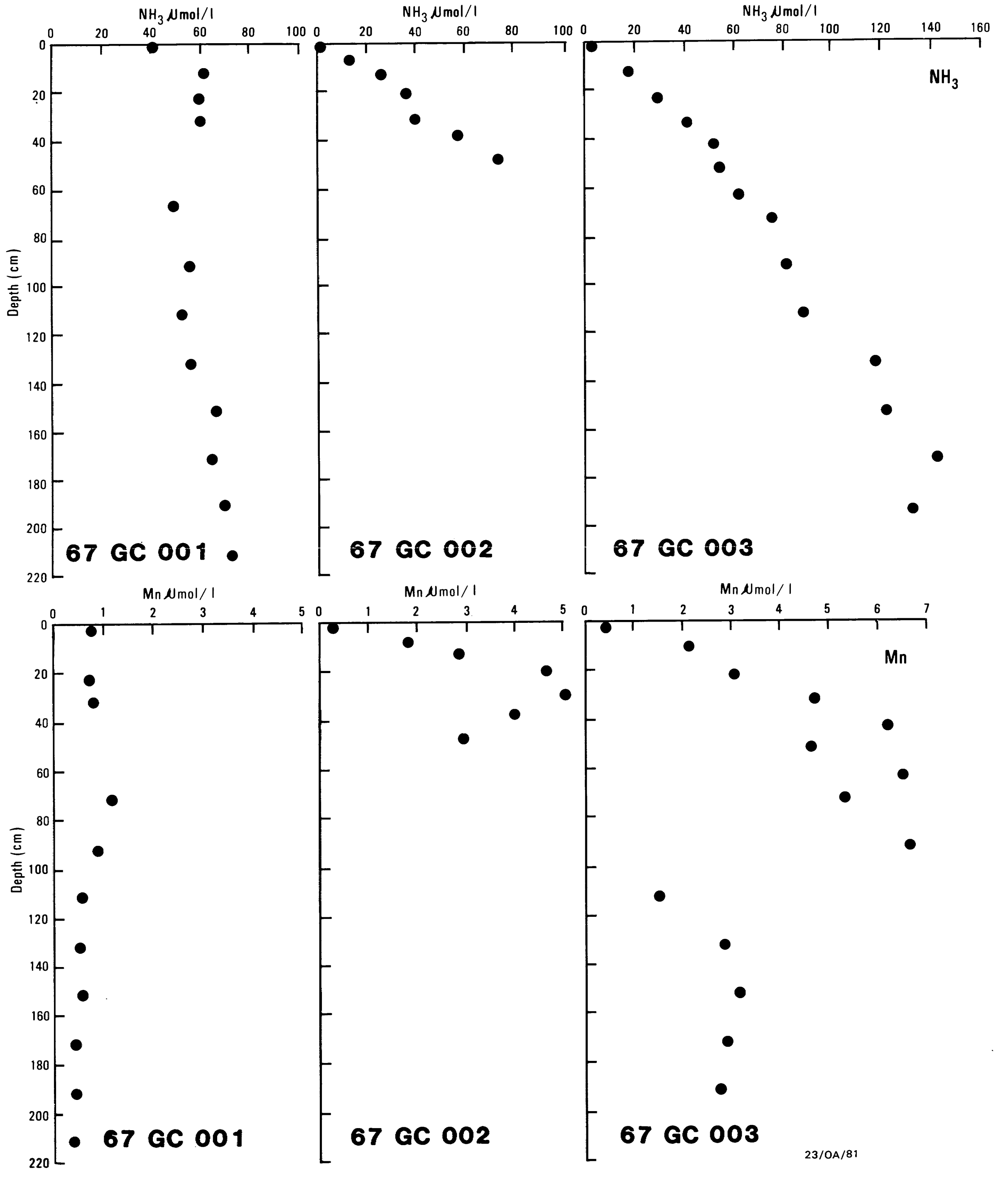


Fig. 29. Porewater ammonia and manganese data for cores off South Australia on BMR seismic line 16/49.

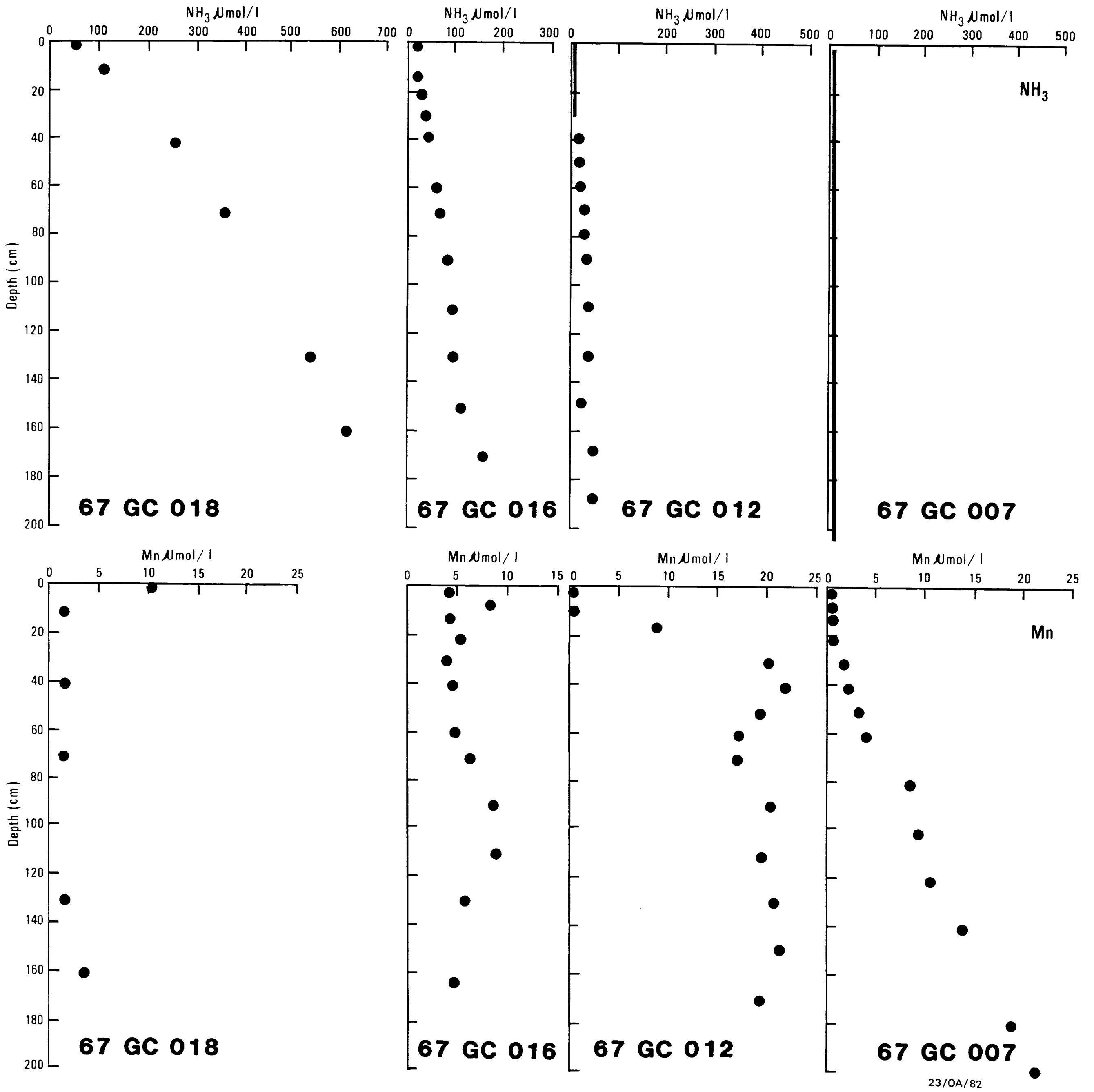


Fig. 30. Porewater ammonia and manganese data from cores off South Australia on BMR seismic line 48/43.

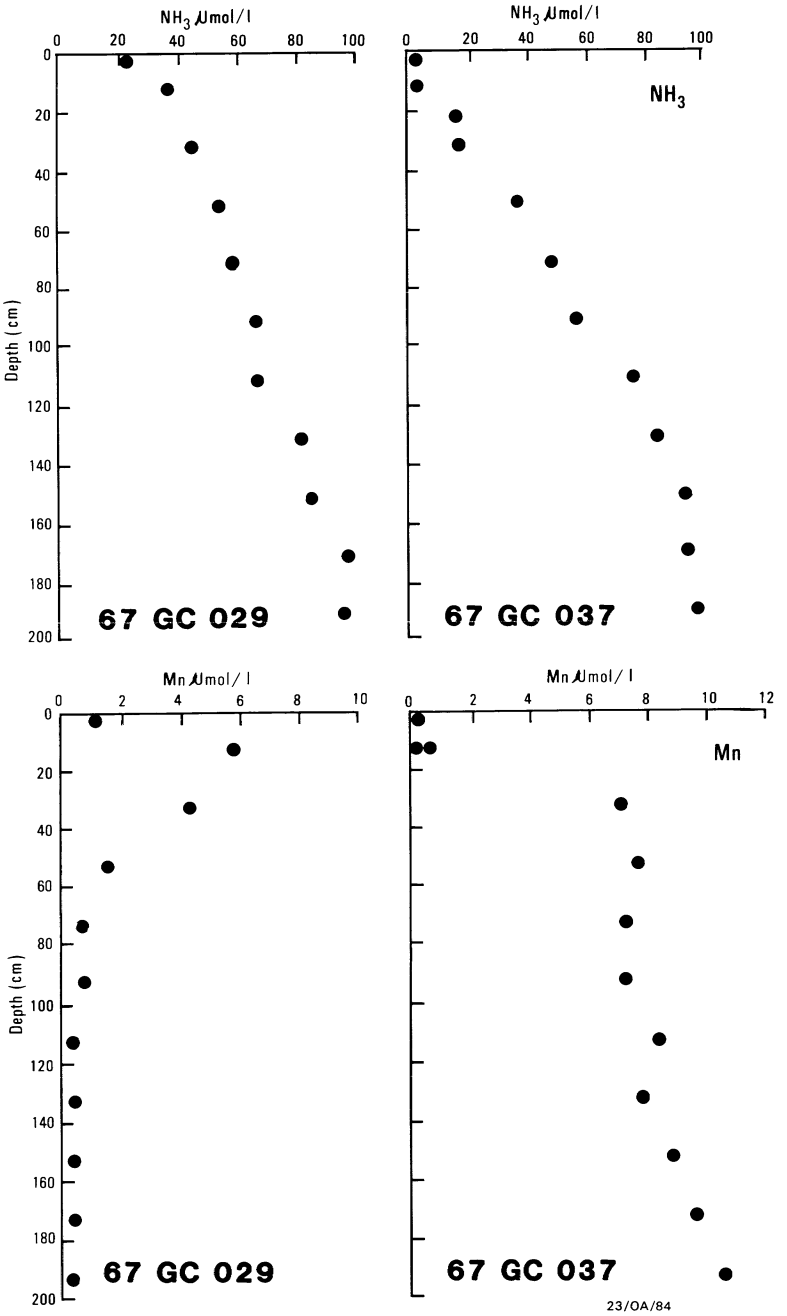


Fig. 31. Porewater ammonia and manganese data from cores off King Island on seismic lines 40/22-23.

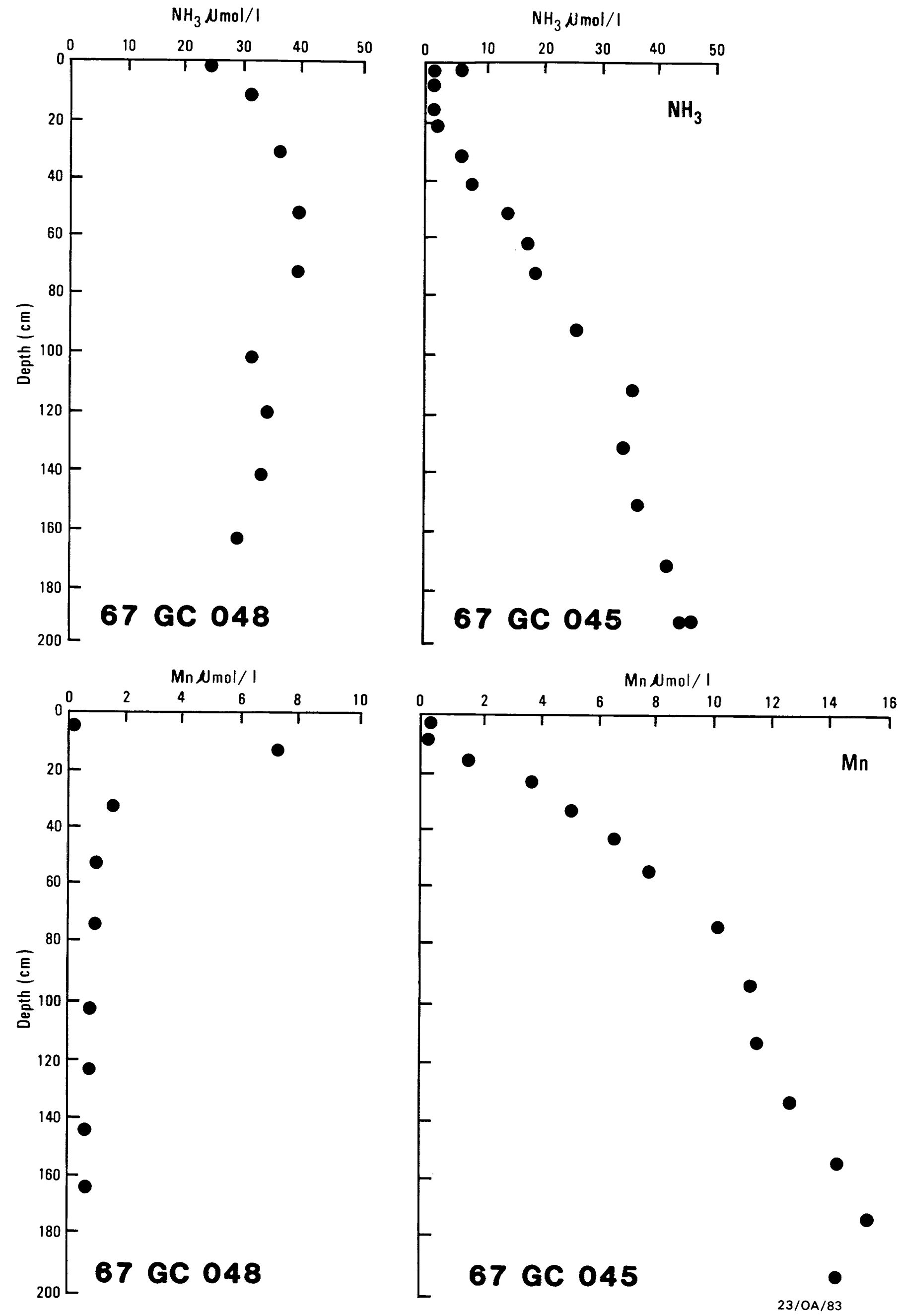


Fig. 32. Porewater ammonia and manganese data from cores off west Tasmania on Sonne seismic line SO36/46.

and they indicated 'anoxic' conditions at the sediment/seawater interface. These data, while indicating 'anoxic' sediments at shallow depths, also indicate that porewater sulphate is not significantly depleted from sediments, and that biogenic methane production is unlikely in the top 2 m of recent sediment.

Different methods of examining organic carbon accumulation processes on Australian margins are being assessed; these would determine the rates of biogeochemical oxidation and preservation processes. The down-core distributions of ammonia provide estimates of sulphate reduction rates from models of ammonia production and transport in recent sediments.

Organic carbon and sedimentary manganese

Manganese in sediments may serve as a useful palaeoceanographic indicator because it exhibits different behaviour in oxic and anoxic sediments. Manganese in oxic sediments is locked in the solid phase, but, under sub-oxic reducing conditions, the solid phase Mn-oxyhydroxide dissolves, releasing Mn II to porewater; the Mn then migrates toward the sediment/seawater interface. When porewater Mn encounters oxygen diffusing down through surface sediments, it is oxidised and removed again to the solid phase. This continuous recycling of Mn in surface sediments results in a surface sediment layer enriched in manganese.

Deepwater cores GC07 and GC45 display Mn oxide dissolution in the top 20-30 cm of sediments, with concentrations approaching 20 micromol/L at 2 m depth in the sediments. With decreasing water depth, the depth of the Mn reduction zone rises in the sediments, and surface sediment porewater Mn concentrations are greater than bottom-water concentrations, indicating a flux of Mn from reduced margin sediments. The asymptotic porewater Mn values at depth systematically decrease with decreasing water depth, being <5 micromol/L in upper slope sediments. These data suggest that the sedimentary Mn inventory is depleted as Mn is lost from anoxic sediments. Additional data on the solid phase Mn concentrations and distributions will provide a quantitative evaluation of the Mn recycling processes.

SUMMARY

Eleven gravity cores from four transects across the continental margins of South Australia, Victoria and West Tasmania were processed for sediment and porewater geochemistry. A preliminary assessment of the shipboard data indicates the following:

1. Anoxic conditions were encountered in near-surface sediments in water depths of less than 3000 m, and upper slope sediments were anoxic at the sediment/seawater interface. Ammonia data indicate that sulphate reduction is widespread. However, sulphate is probably not entirely depleted in the upper 2 m of sediment, suggesting that biogenic methane is probably not being produced.

2. The anoxic sediments of the upper slope, and the rapid rates of organic carbon accumulation therein, may result in depletion of sediment Mn as reduced dissolved Mn is lost from the sediments within the oxygen-minimum zone. These results have application to the use of Mn (and other metals recycled with Mn) as a potential indicator of oxic/anoxic transitions.

SYSTEMS PERFORMANCE

C. Penney

NON-SEISMIC SYSTEM (DAS)

The usually reliable Non-Seismic Acquisition System (DAS) had a high number of unexpected system hardware and software failures, which on several occasions were serious enough to require the system to be restarted. Some of the problems occurred when target positioning was being plotted in the winch control room.

With the large number of geological samples collected during this cruise, site identification proved to be a major problem. The current DAS system numbers the sites sequentially, and disregards whether the site was a dredge, a gravity core, a grab sample, heat flow, etc. This has made the retrieval of a specific type of data from the database difficult without a series of cross-reference tables. There is no reason why the DAS system could not use a better system of filing data internally and produce a database of its own output.

Navigation

Global positioning system (GPS). A MAGNAVOX T-Set (GPS) which can give absolute position to within 20 m r.m.s. was used as the preferred positioning system during the cruise. The GPS was still an experimental system, and the full satellite array was yet to be installed. Delays with installation of the array meant that many of the current satellites had exceeded their expected lifetimes. This explains the erratic performance of satellite 11 of the GPS system on this cruise. The eight hours of coverage expected at these latitudes was reduced because of this satellite's failure.

Apart from this problem, the overall performance of the T-Set was excellent. This in itself has presented a problem, in that complacency and a sense of dependence on T-Set positioning have developed, which the system's results have shown is unwarranted.

Dead reckoning system (DR). Two independent DR systems, incorporating gyro-compass, dual-axis log and TRANSIT satellite receiver, provided basic dead-reckoning positions at all times.

The primary dead-reckoning system consisted of Arma-Brown gyro-compass, Magnavox MX610D sonar-doppler, and Magnavox MX1107RS satnav receiver, which provided the best available positioning of this type on-board ship. The secondary system consisted of a Robertson gyro, Raytheon DSN450 sonar-doppler, and Magnavox-1142 satnav receiver. Both systems had problems in rough weather or when heading into the sea, due to air entrapment under the hull. A small paddle-wheel log proved invaluable during rough weather, because it could be extended beyond the turbulent layer beneath the ship.

The primary system worked very well during transits, but positioning tended to deteriorate when the ship was on station for periods of up to eight hours. Some thought should be given to an automatic output of suspected drift, so that this value can be better taken into account in determining position when remaining on station.

The secondary system proved to be most unsatisfactory and was essentially non-operational for most of the cruise. The Raytheon DSN450 constantly lost track even in very calm sea-states, and consequently consistently corrupted the DR position from that system. There also appeared to be data transmission problems from the sonar-doppler to the Magnavox 1142.

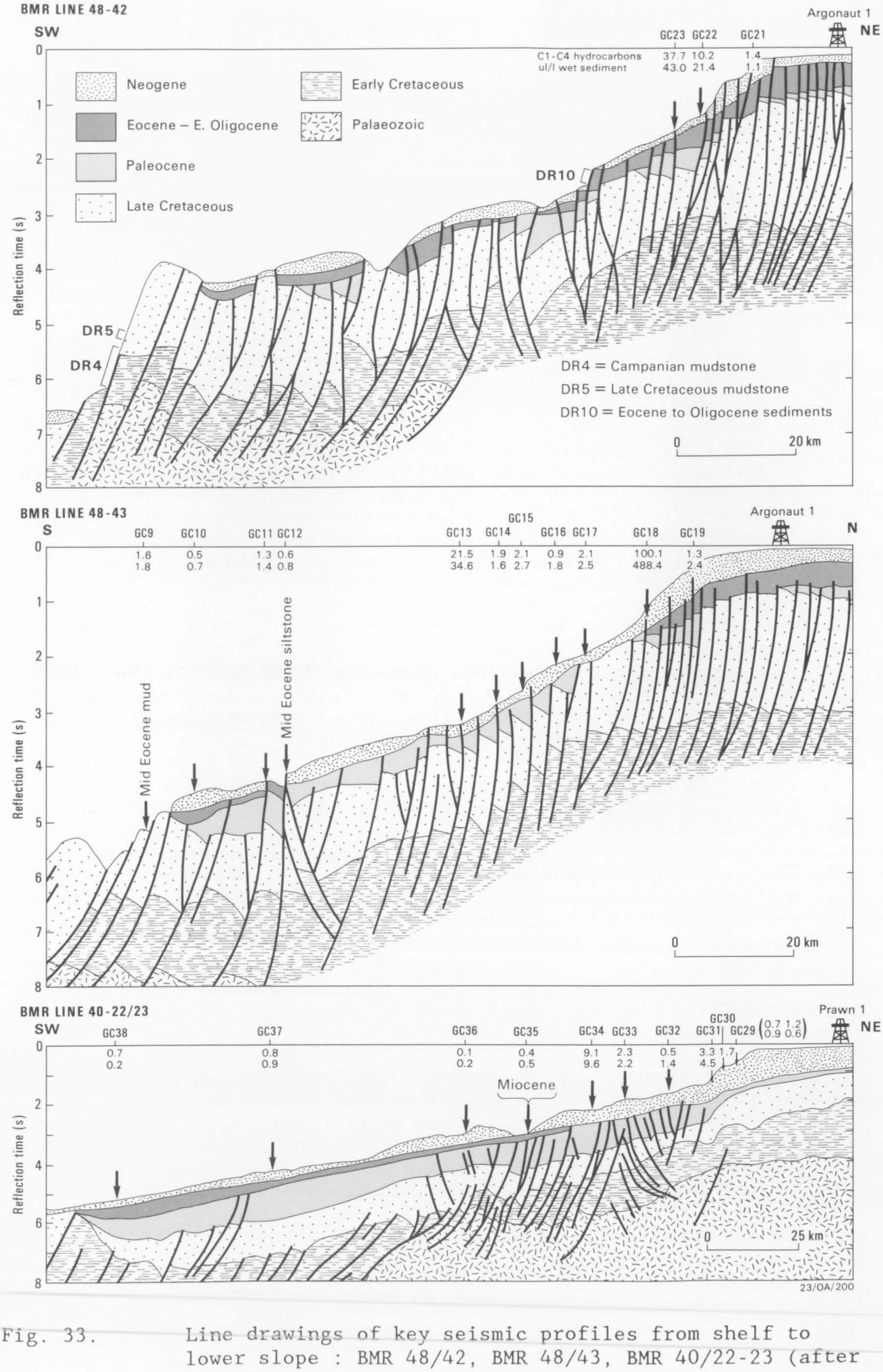


Fig. 33. Line drawings of key seismic profiles from shelf to lower slope : BMR 48/42, BMR 48/43, BMR 40/22-23 (after J.B. Willcox)

Bathymetry

Both 3.5 kHz and 12 kHz echo sounders operated well during the cruise, except in rough seas. Even in rough seas the signal was regained on stations, and quite good results were obtained. The EPC recorders were very unreliable, with all available machines needing to be repaired at some time during the cruise. Serious thought should be given to their replacement, because of the man-power and the large inventory of spares required to keep them going for a month.

Gravity

The Bodenseewerke KSS-31 marine gravity meter performed well and data were collected during the entire cruise. Gravity ties were done in Adelaide and Sydney and a new regional marine gravity station was established at Portland in Victoria. Some problems occurred with the analogue record of gravity, but a digital record was maintained during these periods.

Magnetics

Good single-channel magnetic data were obtained from a Geometrics magnetometer when it was used during the cruise.

Data base and processing

During the cruise, initial processing and verification plots were prepared of all the DAS data collected. All printed data were catalogued and made ready for use by participants.

SEISMIC SYSTEM

The seismic system was used as a site survey tool in several areas where more information was required before dredging began. As the cruise progressed it was felt that there was less need for such site surveys. Intially a GSI airgun with a 40 cubic inch chamber was used as the energy source, but it was found that there was insufficent energy for satisfactory penetration in water depths of over 2000 m. A single Bolt airgun with a 100 cubic inch chamber was then used and gave adequate results for the site surveys.

A short section of high-resolution cable, with four channels and 25 m spacing, configured with stretch sections front and rear, plus a rope and bouy at the rear, was used as the hydrophone streamer. During one of the site surveys, part of a rear stretch section, and the tail rope and buoy, were lost. As this was behind the active sections, its loss was not realised until the cable was retrieved.

CONCLUSIONS

The 1987 Rig Seismic sampling cruise over the Otway Basin and west Tasmanian margin succeeded in its overall aim of providing valuable new geological, geochemical and heatflow data to better define the geological framework and petroleum potential of the region. The cruise time from Adelaide to Sydney was 29 days, but one day was lost through a port call at Portland to repair a damaged core cradle, and half a day through a port call at King Island for a medical emergency. Equipment generally worked very well; the exception was the large vibrocorer which was too cumbersome to deploy from Rig Seismic. Altogether 130 stations were occupied - 23 dredge, 54 core, 33 grab and 20 heatflow - in water depths of 50 to 5000 m (Figs. 1 and 2; Tables 2-4).

The dredge and corer recovered pre-Quaternary rocks and sediments at 22 stations: Palaeozoic volcanics and metasediments in the central

Otway Basin, Late Cretaceous sandstones and siltstones off Tasmania, Late Cretaceous mudstones in much of the Otway Basin, early Tertiary siltstones and peaty siltstone in the Otway Basin, and late Tertiary carbonates in both Otway and Tasmanian regions. These results, in conjunction with earlier ones, show that continental basement and Early and Late Cretaceous detrital sedimentary rocks crop out on the lowermost continental slope in water 4000-5000 m deep. The mid-slope is characterised by early Tertiary detrital sediments, and the upper slope by late Tertiary carbonates. All samples were taken along seismic profiles, and can be added to data from outcrop and shelf wells to help refine our knowledge of the regional geology. Table 13 summarises the character and age of samples recovered in 1985 by Sonne, and in 1985 and 1987 by Rig Seismic.

On the present cruise, Quaternary sediments were obtained in most cores and grab samples, again along seismic profiles. Grab sampling has established the nature of the largely bryozoal outer shelf sands. These sands provide turbidites to the Quaternary sediments on the continental slope, which are otherwise pelagic and hemipelagic in nature. All these samples help to establish, for the first time, a detailed model of sedimentation on the southern margin, which can be extended back well into the Tertiary.

Most lithotypes found beneath the shelf are present on the continental margin. The depths at which sediments originally deposited near sea level were dredged and cored on this cruise are: Early Cretaceous sandstone at 4000-4300 m, Cretaceous mudstone at 3900-4500 m, and Eocene siltstone and peaty siltstone at 1800-4000 m. This compares with depths in shelf wells of Early Cretaceous at 500-3200 m, Late Cretaceous at 350-4500 m, and Eocene at 300-1700 m. Maximum depths are hence comparable in the Cretaceous, where there is thick overburden on the shelf, but Eocene sediments lie much deeper on the slope than anywhere on the shelf. Additional subsidence on the outer margin of the Eocene sediments averages 1500-2000 m.

Temperature-gradient measurements at 20 stations, made by a heatflow probe penetrating the top 3 m of sediment, in conjunction with thermal conductivity measurements on sediment cores, have enabled heatflow calculations to be made. These measurements on BMR seismic line 48/43 south of Argonaut No. 1 well, and Sonne seismic line SO36/46 west of Cape Sorell No. 1 well, vary from 25 to 76 mW/m, values consistent with the accepted breakup history of the margin, and suggest that the zone of thermal maturation of hydrocarbons generally lies at depths of 2-4 km.

Headspace gas analysis of selected intervals from virtually all the cores and many of the grab samples was carried out on board. This work showed that thermogenic hydrocarbons are widespread, with background readings of 1-2 ppm. Particularly high anomalous readings, up to 400 times background, came from twelve cores: four in the western Otway Basin, six in the eastern Otway Basin, and two off western Tasmania. In general, the highest readings were associated with faults extending to (or nearly to) the surface, in areas where Tertiary cover was not thick. It appears that mature hydrocarbon source rocks are present almost everywhere on the upper continental slope.

A full interpretation of the new data, and their integration with new interpretations of the pre-existing seismic data (Fig. 33), will enable a more reliable outline of the margin's stratigraphy, structure and geological history to be established, and will aid in regional assessment of petroleum potential. The study has already shown that continental basement is present to the edge of the abyssal plain, that the rifts in which Cretaceous sandstones were deposited extended well down the western margin of Tasmania, and that most subsidence on the margin occurred after the Eocene.

Table 13. Character and age of samples : Sonne & Rig Seismic cruises

Sequence	Stations	Depth Range
Pleistocene to Recent shelf sands	Many 1987 grabs	27 - 294 m
Pleistocene to Recent ooze and turbidites	27 Sonne and 53 Rig Seismic cores	240 - 4830 m
L. Oligocene - Pliocene marl, limestone, and chalk	S1,2,3,19,23,26,31, 32,33; 1985/5,9,10; GC 35,39,40,46,54; DR10,12,14,18,19	1150 - 4370 m
Eocene - E. Oligocene calcareous siltstone and limestone	S29,32,34; 1985/7; GC5; DR2,10,12,18	650 - 4100 m
Middle Eocene peaty siltstone	S22,30; GC 12	1757 - 3710 m
Late Cretaceous sandstone and mud-stone	S4; DR2,3,4,5,6,7, 21,22; GC 42	3900 - 4700 m
Basement metamorphics and volcanics	S28,29; 1985/6	1800 - 3750 m

NB : S = 1985 Sonne station; 1985 = 1985 Rig Seismic dredge; GC = 1987 Rig Seismic core; DR = 1987 Rig Seismic dredge

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APPENDIX A: TERTIARY CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY, OFFSHORE OTWAY BASIN

Samir Shafik

Contents

ABSTRACT

Calcareous nannofossils from gravity cores and dredge samples recovered during BMR Cruise 67 were examined in order to date the sequences sampled and to elucidate their depositional palaeoenvironments. Seven gravity cores retrieved calcareous nannofossil-bearing pre-Quaternary levels, and the oldest dredged sediments, containing the nannofossils, are assigned a mid Middle Eocene age. Sediments from several dredges are devoid of calcareous microfossils, and these are presumed to be older than the mid Eocene. This is consistent with results obtained during BMR Cruise 48 (Shafik, 1987a) and with the onshore sequence (Shafik, 1983). Open-marine conditions were well established by the mid Middle Eocene in the Otway Basin, but probably not before.

Sediments obtained at six dredge stations were placed within high resolution Eocene and Oligocene biostratigraphic schemes, and correlated with those obtained during BMR Cruise 48. Abundant occurrence of *Chiasmolithus* and a paucity of *Discoaster* in most of the Eocene levels, suggest cool surface waters. However, a warm episode was detected within the Middle Eocene. This is bracketed by the nannofossil datum interval (DI):**Reticulofenestra scissural +Daktylethra punctulata* (correlatable with the low-latitude planktic foraminiferal P.13 zone). The evidence from the Oligocene indicates cooler surface waters than during the Eocene: *Chiasmolithus altus* is abundant in most Oligocene levels, discoasters are rare, and the low-latitude sphenoliths are almost absent. Significantly, however, the low-latitude *Sphenolithus ciperoensis* was recorded in Upper Oligocene sediments recovered in two dredges and at the bottom of a short gravity core. In these sediments *Chiasmolithus altus* is missing. A similar record of the low-latitude *Sphenolithus ciperoensis* in onshore section in the western Otway Basin was noted previously by the writer. This suggests a short warm episode during the Late Oligocene, at least on a regional scale.

Deposition during the Eocene and Oligocene was in nearshore or shallow-water palaeoenvironments. This is based on the presence of several hemipelagic nannofossil taxa (such as *Zygrhablithus bijugatus bijugatus* and *Pontosphaera multipora)* in most samples examined. Partial dissolution of few of the assemblages examined suggests deposition at deeper levels. However, in at least one of these assemblages the undeniable presence of few hemipelagic taxa (albeit very poorly preserved) suggests deposition in a shallow palaeoenvironment and later prolonged exposure to cold bottom waters on the seabed. There is some evidence at two dredge stations to suggest the possibility that shoaling/ sea-level fall occurred during the later part of the Eocene through into the Early Oligocene.

Early/Middle Miocene nannofossils were recovered at two dredge stations and in one of the gravity cores. The index species *Sphenolithus heteromorphus* was identified from several dredge samples. This, together with records of the species from the onshore Victorian Tertiary previously, supports other evidence indicating a global event, very useful in

biostratigraphic correlation at high latitudes.

Late Pliocene sediments were recovered in two gravity cores. Diversity of the assemblages examined is low. Notable is the total lack of slim-rayed discoasters, indicating cool surface waters during the Late Pliocene in the Otway Basin.

INTRODUCTION

Optical microscopy of smear slides of sediments recovered during BMR Cruise 67 was carried out on board R/V *Rig Seismic* to determine their age and palaeoenvironmental conditions, based on their calcareous nannofossil assemblages. Dredging and gravity coring in the offshore Otway Basin and off west Tasmania during Cruise 67 recovered a large number of nannofossil-bearing sediment samples. Most gravity cores and pipe dredges were found to contain Quaternary coccoliths. Only those gravity cores and dredges which yielded *in situ* Tertiary calcareous nannofossils are dealt with herein. A much more detailed report is that of Shafik (1987b).

Tertiary sediments from the offshore Otway Basin had previously been dredged during BMR Cruise 48 (Exon & others, 1987). Their calcareous nannofossils were studied by Shafik (1987a). Earlier, nannofossil biostratigraphy of several Eocene-Oligocene onshore sequences in the Otway Basin have been presented by Shafik (1983).

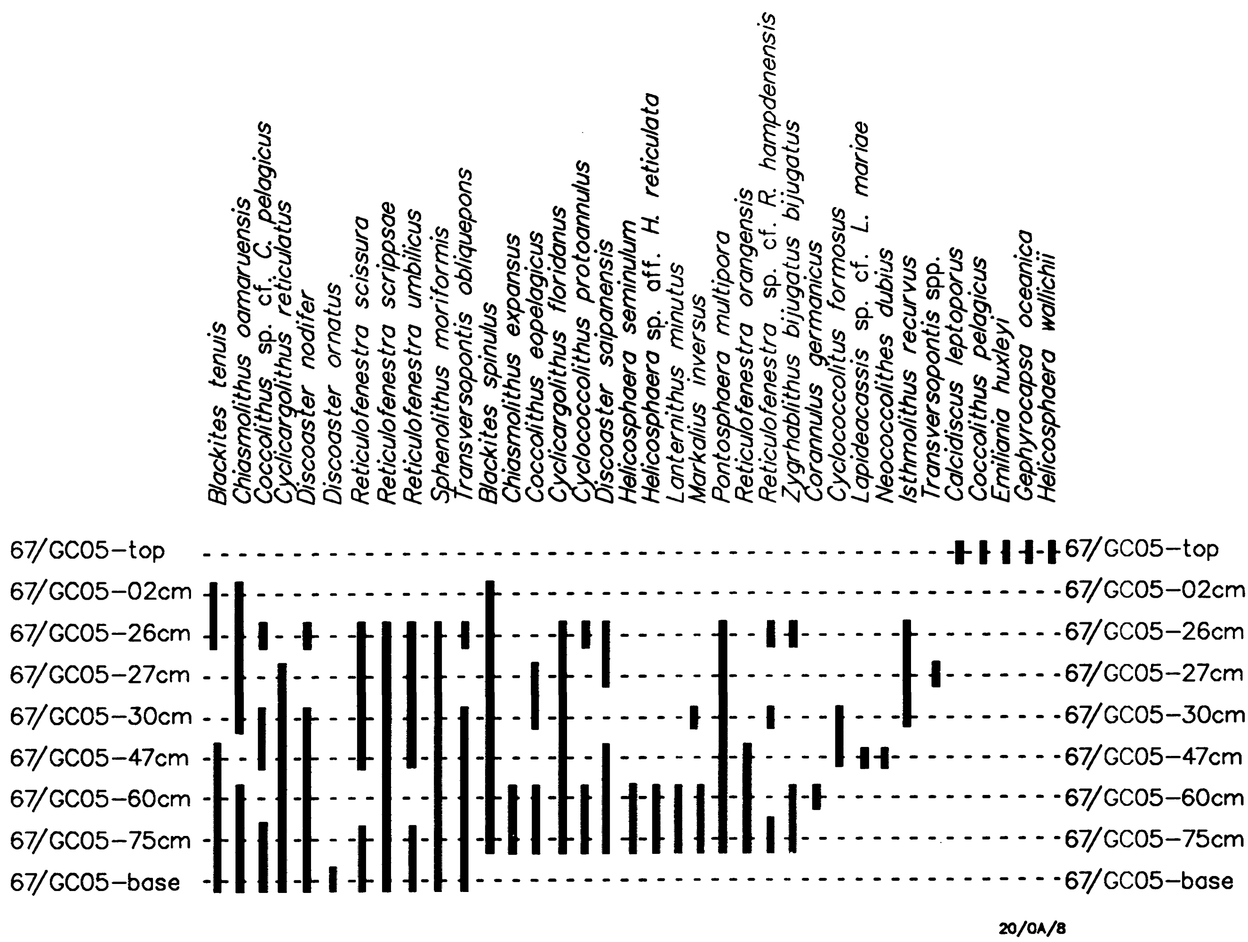
NANNOFOSSIL ASSEMBLAGES

Biostratigraphic assignment to any of the published calcareous nannofossil zonal schemes (e.g. Martini, 1971) was not attempted. Instead, the concept of nannofossil datum interval (DI) was used and assemblages were related to a framework of calcareous nannofossil events (Tables 1 & 2); the symbols * and + are used to denote lowest and highest occurrences of taxa respectively.

GRAVITY CORES

Upper Eocene in gravity core 67/GC 05

This core was taken on the lower slope of the Beachport Terrace in a water depth of 2235 m, at Lat. 37°45.46'S - Long. 138°34.40'E, and recovered about 75 cm of mudstone. Sharp colour changes are present at the 26-cm and 2-cm levels in the core. Nine levels were sampled and examined. Their nannofossil assemblages (Checklist 1), age, and palaeoenvironments are detailed in Shafik (1987b). The colour change at 2 cm level was found to coincide with a distinct biostratigraphic break where Late Eocene assemblages abruptly give way to late Quaternary ones. The Upper Eocene section is assigned to the nannofossil datum interval (DI): **Chiasmolithus oamaruensis*/+*Cyclicargolithus reticulatus* (Table 1). These two species were recorded throughout the Eocene section, in association with *Blackites* spp., *Discoaster saipanensis*, and the hemipelagic taxa *Lanternithus minutus*, *Pontosphaera multipora*, *Transversopontis obliquepons* and *Zygrhablithus*



Checklist 1. Distribution of selected calcareous nannofossil taxa, arranged by lowest occurrence, in Core 67/GC05.

Age	Biostratigraphic events	P.zone	Assignment
Late Eocene	* *Reticulofenestra scissura*	P. 16	← 67/DR 2-2b
	* *Chiasmolithus grandis*	P. 16	
	* *Cyclicargolithus reticulatus*	P. 15	
	* *Discoaster saipanensis*	P. 15	← 67/DR 10-3c
	+ *Isthmolithus recurvus*	P. 14	
	+ *Neococcolithes dubius*		
Middle Eocene	+ *Chiasmolithus oamaruensis*	P. 13	← 48/DR 7-3 ← 48/DR 7-1
	+ *Cyclicargolithus reticulatus*	P. 13	← 67/DR 10-3a
	* *Daktylethra punctulata*	P. 12	

20/OA/6

* Lowest occurrence   + Highest occurrence   Span of core 67/GC05

Table 1. Mid Middle to latest Eocene calcareous nannofossil events and their correlation with the foraminiferal P. zones

bijugatus, suggesting a Late Eocene age and deposition in a shallow-water palaeoenvironment. The index species *Isthmolithus recurvus* first appears (up-section) at the 30-cm level.

An up-section reduction in the abundance and diversity of the hemipelagic taxa in the Eocene part of the core is taken to indicate deepening during the Late Eocene at this site.

Discussion. A comparison between the Late Eocene nannofossil assemblages of core 67/GC 05 and coeval assemblages from onshore sections in the Otway Basin (Shafik, 1983) reveals some noteworthy points:

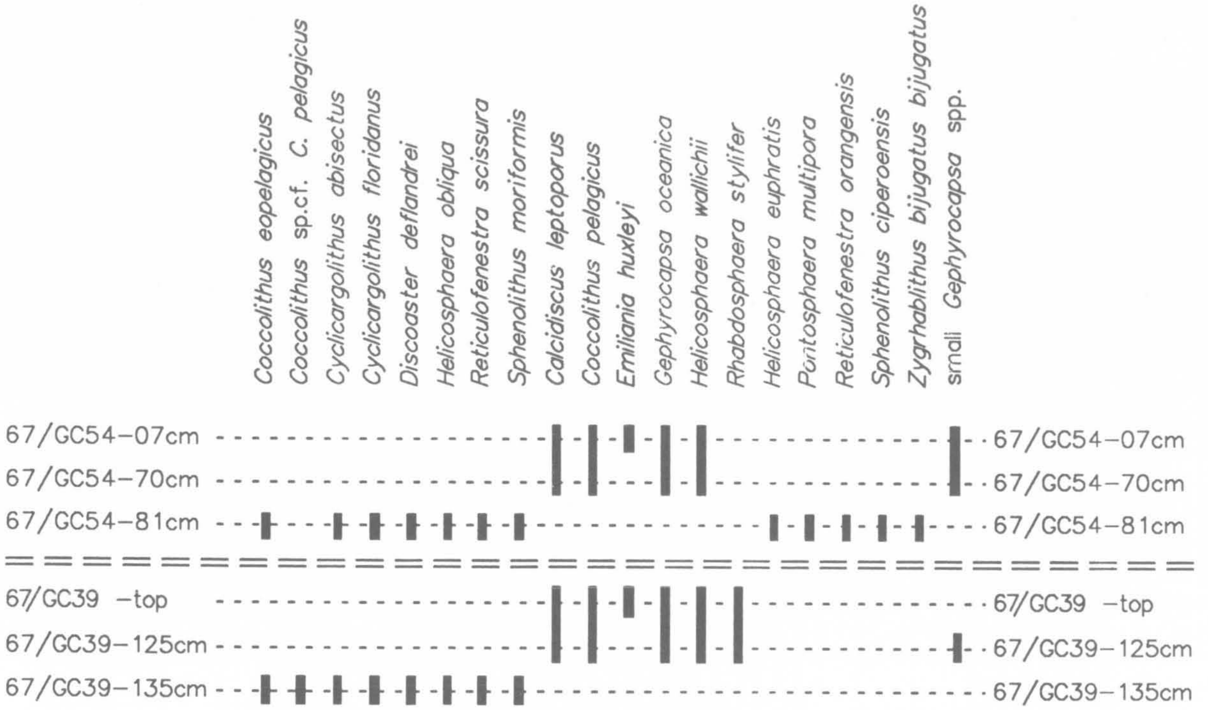
1. Some of the oceanic taxa, particularly *Reticulofenestra umbilicus, R. scissura,* and *Cyclicargolithus reticulatus* are substantially larger in size in offshore core 67/GC 05 than in the onshore material (e.g. Observation Bores #1 & #2: Shafik, 1983).
2. Other taxa, the hemipelagic ones, such as *Zygrhablithus bijugatus bijugatus,* and *Pontosphaera multipora*, are generally smaller in size in the offshore than in the onshore assemblages.
3. Some of the key taxa, particularly *Cyclococcolithus formosus*, are much rarer in the offshore than in the onshore material; these taxa are usually frequent to common in onshore material. This could have serious consequences if age determination of offshore material is based on the absence of such taxa.

Upper Oligocene in gravity core 67/GC 39

Coring at Lat. 40°37.9'S - Long. 140°50.1'E, west of Tasmania and King Island, where the water depth is 4300 m, recovered 135 cm of mainly grey foram nanno ooze, with a thin layer of coarse sand overlying stiff green clays at the bottom. The Late Oligocene nannofossils are restricted to the bottom of the core, at 135 cm. Other levels studied, at 125 cm and the top of the core, recovered late Quaternary coccoliths (Checklist 2). The Late Oligocene age is based on the presence of *Cyclicargolithus abisectus*, *Helicosphaera obliqua* and *Reticulofenestra scissura*. Assemblages, age and palaeonvironments are detailed in Shafik (1987b). Partial dissolution of most taxa encountered in the Late Oligocene assemblages is due to deposition close to the calcium compensation depth (CCD), or the result of prolonged exposure to cold bottom currents, or both.

Upper Oligocene in gravity core 67/GC 54

A core of 97 cm of olive-grey foram nanno ooze over hard greyish olive mudstone was recovered at Lat. 41°10.9'S - Long. 143° 50.2'E, where the water depth is 1634 m. Three samples were examined, and their assemblages, age and palaeoenvironments are detailed in Shafik (1987b). Two samples from the ooze at 7 and 70 cm yielded Quaternary coccoliths, with rare displaced Tertiary specimens. The third sample came from the hard mudstone, at 85 cm. This yielded the Late Oligocene index species *Sphenolithus ciperoensis*, in association with *Cyclicargolithus abisectus*,



Checklist 2. Distribution of selected calcarous nannofossil taxa, arranged by lowest occurrence, in Cores 67/GC54 and 67/GC39

Helicosphaera euphratis, Reticulofenestra scissura and *Zygrhablithus bijugatus* (see Checklist 2). The biostratigraphic position of the Oligocene sample is shown in Table 2.

The presence of the low-latitude *Sphenolithus ciperoensis* suggests an episode of warming during the Late Oligocene in the Otway Basin. The exclusion of the cool to cold-water indicator *Chiasmolithus altus* from the assemblage of 67/GC 54 (85 cm) supports this conclusion. The abundant occurrence of *Zygrhablithus bijugatus* suggests that the depositional palaeoenvironment was much shallower than during the deposition of the Upper Oligocene green clays recovered at the bottom of core 67/GC 39.

Lower Miocene in gravity core 67/GC 40

This 65 cm core was taken at Lat. $40^{o}41.5$'S - Long. $141^{o}46.4$'E, west of Tasmania and King Island, where the water depth is 4370 m. A short section of Quaternary brown foram nanno ooze over a light olive-brown Miocene calcareous clay unit was recovered. The contact between the ooze and the clay units is sharp, at 22 cm. The Miocene assemblage is a mixture of moderately well-preserved and badly corroded specimens. Species identified include *Calcidiscus leptoporus*, *Cyclicargolithus abisectus*, *C. floridanus*, *Discoaster deflandrei*, *?D. druggii*, *?D. exilis*, *Helicosphaera euphratis*, *H. kamptneri*, *H. obliqua*, *?H. granulata*, *Pontosphaera multipora*, *Sphenolithus abies*, *S. conicus*, *S.* sp. aff *S. belemons*, and *S. moriformis*. The age is Early Miocene. Partial dissolution of the assemblage is probably the result of prolonged exposure of the Lower Miocene clays to cold bottom waters. Initially, these clays were probably deposited in a shallow-water palaeoenvironment as attested to by the presence of *Pontosphaera multipora*.

Pliocene in gravity cores (see also Shafik, 1987b)

Gravity core 67/GC 36

This core recovered 244 cm of mainly grey foram nanno ooze at Lat. $40^{o}00.88$'S - Long. $142^{o}40.11$'E, where the water depth is 2182 m. The presence of *Calcidiscus macintyrei* and *Pseudoemiliania lacunosa* and the absence of bridged *Gephyrocapsa* spp. in assemblages from the lower part of the core (at 244 and 195 cm) suggest a Late Pliocene age.

Gravity core 67/GC 45

This core recovered 360 cm of grey and greenish grey foram ooze at Lat. $42^{o}13.6$'S - Long. $142^{o}52.5$'E, where the water depth is 3715 m. The absence of *Gephyrocapsa* spp. and the presence of both *Calcidiscus macintyrei* and *Pseudoemiliania lacunosa* in assemblages from the lower part of the core (at 360 and 198 cm) suggest a Late Pliocene age. The top of the core yielded Quaternary assemblages rich with bridged *Gephyrocapsa* spp. The exclusion of discoasters from the Pliocene section is attributed to cold surface waters and is not considered as reliable biostratigraphic evidence indicating Quaternary age; the abundant occurrence of *Coccolithus pelagicus* in this section indicates cold surface waters.

Gravity core 67/GC 46

This core recovered 176 cm of greenish grey foram nanno ooze, over calcareous sand turbidite, over soft light grey chalk, at Lat. 42°12.1'S - Long. 144°24.8'E, where the water depth is 2360 m. The age of the chalk is Late Pliocene on account of the presence of *Calcidiscus macintyrei* and *Pseudoemiliania lacunosa* and the absence of bridged *Gephyrocapsa* spp. Slim-rayed discoasters are absent and *Coccolithus pelagicus* is common, suggesting cold surface waters during the Late Pliocene in the Otway Basin.

DREDGE SAMPLES

Dredge station 2

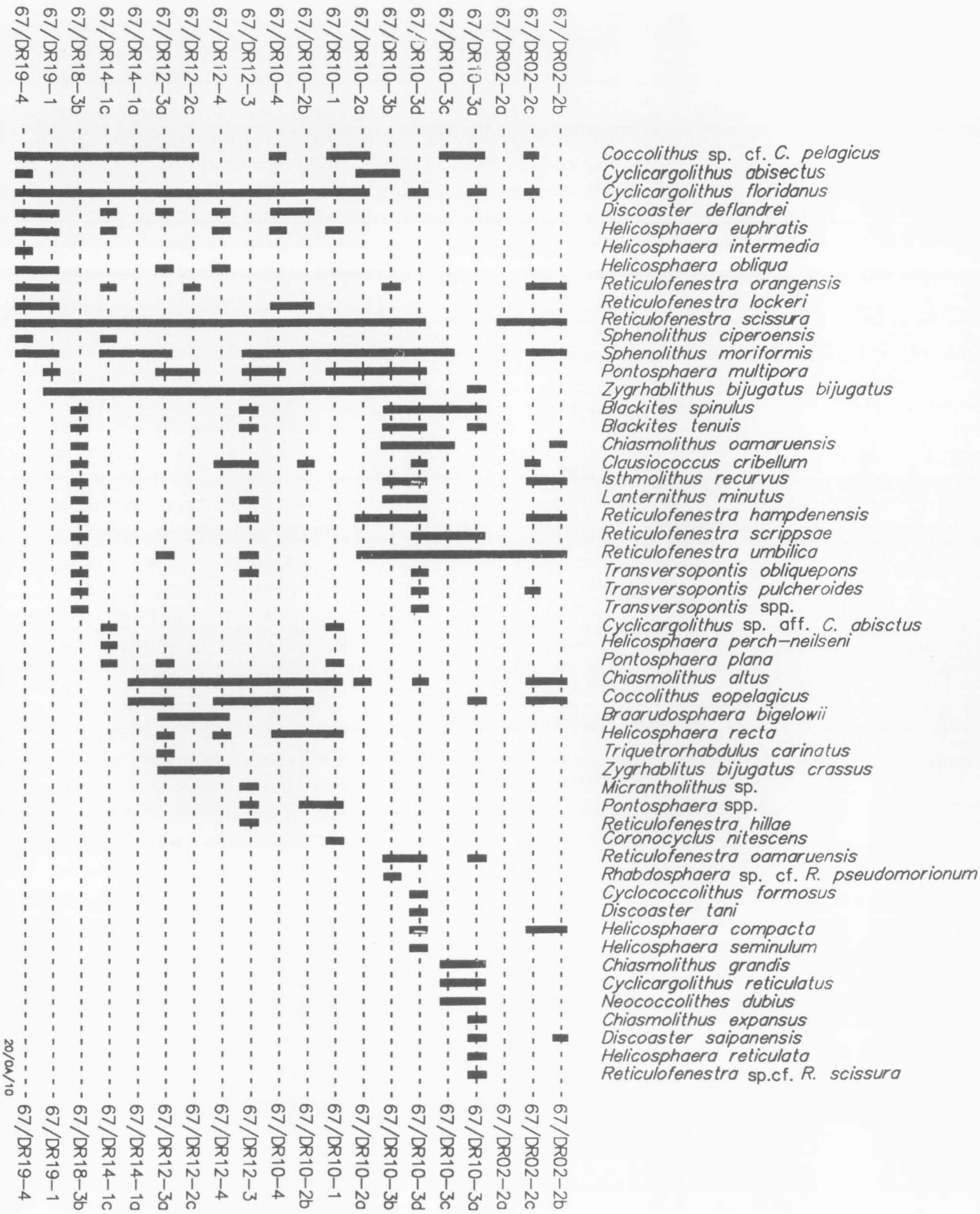
Dredging was attempted along a slope off southeastern South Australia, on the Beachport Terrace, between Lat. 37° 40' - Long. 138° 20' and Lat. 37° 37.6'S - Long. 138°19.6'E. Water depth ranges between 4100 and 3700 m. Two types of sediments were recovered: yellowish grey foram nanno ooze (67/DR2-1), and semi-lithified light olive-grey sandy siltstone with some darker material (67/DR2-2).

Preparation 67/DR 2-2b

A subsample of the semi-lithified olive-grey sandy siltstone yielded abundant poorly-preserved calcareous nannofossils. The assemblage (detailed in Checklist 3) is assignable to the latest Eocene DI: +*Cyclicargolithus reticulatus*/+*Discoaster saipanensis*, + being highest occurrence. The key species *Chiasmolithus oamaruensis*, *Discoaster saipanensis* and *Isthmolithus recurvus* are present. Surface waters were cool to cold, as attested to by the extreme rarity of discoasters and the abundance of chiasmoliths and *Reticulofenestra hampdenensis*. Partial dissolution of most taxa suggests prolonged exposure to cold bottom currents, but the total absence of holococcoliths and indicators of hemipelagic palaeoenvironments suggests that deposition occurred initially beyond the shelf, probably on the continental slope.

Preparation 67/DR 2-2c

Another subsample of the semi-lithified olive-grey sandy siltstone was examined. A poorly preserved assemblage was recovered. Nannofossils are common to abundant, but most specimens show signs of dissolution. The assemblage (Checklist 3) is readily assignable to the biostratigraphic interval coincident with the total stratigraphic range of *Isthmolithus recurvus*. The age is Late Eocene to Early Oligocene. The absence of the Eocene index species *Cyclicargolithus reticulatus* and *Discoaster saipanensis* favours the younger age. However, *D. saipanensis* is usually rare in the uppermost Eocene of the onshore Otway Basin (Shafik, 1983) and its absence from Preparation 67/DR 2-2c may not be biostratigraphically significant. On the



Checklist 3. Distribution of selected calcareous nannofossil taxa, arranged by lowest occurrence, in Eocene and Oligocene dredge samples

other hand, *C. reticulatus* is more common in the same onshore Eocene sequence (Shafik, 1983) but disappears from the record before *D. saipanensis*. Its absence from the assemblage of 67/DR 2-2c is likely to be a true biostratigraphic absence, and assignment to the narrower DI +*Cyclicargolithus reticulatus*/+*Isthmolithus recurvus* can be made.

Specimens of the genus *Chiasmolithus* are overwhelmingly more abundant than those of the genus *Discoaster*, indicating cool to cold surface waters. The great abundance of *Reticulofenestra hampdenensis*, and the presence of *Isthmolithus recurvus* support this conclusion. Deposition on the continental slope and prolonged exposure to cold bottom currents are suggested because of the general paucity of species (reduced diversity partly as a result of absence of holococcoliths and hemipelagic taxa), and the abounding signs of severe dissolution (such as the absence of the crosses in most chiasmoliths).

Preparation 67/DR 2-2a

This preparation is from a third fragment of the semi-lithified olive-grey siltstone. It is almost barren of calcareous nannofossils. The meagre assemblage (see Checklist 3) is assigned to the broad DI: **Cyclicargolithus reticulatus*/+ *Reticulofenestra umbilicus*, based primarily on the co-occurrence of *Reticulofenestra scissura* and *R. umbilicus*. The age is within the bracket latest Eocene to mid Oligocene. Deposition occurred on the continental slope, at depths where cold bottom currents are most effective in corroding and dissolving the nannofossils.

Preparation DR 2-1

A late Quaternary assemblage of abundant, moderately well-preserved coccoliths was identified. Abundant *Coccolithus pelagicus* suggests cold surface waters.

Dredge station 3

This station lies beyond the Beachport Terrace between, Lat. 38^o 14.56'S - Long. 138^{o}34.66'E and Lat. 38^{o}14.13'S - Long. 138^o 35.22'E, near the abyssal plain, on the outer continental margin. The water depth dredged ranges between 4800 and 4100 m. Two main types of sediments were collected at this station: indurated siltstone (partly coated with secondary iron oxides) and dark brown silty claystone with Fe/Mn coating. No calcareous nannofossils were found in two samples examined from these lithotypes. The soft sediment recovered in the dredge pipe yielded poorly preserved coccoliths, indicating late Quaternary age; the poor preservation is mainly because of partial dissolution. These included *Calcidiscus leptoporus*, *Coccolithus pelagicus*, *Gephyrocapsa oceanica* and questionable *Emiliania huxleyi*.

Dredge station 4

This station lies between Lat. 38^{o}26.3'S - Long. 138^{o}49.6'E and Lat. 38^{o}24.3'S - Long. 138^{o}52.3'E, where water depth ranges between 4700 and

4050 m. Several types of hard rock/sediment were recovered. Four types were examined. A preparation from the dominant type 67/DR 4-1 (a dark grey to brown argillite with incipient to distinct slaty cleavage and strongly fractured) is devoid of calcareous nannofossils. Also, preparations from types 67/DR 4-2 (a grey-brown mudrock) and 67/DR 4-5 (dark brown plastic mud) lacked calcareous nannofossils.

Dredge station 5

Dredging was attempted along the lower slope of BMR seismic profile 48/42. Positions dredged are between Lat. 38°25.4'S - Long. 138° 54.7'E and Lat. 38°24.8'S - Long. 138°56.8'E. Water depth ranges between 3900 and 3400 m. Recovered sediments included grey mudstone (dominant) and black mud. Both types lacked calcareous nannofossils; their age could not be determined.

Dredge station 6

Dredging was attempted along a ridge on the abyssal plain SW of Argonaut #1 well between Lat. 38°46.5'S - Long. 139°39.0'E and Lat. 38°46.2'S - Long. 139°39.0'E. Water depths dredged range between 4750 and 4780 m. The dominant lithology is a black mudstone (67/DR 6a) which lacks calcareous nannofossils. The olive-grey pelagic ooze (67/DR 6b) yielded Quaternary coccoliths.

Dredge station 7

Dredging at this station was targeted to sample basement rocks of the continental crust, along a ridge outcrop on the abyssal plain, between Lat. 38°47.4'S - Long. 139°12.4'E and Lat. 38°47.8'S - Long. 139°12.1'E. Water depth ranged between 4450 and 4200 m. Light brown ooze (67/DR 7a) and several small black mudstone pebbles (67/DR 7b) were recovered. Abundant Quaternary coccoliths were recovered from the brown ooze (67/DR 7a). In contrast, none of the mudstone pebbles examined yielded calcareous nannofossils.

Dredge station 8

Dredging was attempted along a ridge near the base of the continental slope between Lat. 39°01.2'S - Long. 140°03.4'E and Lat. 39°02.7'S - Long. 140°00.9'E, in waters ranging in depth from 4351 to 4050 m. Pelagic mud (67/DR 8-1) and fragments of brown mudstone (67/DR 8-1) were recovered. Calcareous nannofossils indicating late Quaternary age were extracted from the pelagic mud 67/DR 8-1, but the brown mudstone lacked nannofossils. The age of the brown mudstone fragments could not be determined.

Dredge station 9

Dredging along the continental slope at the edge of the abyssal plain at Lat. 39°26.9'S - Long. 139°59.5'E, where water depth is 4800 m, recovered hard siliceous cherts, fine-grained igneous rocks, and yellowish brown calcareous ooze (67/DR 9-9). Calcareous nannofossils indicating a late Quaternary age were identified from the ooze.

Dredge station 10

Dredging along a relatively steep slope southwest of Argonaut #1 well, between Lat. 38°05.2'S - Long. 139°45.2'E and Lat. 38° 04.5'S - Long. 139°46.4'E, resulted in the recovery of five rock types plus Quaternary light brown mud. The water depth dredged ranges between 1950 and 1700 m. Dominant rock types are white fossiliferous calcareous claystone with poorly sorted, poorly rounded quartz grains (DR 10-1), light brownish grey sparsely fossiliferous calcareous clay with poorly sorted minor quartz and minor mica (DR 10-3), and chert concretions (DR 10-2) from types 67/DR 10-1 and 67/DR-3. Other types include very highly fossiliferous (90% bryozoans) calcarenite, with concretions and well-rounded minor quartz (DR 10-4).

Biostratigraphic placement of several samples examined from Dredge Station 10 is indicated in Table 2 which shows the nannofossil biostratigraphic events across the Eocene/Oligocene boundary and for the Oligocene.

Preparation 67/DR 10-3a

A subsample of the brownish grey calcareous clay was examined. The assemblage recovered is moderately well-preserved. Dilution by siliceous microfossils caused low nannofossil abundance in the preparation. The assemblage (detailed in Checklist 3) is assigned to the mid Eocene DI: **Cyclicargolithus reticulatus/*Reticulofenestra scissura*, which suggests a correlation within the low-latitude planktic foraminiferal zone interval P. 12 to P. 13, probably early P.13. Based on the relative abundance of specimens of *Chiasmolithus* compared to *Discoaster*, surface water temperatures were temperate. Deposition occurred in relatively shallow waters, on the continental shelf. Coeval assemblages from onshore material in the Perth and Otway Basins (Shafik, 1978; 1983) include more abundant and diversified nearshore nannofossil indicators.

Preparation 67/DR 10-3c

Another subsample of the brownish grey calcareous clay was examined. Abundant moderately well-preserved calcareous nannofossils were recovered. An overlap in the ranges of *Chiasmolithus oamaruensis* and *Neococcolithes dubius* suggests a Late Eocene age. The assemblage (Checklist 3) is assigned to the DI: **Chiasmolithus oamaruensis/ +Neococcolithes dubius*. This interval correlates within the planktic foraminiferal zonal interval P.14-early P. 15 (see Table 1). Deposition probably occurred on the continental shelf, as evidenced by the presence of *Blackites spinulus*.

Preparation 67/DR 10-3d

A third subsample of the brownish grey calcareous clay was examined. Abundant moderately well-preserved calcareous nannofossils were recovered.

The assemblage (Checklist 3) is assigned to DI: +*Cyclicargolithus reticulatus*/+*Cyclococcolithus formosus*, suggesting an age range of latest Eocene to earliest Oligocene. The occurrence of several hemipelagic taxa suggests a nearshore or shallow-water environment of the continental shelf. Surface waters were cool, as evidenced by the abundance of chiasmoliths, the rarity of discoasters, and the great abundance of *Reticulofenestra hampdenensis*.

Preparation 67/DR 10-3b

A fourth subsample of the brownish grey calcareous clay was examined. Abundant moderately well-preserved nannofossils were recorded (Checklist 3) among abundant nannofossil debris in this preparation. Species diversity is relatively high. The assemblage includes species suggesting a latest Eocene to Early Oligocene age, being assignable to the broad DI: +*Cyclicargolithus reticulatus*/+*Isthmolithus recurvus*. Surface waters were probably cool to cold, as discoasters are rare in the assemblage. Deposition was in a relatively shallow-water environment, as attested to by several hemipelagic taxa.

Discussion. The assemblages of subsamples 67/DR 10-3a, 67/DR 10-3b, 67/DR10-3c, and 67/DR-3d include taxa indicative of shallow-water deposition, but in varying proportion and abundance. This probably suggests varying depositional depth. The Middle Eocene assemblage of subsample 67/DR10-3a suggests greater depositional depth compared with the others -- the shallow-water indicator *Zygrhablithus bijugatus bijugatus* was found among this assemblage only in small numbers. In contrast, several shallow-water indicators, including *Z. bijugatus bijugatus, Lanternithus minutus, Pontosphaera multipora* and *Transversopontis* spp., were found in the younger assemblages of subsamples 67/DR 10-3b and 67/DR 10-3d; these assemblages are latest Eocene to Early Oligocene in age. The Late Eocene assemblage of subsample 67/DR 10-3c contains rarer and less diversified shallow-water nannofossil indicators than in the younger assemblages.

Based on the nannofossil evidence in the subsamples of 67/DR 10-3 discussed above, it is not unreasonable to conclude that shoaling/ sea-level fall occurred progressively from the later part of the Eocene through into the Early Oligocene.

Preparation 67/DR 10-2a

A subsample of sediments enclosing the chert concretions (DR 10-2) was examined. Abundant moderately well-preserved calcareous nannofossils were recorded (Checklist 3) among abundant nannofossil debris in this preparation. Species diversity is, however, relatively low. The assemblage suggests an Early to mid Oligocene age. It is assigned to DI: +*Isthmolithus recurvus*/+*Reticulofenestra umbilicus* (see Table 2). The low diversity (compared with coeval low-latitude) suggests cool to cold surface waters, and the presence of hemipelagic taxa suggests that deposition was on the continental shelf.

Age	Biostratigraphic events	Sample assignment
Late Oligocene	+ *Helicosphaera recta*	
	+ *Reticulofenestra scissura*	
	interval with *Sphenolithus ciperoensis*	DR 14-1c; DR 19-4; GC 54(85cm)
	+ *Chiasmolithus altua* ●	DR 19-1; GC 39cc
		DR 10-1, 10-2b, 10-4; DR 12-4, 12-3a; DR 14-1a, 48/DR 7-2; 48/DR 5-2
Early Oligocene	* *Helicosphaera recta; H. obliqua*	
		48/DR 7-7; 48/DR 5-1
	+ *Reticulofenestra umbilicus*	DR 10-2a; DR 12-3
	+ *Isthmolithus recurvus*	
	+ *Cyclococcolithus formosus* ▲	DR 10-3b; DR 18-3b; DR 2-2c
		DR 10-3d; 48/DR 7-1
	+ *Discoaster saipanensis* ▲	
Late Eocene	+ *Cyclicargolitus reticulatus*	

* Lowest occurrence + Highest occurrence 20/0A/7

▲ this event is unreliable because the species is usually rare and inconsistent in the onshore material (see text)

● available data do not exclude the possibility that *Chiasmolithus altus* may reappear after the short interval with *Sphenolithus ciperoensis*

Table 2. Latest Eocene to Late Oligocene nannofossil events

Preparation 67/DR 10-1

A subsample of the white calcareous claystone was examined. The assemblage contains abundant moderately well-preserved calcareous nannofossils (see Checklist 3). It is assigned to the calcareous nannofossil DI: * *Helicosphaera recta/+Reticulofenestra scissura* (see Table 2). The suggested age is Late Oligocene. The absence of low-latitude sphenoliths, and the presence of abundant *Chiasmolithus altus*, suggest cold surface waters, and the presence of hemipelagic taxa, such as *Pontosphaera* spp. and *Zygrhablithus bijugatus bijugatus*, suggests that deposition occurred in a nearshore or shallow-water environment on the continental shelf.

Preparation 67/DR 10-2b

Another subsample of sediments enclosing the chert concretions (DR 10-2) was examined. The assemblage (Checklist 3) recovered is not dissimilar to that of Preparation 67/DR 10-1. The taxa are poorly preserved, evidently as a result of diagenesis. Like that of Preparation 67/DR 10-1, the age is Late Oligocene. The assemblage is assigned to DI: **Helicosphaera recta/+Chiasmolithus altus* (see Table 2). Deposition probably occurred in a nearshore or shallow-water environment, similar to the environment deduced for sample 67/DR 10-1. Diagenetic processes (e.g. recrystallisation) are probably responsible for the reduced diversity of hemipelagic taxa.

Preparation 67/DR 10-4

A subsample of the bryozoal calcarenite was examined. The assemblage (Checklist 3) recovered is similar to that of Preparation 67/DR 10-2b. The age is Late Oligocene. The assemblage is assignable to DI: **Helicosphaera recta/+Chiasmolithus altus*. The assemblage lived in cold surface waters on the continental shelf, similar to the environment deduced for the Late Oligocene assemblages in Preparations 67/DR 10-1 and 67/DR 10-2b.

Dredge Station 12

Dredging was attempted in a canyon on the middle slope, southwest of Beachport, between Lat. 37°46.3'S - Long. 139°25.3'E and Lat 37°46.7'S - Long. 139°26.6'E. Water depth ranges between 1150 and 1350 m. Five types of sediments were recovered: a dark grey sandy mudstone and fine to medium-grained brown ferruginous sandstone (67/DR 12-1), firm white chalk (67/DR 12-2), chert or porcellanite with altered calcareous mudstone (67/DR 12-3), soft white chalk (67/DR 12- 4), and brown to grey mudstone (67/DR 12-5).

Preparation 67/DR 12-3

A subsample of the calcareous mudstone adhering to the chert of sample 67/DR 12-3 was examined. Abundant and moderately well-preserved calcareous nannofossils (Checklist 3) were encountered in this preparation. The age of the assemblage was Early to mid Oligocene. The absence of *Isthmolithus recurvus* favours the younger age. The assemblage is assigned to DI: +*Isthmolithus recurvus*/+*Reticulofenestra umbilicus* (see Table 2). The assemblage suggests cool to cold surface waters, and deposition on the continental shelf. The conclusion is based on the total absence of low-latitude sphenoliths, the abundant occurrence of the cool-water indicator *Chiasmolithus altus*, and the presence of several hemipelagic taxa such as *Lanternithus minutus* and several species of *Micrantholithus*.

Preparation 67/DR 12-2c

A subsample of the firm white chalk was examined. Moderately well-preserved nannofossils (Checklist 3) among abundant fine debris were recovered. The age of the assemblage is mid Oligocene, based on the presence of *Cyclicargolithus* sp. aff. *C. abisectus* and *Reticulofenestra scissura*, in the absence of *Reticulofenestra umbilicus* and *Helicosphaera recta*.

The presence of *Braarudosphaera bigelowii*, *Pontosphaera multipora* and *Zygrhablithus bijugatus* suggests a shallow-water depositional palaeoenvironment. The abundant occurrence of *Chiasmolithus altus* and the absence of sphenoliths indicate cold surface waters.

Preparation 67/DR 12-4

A subsample of the soft white chalk was examined. Calcareous nannofossils (Checklist 3) are abundant and moderately well-preserved. Notable are the key species *Helicosphaera euphratis*, *H. obliqua*, *H. recta*. The age is Late Oligocene. The assemblage is assigned to DI: **Helicosphaera recta*/+*Chismolithus altus* (see Table 2). Coeval low-latitude assemblages (e.g. from Ashmore Reef, NW Australia: Shafik & Chaproniere, 1978) contain the index species *Sphenolithus ciperoensis*. which is notably absent in Preparation 67/DR 12-4. The assemblage contains evidence (such as *Braarudosphaera bigelowii* and abundant *Chiasmolithus altus*) to suggest that deposition occurred in a cold, nearshore or shallow-water environment on the continental shelf.

Preparation 67/DR 12-3a

Another subsample of the calcareous mudstone adhering to the chert of sample 67/DR 12-3 is examined. Abundant moderately well-preserved nannofossils (Checklist 3) were recovered. Notable is the presence of *Triquetrorhabdulus carinatus* and *Reticulofenestra scissura*. The assemblage indicates a Late Oligocene age, and is assigned to the DI: **Helicosphaera recta*/+*Chiasmolithus altus* (see Table 2). Deposition probably occurred in a cold nearshore or shallow-water environment on the continental shelf. The evidence is the presence of several hemipelagic taxa such as *Pontosphaera multipora*, *P. plana* and *Zygrhablithus bijugatus bijugatus* and the abundant occurrence of *Chiasmolithus altus*, in the absence of the low-latitude sphenoliths (such as *Sphenolithus distentus* or *S. ciperoensis*).

Preparation 67/DR 12-2

Another subsample of the firm white chalk was examined. Abundant, moderately well-preserved nannofossils were examined. The assemblage includes *Cyclicargolithus abisectus*, *C. floridanus*, *Helicosphaera kamptneri* and *Calcidiscus leptoporus* which collectively suggest an Early (possibly earliest) Miocene age. Low species diversity (Checklist 4) suggests cool surface waters, and deposition at intermediate depths.

Preparation 67/DR 12-5

A late Quaternary, moderately well-preserved coccolith assemblage was extracted. Rare older taxa were encountered, suggesting possible contaminations.

Preparation 67/DR 12-1

No calcareous nannofossils were found in the sandstone of 67/DR 12-1.

Dredge station 14

Dredging was successful along the western side of a SSW trending canyon, south of Port Macdonnell, between Lat. 38°50.0'S - Long. 140° 35.4'E and Lat. 38°49.8'S - Long. 140°35.0'E, where water depth ranges between 3050 and 3100 m. White, bored and bioturbated, fine-grained chalks containing chert nodules, with pale green weathering surfaces (67/DR 14- 1) were recovered, along with a small piece of white foram-rich chalk with some shelly fragments (67/DR 14-7), and grey foram nanno ooze (67/DR 14-8).

Preparation 67/DR 14-1a

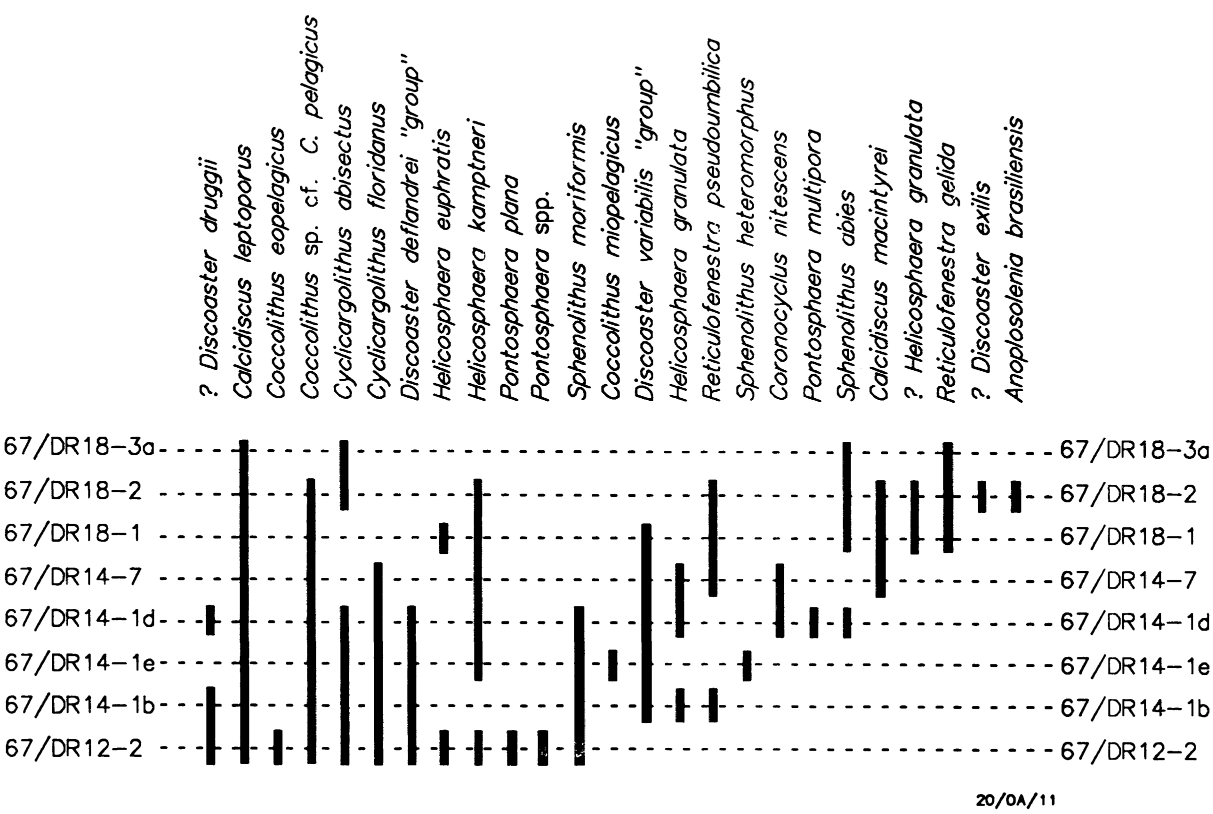
A subsample of the white chalk contained abundant moderately well-preserved calcareous nannofossils. The assemblage (Checklist 3) is Late Oligocene in age, assignable to DI: **Helicosphaera recta/+Chiasmolithus altus* (see Table 2). The assemblage contains evidence (abundant *Chiasmolithus altus* and *Zygrhablithus bijugatus*) to suggest cool to cold surface waters and deposition on the continental shelf.

Preparation 67/DR 14-1c

Another subsample of the white chalk contained a rich assemblage (Checklist 3) of moderately well-preserved calcareous nannofossils. The assemblage suggests a Late Oligocene age. It is assigned to the interval with *Sphenolithus ciperoensis* (see Table 2). The assemblage evidently represents a short warming episode. The absence of the cool-water indicator *Chiasmolithus altus* strongly supports this conclusion.

Preparation 67/DR 14-1b

Another subsample of the white chalk contained an assemblage dominated by two species (*Cyclicargolithus abisectus* and *C. floridanus*), even though the diversity is reasonably high (Checklist 4) .



Checklist 4. Distribution of selected calcareous nannofossil taxa, arranged by lowest occurrence in Miocene dredge samples

The presence of the index species *Sphenolithus heteromorphus* suggests late Early to early Middle Miocene. The vertical range of this species straddles the boundary between the Early and Middle Miocene according to many authors (e.g. Martini, 1971). This boundary is usually drawn at the extinction of *Helicosphaera ampliaperta* (see, e.g. Martini, 1971). *H. ampliaperta* has yet to be found in southern Australia. In contrast, *Sphenolithus heteromorphus* has a wide geographic range, and has been recorded from several Victorian sections (e.g. Sorento Bore, and Fossil Beach section: Shafik, unpublished data); in core 67/GC 35, displaced coeval mudstone containing abundant *Sphenolithus heteromorphus* is bounded by Quaternary clays.

The absence of *Helicosphaera ampliaperta* from Preparation 67/DR 14-1b and the Victorian Tertiary may not be biostratigraphically correlatable with the extinction of this species elsewhere.

Preparation 67/DR 14-1e

Another subsample of the white chalk contained abundant moderately well-preserved calcareous nannofossils (Checklist 4). The age is late Early to early Middle Miocene on account of the presence of the index species *Sphenolithus heteromorphus*.

Preparation 67/DR 14-1d

Another subsample of the white chalk yielded abundant and moderately well-preserved calcareous nannofossils (Checklist 4). It is tentatively considered to be Early to mid Miocene on account of *Calcidiscus leptoporus*, *Helicosphaera kamptneri*, *H. granulata*, *Cyclicarglithus abisectus*, *C. floridanus* and several poorly-preserved discoasters which are tentatively identified as *Discoaster deflandrei* 'group' and *D. variabilis* 'group' .

Preparation 67/DR 14-7

A subsample of white soft calcareous clay contained abundant moderately well-preserved calcareous nannofossils (Checklist 4). The age is tentatively considered to be early Middle Miocene on account of *Calcidiscus macintyrei*, *Discoaster variabilis* 'group', *Helicosphaera kamptneri* and small *Reticulofenestra pseudoumbilicus*.

Preparation 67/DR 14-8

A subsample of pale grey foram nanno ooze contained abundant and moderately well-preserved coccoliths. Its age is late Quaternary. Low species diversity, coupled with the occurrence of common *Coccolithus pelagicus*, suggests cold surface waters.

Dredge station 15

This station lies south of Port Macdonnell, in a canyon at Lat. 38°57.7'S - Long. 140°51.5'E where water depth is 3000 m. No Tertiary calcareous nannofossils were found in the samples examined.

Dredge station 16

This station lies south of Portland, between Lat. $38^{o}54.17$'S - Long. $141^{o}29.32$'E and Lat. $38^{o}53.5$'S - Long. $141^{o}29.2$'E where water depth ranges from 1733 to 1450 m. Light olive-grey mud was recovered and coccoliths indicative of late Quaternary age were extracted.

Dredge station 17

Dredging was attempted between Lat. $39^{o}09$'S - Long. $141^{o}51.1$'E and Lat. $39^{o}09$'S - Long. $141^{o}53.0$'E, where water depth ranges between 2270 and 2060 m. No Tertiary calcareous nannofossils were found.

Dredge station 18

This station lies SW of Portland, between Lat. $39^{o}12.9$'S - Long. $142^{o}7.2$'E and Lat. $39^{o}11.8$'S - Long. $142^{o}11.5$'E, where water depth is between 1950 and 1650 m. A few pieces of recovered sediment could be sorted into six types: moderately lithified foram-bearing white chalk (67/DR 18-1); soft white calcareous mud (67/DR 18-2); pale brown mostly non-calcareous, weakly lithified siltstone (67/DR 18-3); light olive-grey foram nanno ooze (67/DR 18-4); one piece of dark grey lithified mudstone (67/DR 18-5); and soft olive-grey calcareous mud (67/DR 18-6).

Preparation 67/DR 18-3b

A subsample of the pale brown siltstone was examined. Calcareous nannofossils are rare, diversified and moderately well-preserved in this preparation. The nannofossil assemblage (Checklist 3) suggests an Early Oligocene age. It is coeval with the assemblage from Preparation 67/DR 10-3b (discussed above), and probably lived in similar cool surface waters. Deposition occurred on the continental shelf. The two assemblages, being very similar, are assigned to DI: *+Cyclicargolithus reticulatus* /*+Isthmolithus recurvus*. They came from similar water depth ranges, around 1950 to 1650 m.

Preparation 67/DR 18-1

A subsample of the white chalk yielded abundant, poorly preserved calcareous nannofossils. Poor preservation evidently is caused by partial dissolution. The overlap in the ranges of several species (such as *Calcidiscus macintyrei*, *Discoaster variabilis*, *Helicosphaera euphratis*, *H. kamptneri*, *Reticulofenestra pseudoumbilicus* and the high-latitude *R, gelida*; see Checklist 4) suggests a Middle Miocene age. The assemblage includes evidence to suggest cool surface waters.

Preparation 67/DR 18-2

A subsample of the white calcareous mud was examined. Preservation of the abundant calcareous nannofossils (Checklist 4) recovered in this preparation is better than the assemblage of Preparation 67/DR 18-1. The age is Middle Miocene. Low diversity of the discoasters and the abundant occurrence of *Reticulofenestra gelida* suggest cool surface waters.

Preparation DR 18-3a

Another subsample of the pale brown siltstone was examined. Almost non-fossiliferous, but with very rare specimens (Checklist 4) suggesting a Middle Miocene age.

Preparation 67/DR 18-4

A subsample of the foram nanno ooze yielded a late Quaternary coccolith assemblage. The low species diversity and the high abundance of *Coccolithus pelagicus* suggest cold surface waters.

Preparation 67/DR 18-6

A subsample of the soft olive-grey mud was examined. A late Quaternary assemblage was identified similar to that recorded from Preparation 67/DR 18-4. Older mid Tertiary taxa were encountered but as a very minor component.

Dredge station 19

Dredging was attempted on the mid slope, southwest of Nautilus #A-1 well, between Lat. 39°29.2'S - Long. 142°13.4'E and Lat. 39° 29.5'S - Long. 142°16.2'E. Water depth ranges between 2600 and 2100 m. Material recovered included off-white, semi-consolidated chalky material (67/DR 19-1), a few small pebbles of pale brown finely bored mudstone (67/DR 19-2), plastic pale grey foram nanno ooze (67/DR 19-3), and soft pale brownish-grey foram nanno ooze (67/DR 19-4).

Preparation 67/DR 19-1

A subsample of the semi-consolidated chalk yielded a moderately well-preserved calcareous nannofossil assemblage (Checklist 3) that suggests a Late Oligocene age. The assemblage is assigned to DI: +*Chismolithus altus*+*Reticulofenestra scissura* (see Table 2). It includes evidence to suggest that deposition occurred in shallow-water or nearshore environments.

Preparation 67/DR 19-4

A subsample of the soft brownish grey nanno ooze was examined. Common, moderately well-preserved calcareous nannofossils (Checklist 3) were recovered. The assemblage is assigned to the interval with *Sphenolithus ciperoensis* (see Table 2). A Late Oligocene age is indicated. The assemblage may represent a short period of warming during the Late Oligocene in the Otway Basin; the cool-water indicator *Chiasmolithus altus* is absent. The lack of hemipelagic taxa suggests that deposition occurred beyond the shelf.

Preparation 67/DR 19-2.

A subsample of pale brown mudstone yielded a late Quaternary assemblage. In addition, large numbers of Late Oligocene calcareous nannofossils were identified, but these could be contaminants from the associated Late Oligocene sediments (67/DR 19-1 & 67/DR 19-4).

Preparation 67/DR 19-3.

A subsample of the pale grey foram nanno ooze was examined. The assemblage recovered is similar to the late Quaternary one of Preparation 67/DR 19-2, without the association of Late Oligocene taxa.

NANNOFOSSIL CORRELATION WITH BMR CRUISE 48 DREDGES

Middle Eocene

Two Middle Eocene assemblages were identified from material dredged during BMR Cruise 48 from the continental slope WSW of Portland (48/DR 7) (see Figs. 1 & 2 in body of Report): an assemblage characterised by the overlap in the ranges of *Chiasmolithus solitus*, *Daktylethra punctulata* and *Reticulofenestra scissura* occurring in a brown sandy siltstone (48/DR 7-1); and another characterised by the presence of *Reticulofenestra scissura* and the absence of both *Daktylethra punctulata* and *Chiasmolithus solitus* contained in a white semi-consolidated calcareous mud (48/DR 7-3). The Middle Eocene assemblage from a brownish grey calcareous clay (67/DR 10-3a) recovered some kilometres to the north of Station 48/DR 7, does not correlate with the Middle Eocene recovered at 48/DR 7, because it predates the appearance of typical *Reticulofenestra scissura*. Thus the Middle Eocene sequence recovered in the offshore Otway Basin during both BMR cruises, arranged chronologically (starting with the oldest), is:

1. Assemblage found in a brownish grey calcareous clay (67/DR 10-3a) containing the species *Chiasmolithus grandis/C. expansus*, *Cyclicargolithus reticulatus*, *Discoaster saipanensis*, *Helicosphaera reticulata*, *Neococcolithes dubius* and *Reticulofenestra* sp. cf. *R. scissura*. This assemblage probably correlates with the low-latitude foraminiferal early zone P.13.

2. Assemblage recovered from brown sandy siltstone (48/DR 7-1) including the key species *Chiasmolithus grandis/C. expansus*, *Cyclicargolithus reticulatus*, *Daktylethra punctulata*, *Discoaster barbadiensis*, *D. saipanensis*, *Helicosphaera reticulata*, *Neococcolithes dubius* and rare *Reticulofenestra scissura*.

3. Assemblage extracted from a white semi-consolidated calcareous mud (48/DR 7-3) containing *Chiasmolithus grandis/C. expansus*, *Cyclicargolithus reticulatus*, *Discoaster saipanensis*, *Neococcolithes dubius* and *Reticulofenestra scissura*. This assemblage probably correlates with low-latitude late zone P.13.

The middle assemblage (in 48/DR 7-1) is more diversified than the other two, and may represent a warmer period. It probably correlates with the low-latitude planktic foraminiferal mid zone P. 13. *Discoaster barbadiensis* is known to disappear just above this level in the Otway Basin. But, in lower latitude areas (e.g. Italy: Roth, Baumann & Bertolino, 1971; Blake Plateau: Gartner, 1971), this species ranges to near the top of the Eocene.

Late Eocene

Sediments recovered during BMR Cruise 48 did not yield calcareous nannofossils of definite Late Eocene age. A gravity core (67/GC 05) and two dredge samples obtained during BMR Cruise 67 contained several Late Eocene nannofossil assemblages. These can be summarised as follows (in ascending order):

1. Assemblages identified from the lower part of core 67/GC 05, and from the brownish-grey calcareous clay of the dredge sample 67/DR 10-3c. These assemblages are characterised by the overlap in the ranges of the key taxa *Neococcolithes dubius* and *Chiasmolithus oamaruensis*. The index taxa *Cyclicargolithus reticulatus* and *Discoaster saipanensis* are present, and *Isthmolithus recurvus* is absent. Forms similar to *Chiasmolithus grandis* without its teeth were noted in the assemblage of 67/DR 10-3c.

2. Assemblages recorded from the mudstone of core 67/GC 05 between the 30- and 2-cm levels. These assemblages are characterised by the overlap in the ranges of the index taxa *Isthmolithus recurvus, Discoaster saipanensis* and *Cyclicargolithus reticulatus*.

3. Assemblage extracted from the semi-lithified olive-grey sandy siltstone of the dredge sample 67/DR 2-2b. This assemblage can be characterised by the overlap in the ranges of the index taxa *Isthmolithus recurvus* and *Discoaster saipanensis* in the absence of *Cyclicargolithus reticulatus*.

Latest Eocene to Early Oligocene

Two groups of assemblages assignable to the latest Eocene-Early Oligocene are distinguished: one group with *Cyclococcolithus formosus*, possibly the older, and another without the same species. *C. formosus* is usually rare in the Late Eocene-Early Oligocene sediments of the Otway Basin, and therefore its absence in this interval may be considered as biostratigraphically unreliable.

Assemblages containing *Isthmolithus recurvus, Lanternithus minutus, Cyclococcolithus formosus* and *Reticulofenestra umbilicus*, without the association of the key taxa *Cyclicargolithus reticulatus* and *Discoaster saipanensis*, were recovered during both BMR Cruises 48 and 67, from dredge samples 48/DR 7-1a and 67/DR 10-3d respectively. These assemblages were assigned a latest Eocene to Early Oligocene age. The top of the range of *D. saipanensis* has been used by most investigators as good evidence for delineating the Eocene/Oligocene boundary (see, e.g., Perch-Nielsen, 1985), but nannofossil distribution in onshore Otway Basin material (Shafik, 1983) suggests that the absence of this species above the (usually reliable) extinction datum of *Cyclicargolithus reticulatus* is not always reliable as biostratigraphic evidence.

Assemblages containing *Isthmolithus recurvus* and *Reticulofenestra umbilicus* but seemingly lacking *Cyclococcolithus formosus*, were recorded from three dredge stations occupied during BMR Cruise 67; similar assemblages were not identified during BMR Cruise 48.

Early to mid Oligocene

Assemblages predating the appearance of the Late Oligocene index taxa *Helicosphaera recta* and *H. obliqua*, and postdating the extinction of *Isthmolithus recurvus*, were identified from dredge material obtained during BMR Cruises 48 and 67. However, those assemblages are not correlatable. They are differentiated by the presence or absence of *Reticulofenestra umbilicus*.

Assemblages characterised by the presence of *Reticulofenestra umbilicus* were recorded from subsample 67/DR 10-2a and sample 67/DR 12-3 dredged during BMR Cruise 67. These assemblages are slightly older than the assemblages recovered from dredges 48/DR 7-7 and 48/DR 5-1, which were obtained during BMR Cruise 48.

The assemblages of 48/DR 7-7 and 48/DR 5-1 lacked *Reticulofenestra umbilicus* but contained the key taxa *Chiasmolithus altus, Cyclicargolithus floridanus, Reticulofenestra daviesi, R. scrippae* and *R. scissura*. The low-latitude *Sphenolithus predistentus* was also encountered in the 48/DR 5-1 assemblage.

Late Oligocene

Assemblages predating the extinction of *Reticulofenestra scissura* and postdating the appearance of *Helicosphaera recta* and *H. obliqua* were recovered during BMR Cruises 48 and 67. Those obtained during Cruise 48 include the index species *Chiasmolithus altus*, and correlate with similar assemblages obtained from dredge stations 67/DR 10, 67/DR 12 and 67/DR 14. Assemblages lacking *C. altus* were recovered from core and dredge material obtained during BMR Cruise 67 but not Cruise 48.

The low-latitude *Sphenolithus ciperoensis* is found in the Oligocene record of southern Australia. This Late Oligocene key species occurs in the offshore Otway Basin, at three stations occupied during BMR Cruise 67 (DR14, DR19 and GC54) and in the onshore part of the basin, in the Gambier Embayment (Shafik, unpublished data).

CONCLUSIONS

1. The evidence from Dredge Station 67/DR 10 suggests progressive shoaling or sea-level fall during the Middle Eocene through into the Early Oligocene.

2. A temperature decline occurred during the later part of the Eocene and Early Oligocene, subsequent to a peak during the Middle Eocene DI: **Reticulofenestra scissura*/+*Daktylethra punctulata* (= mid planktic foraminiferal zone P.13).

3. An excursion by the low-latitude *Sphenolithus ciperoensis* into the Otway Basin and western Tasmania occurred during the Late Oligocene DI: +*Chiasmolithus altus*/+*Reticulofenestra scissura*, based on evidence from Stations 67/DR 14, 67/DR 19 and 67/GC 54. This is a response to a short warm episode.

4. The widespread occurrence of *Sphenolithus heteromorphus* in the southeastern Australian region, including the offshore Otway Basin, suggests an important event in the Miocene of the region. This event is coeval with a similar worldwide event, and provides a direct correlation with low-latitude nannofossil zonations.

5. During the Late Pliocene, surface waters were cold in the Otway Basin, as evidenced by the total lack of slim-rayed discoasters and the abundant occurrence of *Coccolithus pelagicus*.

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APPENDIX B: QUATERNARY COCCOLITHS, OFFSHORE OTWAY BASIN

Samir Shafik

ABSTRACT

Quaternary coccoliths were extracted from many gravity cores taken along four profiles in the offshore Otway Basin and west of Tasmania during BMR Cruise 67. The absence of the index species *Pseudoemiliania lacunosa* from these cores places them in the late Quaternary. The abundant occurrence of *Coccolithus pelagicus*, and the total absence of several low-latitude coccoliths such as *Umbellosphaera tenuis, U. irregularis* and *Ceratolithus cristatus*, together with the low species diversity of the assemblages, suggest cold surface waters.

A revision of the biostratigraphic scheme, above the highest occurrence of *Pseudoemiliania lacunosa*, is made.

INTRODUCTION

A major coring program along four profiles in the offshore Otway Basin and west of Tasmania was carried out during BMR Cruise 67. Coccoliths indicative of Quaternary age were extracted from most of the cores. Cores which recovered Tertiary sediments invariably contain Quaternary coccoliths at their tops. Also, most of the dredges attempted during the same BMR cruise recovered Quaternary sediments.

ASSEMBLAGES

The assemblages extracted from the Quaternary material examined are not dissimilar. Details of examples of these assemblages (in three gravity cores) are given below.

Gravity core 67/GC 06

This core was taken at Lat. 39°30.8'S - Long. 139°57.7'E, where the water depth is 4956 m, and retrieved 265 cm of pelagic oozes, muds and turbidites. These were found to contain Quaternary coccoliths. Several levels were studied, but no atttempt was made to biostratigraphically subdivide this core.

The bottom of the core (265 cm) is almost barren of calcareous nannofossils, except for a few specimens of *Calcidiscus leptoporus* and *Gephyrocapsa* spp. (which have lost their bridges). While some of these few coccolith specimens could be contaminants, others are a residue left after severe dissolution, as deposition might have occurred below the calcium compensation depth (CCD): some calcareous nannofossil taxa are known to

Level (cm)	Assemblage and remarks
2–3	Small *Gephyrocapsa* spp., *?Emiliania huxleyi, Coccolithus pelagicus, Calcidiscus leptoporus, Helicosphaera carterii* and *Umbilocosphaera sibogae*. Common *Gephyrocapsa oceanica.* Coccolith debris abounds, very minor reworking.
46–47	Preservation is poor and the assemblages are dominated by *?E. huxleyi*/small *Gephyrocapsa* spp.. Also occurring are *Calcidiscus leptoporus, Coccolithus pelagicus, Helicosphaera carterii* and *Rhabdosphaera stylifer*. No reworked taxa.
71–72	Preservation is slightly better than above, and assemblages are very similar to those above. *Gephyrocapsa oceanica* was identified. No reworked taxa.
126–127	Almost barren of coccoliths. Corroded single shields of *Calcidiscus leptoporus* and 'ghosts' of *Coccolithus pelagicus* and *Helicosphaera carterii* were noted.
151–152	Preservation is poor. Assemblages are dominated by *?E. huxleyi*/small *Gephyrocapsa* spp.. Common *Calcidiscus leptoporus, Coccolithus pelagicus* and *Helicosphaera carterii*. Very minor reworking.
170	Same as above, but no reworked taxa were detected.
190	Same as 170 cm
233–234	Small placoliths dominate, but none have a central bridge (*Gephyrocapsa*). *Coccolithus pelagicus* is common and *Calcidiscus leptoporus* and *Helicosphaera carterii* are frequent. Minor reworking, but displaced taxa are more diversified than in other levels.
235–236	Preservation is poor. Assemblages are dominated by *?E. huxleyi* /small *Gephyrocapsa* spp.. *Calcidiscus leptoporus, Coccolithus pelagicus, Helicosphaera carterii, ?Pseudoemiliania lacunosa* and *Rhabdosphaera stylifer* are present. Very minor reworking.
287	Similar to above, but with *Calcidiscus macintyrei.* Very minor reworking.

20/OA/12

Table 1. Quaternary coccolith assemblages of core 67/GC07

persist below the CCD, probably because of protection by an in-built organic film.

The sample from the 190-cm level yielded abundant moderately well preserved Quaternary coccoliths. The assemblage is dominated by small *Gephyrocapsa* spp. but also contains common *Calcidiscus leptoporus, Coccolithus pelagicus, Gephyrocapsa caribbeanica, G. oceanica* and *Helicosphaera carterii. Thoracosphaera* sp. is present.

The samples from the turbidites at 158 and 44 cm contain similar Quaternary coccoliths, but also a large number of reworked taxa, mostly from early and mid Tertiary sources. The reworked taxa include *Chiasmolithus altus, C. eograndis, Cyclicargolithus abisectus, C. floridanus, Discoaster deflandrei, D. tani, Reticulofenestra hampdenensis, R. pseudoumbilica, R. scrippsae, R. scissura* and *Sphenolithus abies*. The Quaternary taxa include both poorly and well preserved elements, and probably have been partly reworked. Ascidian spicules, indicative of shallow-water origin, are present in the turbidite samples.

A sample from 117 cm yielded a Quaternary assemblage of abundant, mainly poorly-preserved taxa, with a very minor reworked component.

The sample from 74 cm contained abundant but mainly poorly-preserved Quaternary taxa, in association with well-preserved Eocene taxa such as *Cyclicargolithus reticulatus, Reticulofenestra umbilica, Sphenolithus moriformis, Transversopontis* spp. and *Zygrhablithus bijugatus bijugatus*, and the later Tertiary *Cyclicargolithus abisectus* and *Sphenolithus abies*. The presence of the holococcolith *Zygrhablithus bijugatus bijugatus* and *Transversopontis* spp. suggests that the reworked Eocene taxa were deposited in shallow water, whereas Quaternary taxa were deposited much deeper, as attested by their poor state of preservation.

The sample from 54 cm contains poorly-preserved but abundant Quaternary taxa, with very minor older elements. The Quaternary taxa are dominated by *Coccolithus pelagicus*, most of the species of the genus *Gephyrocapsa* are without their central bridges, and *Calcidiscus leptoporus* is represented mainly by single corroded shields.

The two samples from 20 cm and from the top of the core contain moderately well-preserved Quaternary taxa in association with a significant number of Early and Mid Tertiary species. The Quaternary assemblage from the top of the core includes *Calcidiscus leptoporus*, *Gephyrocapsa oceanica, Helicosphaera carterii, Pontosphaera plana, Rhabdosphaera stylifer* and several small *Gephyrocapsa* species (including *G. aperta* which was found as an intact coccosphere).

Gravity core 67/GC 07

This core was taken on the continental slope, north of Dredge Station 67/DR 09, at Lat. 39°20.02'S - Long. 139°58.95'E, where water depth is 4120 m, and recovered 287 cm of oozes, mud and clays.

Coccolith assemblages extracted at several levels are Quaternary in age, as proven by the presence of *Gephyrocapsa* spp. at several levels, including the

Magnetic reversals		Coccolith event and its numerical age	
BRUNHES		Acme *Emiliania huxleyi*	0.07 Ma
		* *Emiliania huxleyi*	0.27 Ma
		+ *Pseudoemiliania lacunosa*	0.45 Ma
Jaramillo		* *Gephyrocapsa oceanica*	
MATUYAMA		+ *Helicosphaera sellii*	
		+ *Calcidiscus leptoporus*	
Olduvai		+ *Discoaster brouweri*	

20/OA/13

	Normal polarity	*	*Lowest occurrence*
	Reversed polarity	+	*Highest occurrence*

Table 2. Quaternary coccolith biostratigraphy

Acme *Emiliania huxleyi*
Acme *Gephyrocapsa oceanica*
* *Emiliania huxleyi*
Acme small *Gephyrocapsa* spp.
+ *Pseudoemiliania lacunosa*

* *Lowest occurrence* + *Highest occurrence*

20/OA/14

Table 3. Late Quaternary coccolith biostratigraphy, Offshore Otway Basin, southeastern Australia

bottom of the core at 187 cm (see Table 1). Preservation is generally poor because of partial dissolution, seemingly as a result of deposition near the CCD. Most of the assemblages are dominated by small placoliths, similar in size to the late Pleistocene-Holocene *Emiliania huxleyi*, but often include forms with central bridges referable to the genus *Gephyrocapsa*. Displaced older taxa constitute a very minor component of the assemblages, but their presence is undeniable. They are mainly *Chiasmolithus altus, Cyclicargolithus abisectus, Discoaster deflandrei* 'group' and *Reticulofenestra scissura*, suggesting Mid Tertiary source(s).

Gravity core 67/GC 11

This core was taken on the continental slope at Lat. 38^{o} 45.00'S Long. 140^{o}7.70'E, where water depth is 3224 m, and retrieved 308 cm of oozes and mud. It was targeted to sample Eocene sediments, but the sediments recovered are dated as late Quaternary.

The sample from the corecatcher at 308 cm yielded abundant moderately preserved late Quaternary taxa, a few older species, and abundant nannofossil debris. The Quaternary taxa include *Calcidiscus leptoporus, Coccolithus pelagicus, C. doronicoides, Gephyrocapsa caribbeanica, G. oceanica,* small *Gephyrocapsa* spp., *Helicosphaera carterii, H. colombiana,* and *Rhabdosphaera stylifer*. Older species encountered are *Chiasmolithus altus, Cyclicargolithus abisectus* and *Reticulofenestra pseudoumbilica*, which suggest that reworking was from mid and upper Tertiary sources.

Assemblages recovered at 280, 209, 140, and 73 cm, and from the top of the core, are similar to the assemblage of the corecatcher; abundant nannofossil debris occurs in all samples examined. Forms probably referable to both *Emiliania huxleyi* and *Calcidiscus macintyrei* range up to the top of the core. The ranges of these two taxa elsewhere are mutually exclusive. *Pontosphaera plana* was found at the top of the core. Minor reworking was detected at most levels, and the displaced taxa suggest mid Tertiary source(s).

DISCUSSION AND CONCLUSIONS

The absence of *Pseudoemiliania lacunosa* from the assemblages examined suggests a late Quaternary age.

The assemblages are interpreted as having lived in cold waters during the late Quaternary, for the following reasons:

1. The virtually total lack of low-latitude taxa such as *Umbellicosphaera tenuis, U. irregularis* and *Ceratolithus cristatus* in most of the cores, the very few occurrences of *U. irregularis* encountered notwithstanding.

2. The abundant occurrence of *Coccolithus pelagicus* in most of the cores. *C. pelagicus* is restricted to the northern subpolar region of modern oceans.

3. The generally low species diversity of all assemblages, also suggestive of cold surface waters.

There are only two coccolith events younger than the highest occurrence of *Pseudoemiliania lacunosa* in most widely-used zonations, but resolution is great as the extinction of *P. lacunosa* is dated as 0.45 Ma (see Table 2). These events are the lowest occurrence of *Emiliania huxleyi* and the subsequent world-wide dominance of the same species. However, *E. huxleyi* is very small and is usually difficult to recognise in optical microscopy, especially where it is not very abundant. The shipboard study of the Quaternary cores recovered during BMR Cruise 67 has led to a possible refinement of the biostratigraphic scheme above the highest occurrence of *Pseudoemiliania lacunosa* (see Table 3). It made use of an acme of several small *Gephyrocapsa* spp. occurring above the extinction of *P. lacunosa*, and also an acme of the larger *Gephyrocapsa oceanica* above the lowest occurrence of *Emiliania huxleyi*.

APPENDIX C: PLANKTONIC FORAMINIFERA AND BIOSTRATIGRAPHY OF CAINOZOIC GRAVITY CORE AND DREDGE SAMPLES FROM THE OFFSHORE OTWAY BASIN

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Figure

During research cruises by the R/V Rig Seismic in 1985 and 1987 many samples were collected from the offshore Otway Basin and the west Tasmanian margin by the Bureau of Mineral Resources, Geology and Geophysics (BMR). The 1985 cruise and its results were described by Exon & others (1987a), and the 1987 cruise and preliminary results by Exon & others (1987b). Identification of Cainozoic calcareous nannofossils, and discussion of biostratigraphy and depositional environments (Shafik 1987a; 1987b; 1987c) are incorporated in these reports, and in this volume as Appendixes A and B.

Twenty-three samples, selected by S. Shafik and N.F. Exon, and washed by P. Davies (all of BMR) were submitted for foraminiferal investigation at the end of April 1987. They comprise 4 dredge samples collected during the 1985 Cruise 48, and 14 dredge and 5 gravity core samples from the 1987 Cruise 67. Most of the samples are Eocene or Oligocene, and a few are Miocene or Quaternary.

In all of the offshore samples the ratio of planktonic to benthonic foraminifera is high; as expected, higher than in most onshore samples from the Otway Basin. No detailed counting was done, partly because many of the assemblages are contaminated, especially by Quaternary foraminifera. Thus the present investigation is restricted largely to identification of planktonic foraminifera and discussion of biostratigraphy. The only benthonic species of obvious biostratigraphic significance is Bolivinopsis cubensis. It is present in most Middle Eocene and Late Oligocene samples, and absent from Late Oligocene and younger samples (in onshore sections B. cubensis extends into the Upper Oligocene).

In the following text, information about the locations of dredge stations and gravity cores, and brief general lithological sample descriptions, are from Exon & others (1987b) and Exon & others (1987a). Additional lithological descriptions of the individual samples, in parentheses, were provided by N.F. Exon.

FORAMINIFERAL DETERMINATIONS FOR DREDGE AND CORE SAMPLES

DREDGE STATION 48/5 DR

Lat. 38|39.4′ Long. 140|50.5′
Southwest of Portland; depth 1650-1450 m

SAMPLE 48/5 DR-1a

Chalky white marl (white chalk).
Planktonic foraminifera are abundant and moderately well preserved.
Subbotina angiporoides and Globorotaloides suteri predominate; also present are Globigerina labiacrassata, G. euapertura, rare G. praebulloides and G. angustiumbilicata, Tenuitella munda (in part transitional to Globigerinita juvenilis), common Chiloguembelina cubensis and very rare Guembelitria triseriata (two specimens). Rare Quaternary contaminants include Globorotalia truncatulinoides.
Age: Abundant Subbotina angiporoides, and Guembelitria triseriata, indicate Early Oligocene (zone P 19/20 or older).

DREDGE STATION 48/7DR

Lat. 38°31.4′ Long. 139°37.5′
South-southwest of Beachport; depth 3250 m

SAMPLE 48/7 DR-1a

Calcareous silty mudstone (light grey calcareous siltstone).
The rock is fairly strongly cemented and has yielded few loose foraminifera. Sparse and poorly preserved planktonic foraminifera include Globigerinatheka index, Subbotina linaperta, S. angiporoides, Globorotaloides suteri and Chiloguembelina cubensis.
Age: Globigerinatheka index indicates Middle to Late Eocene.

SAMPLE 48/7 DR-3a

White semi-consolidated nannofossil ooze (soft off-white chalk).
Planktonic foraminifera are abundant and moderately well preserved. Globigerinatheka index, Subbotina linaperta (a few specimens comparable with S. frontosa) and Globorotaloides suteri predominate; also present are Subbotina angiporoides (mostly referable to minima), rare Globigerina officinalis, Tenuitella insolita, Pseudohastigerina micra, Chiloguembelina cubensis and rare Acarinina collactea (eight specimens). Sponge spicules and radiolarians were also noted.

Age: Acarinina collactea, in the absence of A. primitiva, indicates very late Middle Eocene to early Late Eocene.

SAMPLE 48/7 DR-7a

Soft white sandy marlstone (white chalk).

The rock is moderately cemented, and loose foraminifera are somewhat sparse and rather poorly preserved. Globorotalia miotumida is fairly common; the strongly compressed variants are referable to G. dalii, and a few specimens to G. conomiozea (or very close to it). Also present are G. acostaensis and Orbulina. Rare Quaternary contaminants include Globorotalia truncatulinoides.

Age. G. acostaensis indicates Late Miocene, G. conomiozea very late Miocene.

DREDGE STATION 67/DR 2

Lat. $37^{\circ}40.3'$ - $37^{\circ}37.7'$ Long. $138^{\circ}16.8'$- $138^{\circ}19.6'$
West-southwest of Beachport; depth 4100-3800 m.

SAMPLE 67/DR 2-2a

Lithified light olive grey sandy siltstone (brown siltstone).

Planktonic foraminifera are sparse and moderately well preserved. They include rare Subbotina angiporoides (1 "good" and 8 small specimens), Globigerina euapertura, G. praebulloides, Globorotaloides suteri, very rare G. testarugosa, Catapsydrax dissimilis, Globigerinita juvenilis, Tenuitella munda and very rare Chiloguembelina cubensis (4 specimens). Rare Quaternary contaminants include Globorotalia truncatulinoides.

Age: The sparse assemblage, with rare Subbotina angiporoides and very rare Chiloguembelina cubensis, indicates late Early Oligocene (zone P 21a or slightly older).

DREDGE STATION 67/DR 10

Lat. $38^{\circ}05.2'$ - $38^{\circ}04.5'$ Long. $139^{\circ}45.2'$ - $139^{\circ}46.4'$
South-southwest of Beachport; depth 1950-1700 m

SAMPLE 67/DR 10-1

Soft white fossiliferous calcareous claystone (chalk).

Planktonic foraminifera are somewhat sparse and poorly preserved. Catapsydrax dissimilis is fairly common; also present are very rare Subbotina angiporoides (two specimens), Globigerina praebulloides, Globorotalia nana, Globorotaloides suteri, Globigerinita juvenilis and common Chiloguembelina cubensis and Guembelitria triseriata.

Age: Very rare Subbotina angiporoides, and common Chiloguembelina cubensis and Guembelitria triseriata, indicate late Early Oligocene (zone P 21a or slightly older).

SAMPLE 67/DR 10-2b

Cherty chalk.

Planktonic foraminifera are somewhat sparse and moderately well preserved. Subbotina angiporoides is common; also present are rare Globigerina ampliapertura and G. praebulloides, Globorotalia nana, Globorotaloides suteri, rare Globigerinita juvenilis, Tenuitella munda, common Chiloguembelina cubensis and very rare Guembelitria triseriata (four specimens).

Age: Common Subbotina angiporoides, and Guembelitria triseriata, indicate Early Oligocene (zone P 19/20 or older).

SAMPLE 67/DR 10-3a

Light brownish grey sparsely fossiliferous calcareous claystone (light brown sandy siltstone).

Planktonic foraminifera are fairly common and moderately well preserved. Subbotina linaperta (a few specimens comparable with S. frontosa) and Globorotaloides suteri predominate; also present are Globigerinatheka index, Subbotina angiporoides (referable to minima), rare Globigerina officinalis and Tenuitella insolita, common Pseudohastigerina micra, Chiloguembelina cubensis, common Acarinina collactea and very rare A. primitiva (five specimens). Sponge spicules and radiolarians were also noted.
Age: Acarinina primitiva, together with the associated species, indicates late Middle Eocene.

SAMPLE 67/DR 10-3b

Lithologically presumably similar to sample 3a.

Planktonic foraminifera are abundant and well preserved. Globigerinatheka index, Subbotina linaperta and Globorotaloides suteri predominate; also present are common representatives of the Globigerina officinalis - ouachitaensis - praebulloides group, Subbotina angiporoides (mostly referable to minima), very rare Turborotalia cerroazulensis pomeroli, common Tenuitella insolita and T. gemma, T. aculeata, rare Testacarinata inconspicua, very rare Pseudohastigerina micra, abundant Chiloguembelina cubensis, fairly common Acarininina collactea and very rare A. primitiva (one specimen). Sponge spicules and radiolarians were also noted.
Age: Common Tenuitella gemma casts doubt on the significance of the single specimen of Acarinina primitiva and, together with A. collactea, indicates early Late Eocene.

SAMPLE 67/DR 10-3c

Very light brown very fine soft sandstone.

Planktonic foraminifera are moderately common and moderately well preserved. Subbotina linaperta (a few specimens comparable with S. frontosa) and Globorotaloides suteri predominate; also present are Globigerinatheka index, Subbotina angiporoides (referable to minima), rare Globigerina officinalis, Tenuitella insolita, very rare T. gemma (two specimens), common Pseudohastigerina micra, Chiloguembelina cubensis, and common Acarinina collactea, and very rare A. primitiva (four specimens). Sponge spicules and radiolarians were also noted.

Age: Acarinina primitiva, together with the associated species, indicates late Middle Eocene (the two specimens of Tenuitella gemma may be contaminants).

SAMPLE 67/DR 10-4

White bryozoal calcarenite with chert concretions.

Planktonic foraminifera are common and moderately well preserved. Globigerina praebulloides, Globorotalia nana (in part referable to G.

pseudocontinuosa), Globorotaloides suteri and Catapsydrax dissimilis predominate; also present are fairly common, well developed Subbotina angiporoides, Globigerina labiacrassata, G. euapertura, G. angustiumbilicata, Globigerinita juvenilis, rare Tenuitella munda, and common Chiloguembelina cubensis and Guembelitria triseriata. Rare Quaternary contaminants include Globigerinoides ruber.
Age: Fairly common Subbotina angiporoides, and Guembelitria triseriata, indicate Early Oligocene (zone P 19/20 or older).

DREDGE STATION 67/DR 12

Lat. 37°46.3′ - 37°46.7′ Long. 139°25.3′ - 139°25.6′
Southwest of Beachport; depth 1350-1150 m

SAMPLE 67/DR 12-3

Brown silty mudstone.

The rock is cemented, and loose foraminifera are somewhat sparse and moderately well preserved. Subbotina angiporoides, Globorotaloides suteri and Chiloguembelina cubensis are common; also present are Globigerina praebulloides and Tenuitella munda. Rare Quaternary contaminants include Globorotalia inflata.
Age: Common Subbotina angiporoides, in the absence of species restricted to the Eocene, indicates Early Oligocene (zone P 19/20 or older).

SAMPLE 67/DR 12-4 & 5

Soft white chalk and brown to grey mudstone (white calcareous clay). The assemblage is a mixture of foraminifera representing three distinct age intervals.

Late Early Oligocene:	common Chiloguembelina cubensis and very rare Guembelitria triseriata (Subbotina angiporoides is absent; also present are Globorotaloides suteri and Catapsydrax dissimilis).
Early Miocene :	common Globoquadrina dehiscens, Globigerina woodi and Globorotalia semivera.
Quaternary :	Globorotalia truncatulinoides, also G. inflata, Globigerinoides ruber and Globigerina bulloides.

DREDGE STATION 67/DR 14

Lat. 38°50.0′ - 38°49.8′ Long. 140°35.4′ - 140°35.0′
Southwest of Portland; depth 3050-2450 m

SAMPLE 67/DR14-1a

White chalk with chert nodules.

Planktonic foraminifera are abundant and moderately well preserved. Subbotina angiporoides, Globigerina labiacrassata, G. euapertura, Globorotaloides suteri and Catapsydrax dissimilis predominate; also present are rare Globigerina praebulloides and

Globorotalia nana, common Tenuitella munda and Chiloguembelina cubensis, and rare Guembelitria triseriata (6 specimens).
Age: Common Subbotina angiporoides, and Guembelitria triseriata, indicate Early Oligocene (zone P 19/20 or older).

SAMPLE 67/DR 14-1c

Soft white chalk.

Planktonic foraminifera are abundant and moderately well preserved. Globigerina praebulloides, G. euapertura, G. cf. gortanii, Globorotaloides suteri, G. testarugosa, Catapsydrax dissimilis and Globigerinita juvenilis are common to abundant; also present is Tenuitella munda. Rare Quaternary contaminants include Globorotalia truncatulinoides.
Age: Well developed, abundant Globigerina euapertura, in the absence of species not ranging above Early Oligocene or below Miocene, indicates Late Oligocene.

SAMPLE 67 DR 14-3

White chalk (buff clayey calcarenite).

The rock is somewhat cemented, but loose foraminifera are fairly common and moderately well preserved. Globigerina bulloides, Globigerinoides ruber, Orbulina, Globorotalia inflata and G. truncatulinoides are common; also present are Globigerina quinqueloba, Globigerinella aequilateralis, Globorotalia scitula, G. hirsuta, Neogloboquadrina pachyderma, N. dutertrei s.l. and Globigerinita glutinata. Rare Early Oligocene contaminants include Chiloguembelina cubensis, Globorotaloides suteri and Catapsydrax dissimilis.
Age: Globorotalia truncatulinoides indicates Quaternary.

DREDGE STATION 67/DR 18

Lat. $39^{o}12.9'$ - $39^{o}11.8'$ Long. $142^{o}07.2'$ - $142^{o}11.5'$
Southeast of Portland (southwest of Nautilus 1 well); depth 1950 - 1650 m

SAMPLE 67/DR 18-3b

Pale brown weakly lithified siltstone (calcareous siltstone).

Planktonic foraminifera are abundant and moderately well preserved. Subbotina linaperta and Globorotaloides suteri predominate; also present are Subbotina angiporoides (in part referable to minima), representatives of the Globigerina ouachitaensis - praebulloides group, common Tenuitella gemma, T. aculeata, very rare Pseudohastigerina micra and Hantkenina primitiva (1 specimen), abundant Chiloguembelina cubensis, common Acarinina collactea and rare A. primitiva (six specimens). Common Quaternary contaminants include Globorotalia truncatulinoides.
Age: Common Tenuitella gemma casts doubt on the significance of the rare specimens of Acarinina primitiva and, together with A. collactea, indicates early Late Eocene. The single specimen of Hantkenina primitiva may be regarded as a contaminant.

DREDGE STATION 67/DR 19

Lat. $39^{o}29.2'$ - $39^{o}29.5'$ Long. $142^{o}13.4'$ - $142^{o}6.2'$. Southeast of Portland (south-southwest of Nautilus 1 well); depth 2600-2100 m.

SAMPLE 67/DR19-1

Off-white semi-consolidated chalky material (soft calcareous siltstone).

Planktonic foraminifera are abundant and moderately well preserved. Globigerina praebulloides, G. euapertura, Globorotalia nana (in part referable to G. pseudocontinuosa, a few specimens comparable with G. opima s.s.), Globorotaloides suteri and Catapsydrax dissimilis are common to abundant; also present are Globigerina c.f. gortanii, Glorotaloides testarugosa, Globigerinita juvenilis and Tenuitella munda. Common Quaternary contaminants include Globorotalia truncatulinoides.

Age: Common Globigerina euapertura, in the absence of species not ranging above Early Oligocene or below Miocene, indicates Late Oligocene.

CORE STATION 67/GC 05

Lat. $37^{o}45.5'$ Long. $138^{o}34.9'$

West-southwest of Beachport; depth 2235 m; recovery 80 cm.

SAMPLE 67/GC 05 BOTTOM

Semi-lithified olive-grey mud.

Planktonic foraminifera are common and well preserved. Globigerinatheka index, Subbotina linaperta and Globorotaloides suteri predominate; also present are Subbotina angiporoides (referable to minima), Turborotalia increbescens (in part comparable with pseudoampliapertura), rare Tenuitella insolita, very rare T. gemma, common T. aculeata, rare Testacarinata inconspicua, very rare Pseudohastigerina micra, common Chiloguembelina cubensis and abundant Acarinina collactea. Fairly common Quaternary contaminants include Globorotalia truncatulinoides. Sponge spicules and radiolarians were also noted.

Age: Acarinina collactea, in the absence of A. primitiva, indicates very late Middle Eocene to early Late Eocene.

SAMPLE 67/GC 05 MIDDLE

Semi-lithified olive-grey mud.

The assemblage is similar to that from the bottom of the core, but planktonic foraminifera are less common. Tenuitella gemma, Testacarinata inconspicua and Pseudohastigerina micra were not observed.

Age: Very late Middle Eocene to early Late Eocene.

SAMPLE 67/GC 05 TOP

Olive-grey foram/nanno ooze.

Planktonic foraminifera are abundant and well preserved. Globigerina bulloides, Globigerinoides ruber, Globorotalia inflata and G. truncatulinoides predominate; also present are Globigerina quinqueloba, Globigerinella aequilateralis, Orbulina, Globorotalia

scitula, G. hirsuta, Neogloboquadrina pachyderma, N. dutertrei s.l. and Globigerinita glutinata. Rare Middle to Late Eocene contaminants include Acarinina collactea, Globigerinatheka index, Subbotina linaperta, Tenuitella aculeata, Chiloguembelina cubensis and Globorataloides suteri.
Age: Globorotalia truncatulinoides indicates Quaternary.

CORE STATION 67/GC 39

Lat. 40°37.9′ Long. 141°50.1′
Southwest of King Island; depth 4300 m; recovery 135 cm.

SAMPLE 67/GC 39 CORE CATCHER

Olive-grey foram/nanno ooze.
Planktonic foraminifera are abundant and well preserved. Globigerina bulloides, Globigerinoides ruber, Orbulina, Globorotalia inflata, G. truncatulinoides, Neogloboquadrina pachyderma and N. dutertrei s.l. are common to abundant; also present are Globigerina quinqueloba, Globigerinella aequilatera, Globorotalia scitula, G. hirsuta, G. crassaformis, G. viola and Globigerinita glutinata.
Age: Globorotalia truncatulinoides indicates Quaternary.

CORE STATION 67/GC 54

Lat. 41°10.9′ Long. 143°50.2′
West of northwestern Tasmania; depth 1634 m; recovery 97 cm.

SAMPLE 67/GC 54 85 cm

Olive-grey foram/nanno ooze (hard mudstone?).
Planktonic foraminifera are abundant and well preserved. Globigerina bulloides, Globorotalia inflata, G. truncatulinoides and Neogloboquadrina pachyderma are common to abundant; also present are Globigerina quinqueloba, Globigerinoides ruber, Orbulina, Globorotalia scitula, G. hirsuta, Neogloboquadrina dutertrei s.l. and Globigerinita glutinata. Rare Oligocene contaminants" include Globorotaloides suteri and G. testarugosa.

Age: Globorotalia truncatulinoides indicates Quaternary.

COMPARISON WITH CALCAREOUS NANNOFOSSIL EVIDENCE AND DISCUSSION OF BIOSTRATIGRAPHY

There are discrepancies (see Fig. 34) between the ranges of some planktonic foraminifera in the Late Eocene in the onshore Otway Basin (McGowran 1973; 1978; 1986) and in the St Vincent Basin (Lindsay, 1967; 1969, 1985). There are also unresolved differences in the placement of planktonic foraminiferal datum levels against the time scale (the P zones) by McGowran (1978; 1986) and by Shafik (1981; 1983), who used nannofossil evidence for correlation. Taking such differences into account, there is, in general, good agreement between age assignments based on planktonic foraminifera and on nannofossils in the offshore Otway Basin samples.

In the few cases of significant disagreement, it appears that dredge samples labelled similarly but differing in age were investigated. Lithological similarity is no guarantee of similarity in age, as already shown by the different nannofossil age assignments to subsamples of the 'same' brown sandy siltstone (48/7 DR - 1a) and the 'same' brownish grey calcareous clay (67/DR 10 - 3a and 3b).

Possibilities for contamination are inherent in the very nature of dredge samples. Contamination of early Tertiary assemblages by Quaternary foraminifera is usually easily detected; not only the species involved but also their state of preservation are different. Mixing of foraminifera from slightly but significantly different age intervals is much harder to discern, but may be responsible for some anomalous overlaps in ranges.

1. Samples with **Acarinina primitiva,** also **A. collactea:** late Middle Eocene.

	Nannofossil age:
67/DR 10-3a	mid-Middle Eocene (early zone P 13)
67/DR 10-3c	early Late Eocene

In the case of sample 67/DR 10-3a, the planktonic foraminiferal and nannofossil age assignments essentially agree. Species not ranging above early Middle Eocene are absent and, irrespective of whether the top of **Acarinina primitiva** is placed in zone P 14 (McGowran 1978, 1986) or P 13 (Shafik; 1983), the assemblages may be regarded as late Middle Eocene.

In the case of sample 67/DR 10-3c, the nannofossil age assignment appears to question the significance of very rare **A. primitiva** specimens. However, the planktonic foraminiferal assemblages in samples 3a and 3c agree closely in most respects (two specimens of **Tenuitella gemma** in 3c may be regarded as contaminants) and are considered to be similar in age.

2. Samples with **Acarinina collactea** but not **A. primitiva:** very late Middle Eocene to early Late Eocene.

	Nannofossil age:
48/7 DR-3a	very late Middle Eocene

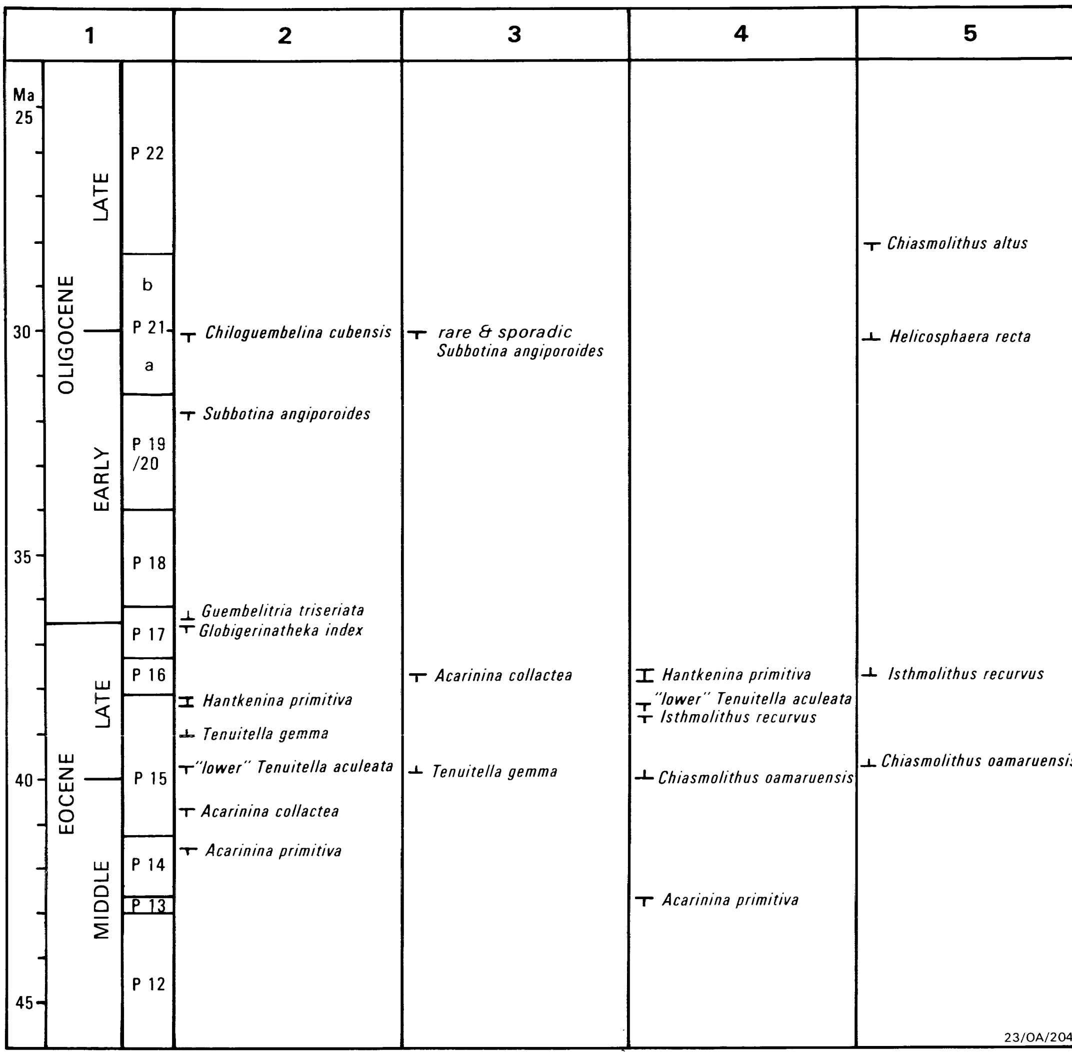

Fig. 34 Middle Eocene - Oligocene time scale and biostratigraphic datum levels. (1) & (5) After Berggren, & others 1985a; (2) After Berggren & others, 1985a and McGowran, 1986; (3) After Lindsay, 1985; (4) After Shafik, 1983.

67/GC 05 Bottom	early Late Eocene (above base Chiasmolithus oamaruensis, below base Isthmolithus recurvus)
67/GC 05 Middle	as above

Berggren & others (1985a) recorded the last appearances of Acarinina and Truncorotaloides as 40.6 Ma, in the lower part of zone P 15, slightly below the top of Middle Eocene, and McGowran (1986) placed the top of Acarinina collactea at a similar level. However, Lindsay (1985) showed A. collactea ranging upwards well into Upper Eocene, above the Hantkenina primitiva interval, in the St Vincent Basin. Shafik (1983) considered the top of Acarinina collactea as unreliable, and stated that in the Gambier Embayment the species ranges above the base of Isthmolithus recurvus, well above the base of Chiasmolithus oamaruensis. The base of C. oamaruensis is generally placed at or near the base of Upper Eocene; Berggren & others (1985a) recorded it as 39.8 Ma.

It may be convenient to regard the presence of Acarinina collactea as generally indicating Middle Eocene in southeastern Australia. However, there is good evidence that it extends into Upper Eocene.

3. Samples with common Tenuitella gemma and Acarinina collactea, and rare A. primitiva: early Late Eocene.

	Nannofossil age:
67/DR 10-3b	latest Eocene - Early Oligocene
67/DR 18-3b	" " " "

Quite apart from the disagreement with the nannofossil age assignments, the association of common Tenuitella gemma and Acarinina collactea (also fairly rare Tenuitella aculeata), and rare Acarinina primitiva calls for discussion.

McGowran (1978; 1986) showed the base of Tenuitella gemma above the successive tops of Acarinina collactea and 'lower' Tenuitella aculeata, but below the Hantkenina primitiva interval, in southern Australia (more specifically, onshore Otway Basin), and still higher, above H. primitiva, in the Great Australian Bight Basin and in New Zealand (as recorded earlier by Jenkins 1971; 1985). However, Lindsay (1985) placed the base of Tenuitella gemma well below the top of Acarinina collactea and also below the top of 'lower' Tenuitella aculeata in the St Vincent Basin.

T. gemma has not been recorded in association with Acarinina primitiva, and the rare A. primitiva specimens in the two samples considered here may be regarded as contaminants (or as reworked?). However, the overlap of Tenuitella gemma with Acarinina collactea and 'lower' Tenuitella aculaeta appears to be 'real', although it is difficult to explain why in this respect the offshore Otway Basin resembles the restricted St Vincent Basin rather that the onshore Otway Basin.

Sample 67/DR18-3b is the most easterly of the Eocene samples and the only one lacking Globigerinatheka index. The single specimen of Hantkenina primitiva may be regarded as a contaminant.

4. One sample with a sparse foraminiferal assemblage including Globigerinatheka index: Middle to Late Eocene.

	Nannofossil age:
48/7DR-1a	latest Eocene - Early Oligocene (samples 1b and 1c: Middle Eocene)

5. Samples with common to abundant Subbotina angiporoides (and common Chiloguembelina cubensis); Guembelitria triseriata is present (except in 67/DR 12 - 3) and species restricted to Eocene are absent: Early Oligocene (zone P 19/20 or older).

	Nannofossil age:
67/DR 12-3	Early Oligocene
48/5 DR-1a	early Late Oligocene (below top Chiasmolithus altus)
67/DR 14-1a	" " " " "
67/DR 10-2b	early Late Oligocene (below top Chiasmolithus altus, above base Helicosphaera recta)
67/DR 10-4	" " " " "

Berggren & others (1985a) recorded the last appearance of Chiloguembelina as 30 Ma, marking the zone P 21 a/b and Lower/Upper Oligocene boundaries, and the last appearance of Subbotina angiporoides as 32 Ma, in the upper part of zone P 19/20. The latter datum appears to correspond with the top of 'good', i.e. common, well developed S. angiporoides; McGowran (1986) placed it in the lower part of zone P 19/20.

The base of zone NP 24, shown as corresponding with the base of Helicosphaera recta by Perch-Nielsen (1985), was placed slightly below the top of Early Oligocene by Berggren & others (1985a). The presence of H. recta in samples 67/DR 10-2b and 4 suggests that it ranges somewhat lower.

Guembelitria triseriata first appeared in southeastern Australia very near the beginning of the Oligocene (Lindsay, 1985; McGowran & Beecroft, 1985).

6. Samples with rare Subbotina angiporoides, also Chiloguembelina cubensis; Guembelitria triseriata is present in 67/10-1 and species restricted to Eocene are absent: late Early Oligocene (zone P 21 a or slightly older).

	Nannofossil age:
67/DR 2-2 a	mid-Eocene - mid-Oligocene
67/DR 10-1	early Late Oligocene (below top Chiasmolithus altus, above base Helicosphaera recta)

Taylor (1968) noted that in offshore sections in the Otway Basin Subbotina angiporoides ranges almost as high as Chiloguembelina cubensis. In New Zealand Subbotina angiporoides ranges upwards lower than Chiloguembelina cubensis according to Jenkins (1971; 1985), higher according to Hornibrook & Edwards (1971) and to about the same level according to Hoskins (1982).

Such different opinions appear to reflect observations that rare, sporadic specimens occur higher than the top of common, well developed Subbotina angiporoides, probably extending into zone P 21 (Blow, 1979,

p. 296; Lindsay, 1985; McGowran & Beecroft, 1985).

7. Samples with common to abundant Globigerina euapertura; species not ranging above Early Oligocene or below Miocene are absent: Late Oligocene.

	Nannofossil age:
67/DR 14-1 c	mid-Late Oligocene
67/DR 19-1	" " "

8. One sample with Globorotalia acostaensis and rare G. conomiozea; species restricted to Pliocene are absent: very late Miocene.

	Nannofossil age:
48/7 DR-7a	Late Oligocene (sample 48/7 DR - 7)

Berggren, & others (1985b) recorded the first appearance of G. acostaensis as 10.2 Ma, slightly above the base of Late Miocene. Mallett (1978) placed the base of G. conomiozea in the Otway Basin within zone N 16; Heath & McGowran (1984) shifted it up within zone N 17, in agreement with the Berggren & others (1985b) record of the first appearance of G. conomiozea as 6.1 Ma.

9. Samples with common to abundant Globorotalia truncatulinoides, indicating Quaternary, and (except in 67/GC 39) older species indicating different ages.

	Foram age(s)	Nannofossil age(s)
67/DR 12-4 & 5	Quaternary	late Quaternary (67/DR 12-5)
	Early Miocene Early Oligocene	early Late Oligocene (67/DR12-4)
67/DR 14-3	Quaternary Early Oligocene	
67/GC 05 Top	Quaternary late Middle Eocene - early Late Eocene	late Quaternary
67/GC 39 cc	Quaternary	late Quaternary
67/GC 54 85 cm	Quaternary Late Oligocene	(Quaternary) mid-Late Oligocene

Berggren & others (1985b) recorded the first appearance of Globorotalia truncatulinoides as 1.9 Ma, shortly before the beginning of Quaternary, but its base may be regarded as a good approximation of the base of Quaternary in southeastern Australia (Singleton & others 1976; Mallett, 1978). In contrast to calcareous nannofossils, planktonic foraminifera enabling distinction of late Quaternary have not been observed in this region.

In the case of 67/DR 12-4 & 5, planktonic foraminiferal and nannofossil evidence agrees in respect to the Quaternary and Oligocene age assignments. It is noted that 67/DR 12-2 was dated as Early Miocene on the basis of nannofossils.

In the case of 67/GC 54 85 cm, the 'normal' and 'contaminant' parts are reversed - Quaternary foraminifera dominate the assemblage, whereas Quaternary nannofossils were noted as rare contaminants.

COMMENTS ON SOME SPECIES

Acarinina collactea is morphologically rather variable. No attempt was made to distinguish different morphotypes, or groups A and B of McGowran (1973).

In three samples (67DR 10-3a and 3c, 48/7 DR-3a), in which Subbotina linaperta commonly has strongly compressed chambers, a few specimens are comparable with S. frontosa in having arched, rather than slit-like apertures. It is uncertain how closely they resemble S. cf. frontosa of McGowran (1978, and other papers).

Globorotaloides suteri is morphologically very variable as shown by Bolli (1957), Stainforth & others (1975, p. 322-324) and other authors. Some of the Eocene specimens may be referable to G. turgida. Other specimens may be referable to G. testarugosa, although "typical" G. testarugosa was distinguished from G. suteri in Upper Oligocene samples.

Catapsydrax dissimilis agrees well with the description and illustrations in Stainforth & others (1975, p. 268-269).

Globigerina cf. gortanii is not as high-spired as G. gortanii sensu stricto.

Tenuitella insolita commonly has 5 or 6 (occasionally 7) chambers in the last whorl, rather than 4 to 4½ as shown by Jenkins (1966; 1971).

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APPENDIX D. PALYNOLOGICAL ANALYSIS OF SAMPLES FROM THE OFFSHORE OTWAY BASIN AND OFF WESTERN TASMANIA

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INTRODUCTION

In 1985, BMR commenced a program aimed at increasing knowledge of the geology and resource potential of the offshore Otway Basin and continental shelf and slope off western Tasmania. This research program included extensive sampling of rocks and soft sediments on the seafloor (Hinz & others, 1986; Exon & others, 1989; and this Report).

Thirteen samples of mud and hard rock, recovered by dredge and piston coring during BMR surveys 67 & 78 and processed by BMR, as listed in Table 1, were examined for spore-pollen and dinoflagellates.

Yields and preservation were adequate to good, but the confidence of many age-determinations was reduced by reworking (see Geological Comments) and/or poor slide preparation (see Biostratigraphic Comments).

Palynological age-determinations and interpreted palaeoenvironments of deposition are summarised below (Table 2). Full interpretive data for each sample are given in Annexure 1.

GEOLOGICAL COMMENTS

1. All samples were deposited in marine-influenced depositional environments, ranging from marginal to fully open-marine.

2. The oldest sample recorded (78 DR06A) is Santonian, *T. apoxyexinus* Zone, similar in age to the earliest recorded marine influence in the Gippsland Basin (Macphail, 1984; Marshall, 1988). The depositional environment (marginal-marine) interpreted for this and the other Late Cretaceous samples examined are broadly consistent with Late Cretaceous shoreline developments (Frakes & others, 1987) and patterns of sedimentation (Deighton & others, 1976) during the Late Cretaceous evolution of the Southern Ocean.

Irrespective of the dinoflagellate yield, it is noted that all of the early Tertiary samples contained abundant spore-pollen, a characteristic of marginal-marine palynofloras. This implies that the sediments were, in fact, deposited in near-shore or lagoonal environments and therefore that these localities have since undergone massive subsidence since the early Tertiary. The only unequivocal mid Tertiary sample (67 GC12CC) yielded a diverse dinoflagellate assemblage indicative of open-marine conditions.

Table 1. Station data for palynological samples

A. <u>1987 BMR Cruise 67 : Otway Basin/West Tasmania</u>

<u>67 DR3/1</u> (MFP 8868). Dredge at 38°14.3'S, 138°37.2'E, 4000-4500 m. Dark brownish grey indurated siltstone. Half of dredge haul.

<u>67 DR3/2A</u> (MFP 8869). Dredge at 38°14.3'S, 138°37.2'E, 4000-4500 m. Dark brown plastic mud of silt size. Common in dredge haul.

<u>67 DR4/2A</u> (MFP 8870). Dredge at 38°25.5'S, 138°51.0'E, WD4050-4700 m. Laminated, burrowed medium grey-brown mudstone. Minor in dredge haul.

<u>67 DR6/A</u> (MFP 8866). Dredge at 38°46.0'S, 139°9.0'E, 4450-4660 m. Black non-fissile mudstone. Small pieces in dredge haul.

<u>67-DR8</u> (MFP 8865). Dredge at 39°02.0'S, 140°02.0'E, 4050-4350 m. Dark brown mud and soft mudstone. Limited quantity in small dredge haul.

<u>67 DR21/2</u> (MFP 8872). Dredge at 40°50.0'S, 141°47.5'E, 4155-4580 m. Thinly well-bedded, fine-grained carbonaceous micaceous clayey sandstone with mud clasts and clay lenses. Minor part of moderate dredge haul.

<u>67 DR22/2</u> (MFP 8871). Dredge at 42°41.35'S, 143°43.2'E, 3900-4200 m. Tough dark grey mud. Most of small recovery of semi-lithified material.

<u>67GC 09CC</u> (MFP 8867). Core at 38°57.1'S, 146°06.6'E, 3615 m. Core catcher, at 203-213 cm depth, of firm brown mud.

<u>67GC 12CC</u> (MFP 8864). Core at 38°42.6'S, 140°07.1'E, 3150 m. Core catcher in 10 cm recovery of highly carbonaceous mudstone.

B. <u>1988 BMR Cruise 78 : West Tasmania</u>

<u>78GC 05A</u> (MFP 9125). Core at 42°50.1 'S, 143°51.1'E, 3530 m. Grey mudstone at 48 cm in core.

<u>78GC 05/CC</u> (MFP 9126). Core at 42° 50.1'S, 143°51.5'E, 3530 m. Dark grey mudstone in core catcher at 50-60 cm depth. (Same core as 78GC 05A).

<u>78DR 06A</u> (MFP 9124). Dredge at 43°36.2'S, 144°11.8'E, 3760-3915 m. Dark grey mudstone.

<u>78DR 09B</u> (MFP 9123). Dredge at 42°50.0'S, 143°49.7'E, 3700-4370 m. Grey mudstone.

Table 2 : Summary of results

Sample	Age	Zone: Spore-pollen	Zone: Dinoflagellate	Environment
67GC12CC	Middle Eocene	Lower N. asperus	T. pandus	open marine
67DR08	Late Santonian-early Campanian	Upper T.apoxyexinus	N. aceras	restricted-open marine
67DR06A	Early Eocene	Lower M. diversus	-	marginal marine
67GC09CC	Middle Eocene?	Lower N. asperus?	T. pandus	marginal marine
67DR3/1	Campanian	T. lilliei	O. porifera Int.	marginal marine
67DR03/2	Early Eocene	P. asperopolus	W. edwardsii?	marginal marine
67DR04/2A	Campanian	T. lilliei	I. korojongense	marginal marine
67DR22/2	Maastrichtian	Upper T. longus	M. druggii	restricted-marginal marine
67DR21/2	Maastrichtian	Lower T. longus	-	marginal marine
78DR09B	Paleocene	Lower L. balmei	E. crassitabulata	restricted marine
78DR06A	Santonian	T. apoxyexinus	O. porifera Int.	marginal marine
78GC05A	Early Eocene	Lower M. diversus	-	marginal marine
78GC05CC	Early Eocene	Upper M. diversus	-	marginal marine

3. Several samples contained distinctive dinoflagellate assemblages which should allow the rock units to be correlated with sections/marine transgressions elsewhere, particularly in the Otway and Gippsland basins. These are : 67 GC12CC (ms T. pandus Zone); 67 DR08 (Paaratte Fm, Whelk-1, Otway Basin); 67 DR03/2 (W. edwardsii/W. thompsonae Zone); 67 DR22/2 (M. druggii Zone); and 67 DR21/2 (? Haumuri Bluff section, NZ).

4. A comparision of spore-pollen assemblages analysed here, and those of equivalent age in the Gippsland Basin, reveals both qualitative and quantitative differences. The former is most clearly expressed in the Tertiary samples, most of which contain species or varieties which are not recorded in the Gippsland Basin. This probably reflects increasing regionalisation of the Southern Australian flora and vegetation during the Tertiary. Examples of quantitative differences, chiefly expressed in the relative abundance of the more common species found in both basins, are the sparsity of Lygistepollenites balmei and Gambierina rudata in Late Paleocene and Maastrichtian assemblages from the Otway/west Tasmanian margin.

The point is of geologic as well as biogeographic interest, since it underscores the need for caution when applying spore-pollen zonation criteria from one basin to another. Dinoflagellate floras are less provincial and thus are a more reliable basis for inter-basin comparisons.

BIOSTRATIGRAPHIC COMMENTS

Zonation

The sparse range data published by Harris (1971) predate the extensive drilling of the Bass Strait basins and the revisions of planktonic foraminiferal zonation schema widely used to tie palynological zones to the geologic time scale.

Accordingly, zone and age-determinations have been made using criteria proposed by Stover & Partridge (1973), Helby & others (1987), and unpublished observations made on Gippsland and Otway Basin wells drilled by Esso Australia Ltd. The informal subdivision of the T. longus Zone proposed by Macphail (1983: see Helby & others, 1987, p. 58) is followed here. Zone names have not been altered to conform with nomenclatural changes to nominated species such as Tricolpites longus (now Forcipites longus: see Dettman & Jarzen, 1988).

A recurrent problem with marine-influenced facies is reworking of older palynomorphs into younger sediments. Moreover, where depositional rates are very low, a condensed section will develop, e.g. at the base of a highstand systems tract. In such units, it is not uncommon for species whose ranges do not overlap in geologic time to occur in the same sample, or for the geologic age of a sediment based on spore-pollen to differ from (usually to be older than) the age indicated by dinoflagellates.

The approach adopted here is to base age-determination on dinoflagellates when these indicate a younger date than the spore-pollen do, e.g. samples 67 GC 12 CC and 67 GC 09 CC (both yielding Middle Eocene dinoflagellates and Early Eocene spore-pollen assemblages). It is noted that the age-determination may reflect the latest episode of in situ reworking rather than any accumulation of additional clastic sediments. The converse situation, where spore-pollen indicates an age younger than that indicated by the dinoflagellates, has to be decided on an individual basis. Where the dinoflagellate flora is substantially older than the spore-pollen flora (usually Late Cretaceous versus Eocene), reworking of the dinoflagellates almost certainly has occurred. Where no great disparity in age exists, a condensed section is indicated, e.g. sample 67 DR 06A. The one exception in this report is sample 78 DR 09B, dated as Paleocene despite the occurrence of the middle-late Tertiary species Nothofagidites falcatus. Here, contamination or minor bioturbation is proposed.

Interpretation of palaeoenvironments

The reconstruction of depositional conditions using palynology depends on the presence/absence of marine dinoflagellate species and subjective estimates of (i) the absolute concentration of palynomorphs in the rock sample, (ii) the relative abundance of spore-pollen and dinoflagellates, and (iii) the diversity of dinoflagellate species. Algal species diagnostic of freshwater lacustrine conditions were not recorded.

The criteria broadly adopted here are:

(a) Open marine - dinoflagellates diverse and very abundant relative to spore-pollen (often wind-distributed pollen and water-transported spore types).

(b) Restricted marine - dinoflagellates diverse, approximately equal relative to spore-pollen.

(c) Marginal marine - dinoflagellates sparse relative to spore-pollen or, if abundant, then 1-3 species present only.

Processing

The majority of strew-mounts contained very abundant plant macerals, mostly ranging from less than 1 micron to less than 100 microns in diameter, but usually clumped with spore-pollen into larger aggregrates.

This has reduced the confidence of the age-determinations, since many palynomorphs were too obscured by structured organic matter to be identified - leading to an incomplete analysis of species present. Good concentration and dispersal of palynomorphs within a strew-mount is critical when the index species are small (less than 20 microns), e.g. the Early-Middle Eocene dinoflagellate genus Tritonites.

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ANNEXURE 1 : INTERPRETIVE DATA FOR ALL SAMPLES

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 01

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3504

2. **SAMPLE NO:** 67 GC 12 CC TYPE: core catcher DEPTH: sea-floor WD 3150m
   LITHOLOGY: carb. mudstone YIELD: high PRESERVATION: good
   STREW MOUNT CODE: MFP 8864 NO. OF MOUNTS WORKED: 2

3. **AGE DETERMINATION**

   GEOLOGIC AGE: Middle Eocene
   ZONE (SPORE-POLLEN): Lower N. asperus **CONFID. RATING:*** 2
   ZONE (DINOFLAGELLATE) T. pandus (informal) **CONFID. RATING:*** 0

   INDEX SPP: Tritonites pandus, T. tricornus

4. **AGE RANGE**

   MAXIMUM AGE: Foram Zone P.14 **based on:** T. Pandus, absence of T. spinosus

   MINIMUM AGE: Foram Zone P.10 **based on:** T. tricornus, absence of T. asteris

5. **RECYCLED SPP:** Isabelidinium korojongense (Late Cretaceous), Veryhachium sp (Mesozoic)

6. **PALAEOENVIRONMENT:** Open marine

7. **REFERENCES:** Marshall, N.G. & Partridge, A.D. (1988). Mem. Ass. Australas. Palaeontols., 5: 239-257.

8. **COMMENTS:** The date is wholly based on the presence/absence of Tritonites spp. The associated spore-pollen is Early Eocene, Upper M. diversus-P. asperopolus Zone in age, based on Deflandrea truncata, Myrtaceidites tenuis and Tricolporites leuros. This indicates that the sample is a condensed sequence, probably coeval with the Gurnard Formation in Marlin Field wells and the middle section of the Turrum Formation in the central Marlin Channel, Gippsland Basin. Tritonites pandus occurs at 392.5m, and T. tricornus at 422.1 & 435.3m in Whelk-1, Otway Basin (see Marshall & Partridge ibid, pp. 241-242.)

   * Note : Based on the Esso system of confidence ratings in which the highest rating is O and the lowest, for conventional core, SWC and outcrop, is 2.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 02

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3505

2. **SAMPLE NO:** OT 67 DR 08 **TYPE:** dredge **DEPTH:** sea-floor WD 4050+m
   LITHOLOGY: mud/mudstone **YIELD:** high **PRESERVATION:** good
   STREW MOUNT CODE: MFP 8865 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

   GEOLOGIC AGE: Late Santonian-Early Campanian
   ZONE (SPORE-POLLEN): Upper *T. apoxyexinus* **CONFID. RATING:** 2
   ZONE (DINOFLAGELLATE) *N. aceras* **CONFID. RATING:** 1

   INDEX SPP: *T. apoxyexinus*, *Forcipites spp.*, *T. confessus*, *Camarozonosporites bullatus*, *Phimopollenites pannosus*, *Isabelidinium cretaceum*, *Nelsoniella truncata*, *Heterosphaeridium heterocanthum*, *Odontochitona porifera* (common)

4. **AGE RANGE**

   MAXIMUM AGE: latest Santonian to earliest Campanian **based on:** *N. tuberculata*, *O. porifera*

   MINIMUM AGE: middle-late Campanian **based on:** *Stereisporites regium* ms. *Phimopollenites pannosus*

5. **RECYCLED SPP:** Mostly Early Cretaceous spp., including *Dictyotosporites speciosus*, *Dictyophyllidites crenatus*.

6. **PALAEOENVIRONMENT:** Open to restricted marine

7. **REFERENCES:** Helby, R., Morgan, R. & Partridge, A.D. (1987) p.66. *Mem. Ass. Australas. Palaeontols.*, 4: 1-94

8. **COMMENTS:** Dinoflagellate spp. dominate the sample, particularly *Odontochitona porifera* and *Heterosphaeridium heterocanthum*. Although neither *Nothofagidites* nor *Xenikoon australis* were recorded, the sample may be lowermost *N. senectus* Zone. The reference section of the *N. aceras* Zone is Whelk-1 1096-1208m (Paaratte Formation).

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 03

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3505

2. **SAMPLE NO:** OT 67 DR 06A **TYPE:** dredge **DEPTH:** sea-floor WD 4450+m
   LITHOLOGY: black mudstone **YIELD:** high **PRESERVATION:** good
   STREW MOUNT CODE: MFP 8866 **NO. OF MOUNTS WORKED:** 1

3. **AGE DETERMINATION**

   GEOLOGIC AGE: Early Eocene
   ZONE (SPORE-POLLEN): Lower _M_. _diversus_ **CONFID. RATING:** 2
   ZONE (DINOFLAGELLATE) - **CONFID. RATING:** -

   INDEX SPP: _Cyathidites gigantis_, _Camarozonosporites bullatus_, _Intratriporopollenites notabilis_, _Deflandrea obliquipes_, _Cordosphaeridium inodes_ (freq.),

4. **AGE RANGE**

   MAXIMUM AGE: Late Paleocene **based on:** _L_. _balmei_, _G_. _rudata_, _C_. _gigantis_, _P_. _incurvatus_, _A_. _obscurus_
   MINIMUM AGE: Early Eocene **based on:** _C_. _gigantis_, _D_. _obliquipes_

5. **RECYCLED SPP:** _Odontochitona porifera_. Possible recycled spp. are _L_. _balmei_, _G_._rudata_; probable recycled spp. include _Tetracolporites verrucosus_, _Isabelidinium_ cf _bakeri_ and an undescribed _Alisocysta_ sp.

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:**

8. **COMMENTS:** It is possible that this sample represents a condensed section rather than an Early Eocene sediment containing reworked Late Paleocene spp.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 04

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3506

2. **SAMPLE NO:** 67 GC 09 CC **TYPE:** core catcher **DEPTH:** sea-floor WD 3615m
   LITHOLOGY: **YIELD:** high **PRESERVATION:** poor
   STREW MOUNT CODE: MFP 8867 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

   GEOLOGIC AGE: Middle Eocene or Campanian reworked during the Middle Eocene

   ZONE (SPORE-POLLEN): Lower N. asperus (T. lilliei) **CONFID. RATING:** 2
   ZONE (DINOFLAGELLATE) T.pandus (informal)(I.koroj.) **CONFID. RATING:** 2

   INDEX SPP: Anacolosidites rotundus ms, Tritonites tricornus (Tricolporites lilliei, Isabelidinium korojongense)

4. **AGE RANGE**

   MAXIMUM AGE: T. lilliei **based on:** T. lilliei, I. korojongense

   MINIMUM AGE: Lower N. asperus **based on:** T. tricornus

5. **RECYCLED SPP:** Nelsoniella cf tuberculata, Heterosphaeridium heterocanthum Gambierina spp., Myrtaceidites tenuis, Cyatheacidites tectifera, Ornamentifera sentosa, Tetracolporites verrucosus

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:**

8. **COMMENTS:** This sample contains a diverse palynoflora, dominated by spore-pollen taxa which include index spp. from the Late Cretaceous, I. korojongense Zone, Paleocene, L. balmei Zone and Early Eocene, Upper M. diversus-P. asperopolus Zone. Either extensive reworking or a highly condensed sequence is suggested.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 05

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3506

2. **SAMPLE NO:** OT 67 DR 3/1 **TYPE:** dredge **DEPTH:** sea-floor WD 4000+m
LITHOLOGY: siltstone **YIELD:** high **PRESERVATION:** fair
STREW MOUNT CODE: MFP 8868 **NO. OF MOUNTS WORKED:** 1

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Campanian	
ZONE (SPORE-POLLEN):	T. lilliei	**CONFID. RATING:** 2
ZONE (DINOFLAGELLATE)	O. porifera Interval	**CONFID. RATING:** 1

INDEX SPP: Tricolporites lilliei, Triporopollenites megasectilis ms, Tetracolporites verrucosus, Stereisporites regium ms, Grapnelispora sp. nov., Ornamentifera sentosa, Odontochitona porifera.

4. **AGE RANGE**

MAXIMUM AGE: Maastrichtian **based on:** T. verrucosus, Grapnelispora sp.

MINIMUM AGE: Campanian **based on:** T. lilliei, T. megasectilis ms

5. **RECYCLED SPP:** Early Cretaceous spp. such as Dictyotosporites speciosus, Classopollis sp. Cyatheacidites tectifera may be reworked. ,

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:**

8. **COMMENTS:** The confidence of the age-determination is reduced by the presence of Tricolpites phillipii and Cyatheacidites tectifera. The former species first appears in the T. longus Zone and the latter may range no higher than the T. apoxyexinus Zone.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO: 06**

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3507

2. **SAMPLE NO:** OT 67 DR 03/2A **TYPE:** dredge **DEPTH:** sea-floor WD 4000+m
   LITHOLOGY: silt mud **YIELD:** high **PRESERVATION:** good
   STREW MOUNT CODE: MFP 8869 **NO. OF MOUNTS WORKED:** 1

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Early Eocene	
ZONE (SPORE-POLLEN):	P. asperopolus	**CONFID. RATING:** 1
ZONE (DINOFLAGELLATE)	W. edwardsii?	**CONFID. RATING:** 2

INDEX SPP: Myrtaceidites tenuis (abundant), Tricolporites leuros, Proteacidites pachypolus (freq.), P. ornatus, Intratriporopollenites notabilis, Wilsonidinium spp., Kisselovia sp. nov.

4. **AGE RANGE**

MAXIMUM AGE:	Upper M. diversus	**based on:**	Wilsonidinium, Kisselovia spp. M. tenuis, P. pachypolus
MINIMUM AGE:	P. asperopolus	**based on:**	T. leuros, P. ornatus, I. notabilis

5. **RECYCLED SPP:** Lygistepollenites balmei, Gambierina rudata, Deflandrea truncata

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:** Wilson, G.J. (1967) N.Z. J. Botany, 5: 469-97.
   Partridge, A.D. (1976) APEA J., 16: 73-79.

8. **COMMENTS:** The Wilsonidinium (al. Wetzeliella) spp. in this sample more closely resemble the N.Z. species W. tabulatum and W. articulata than any described Australian spp. The Kisselovia sp. is distinct from any described species, but is likely to be contemporary with K. edwardsii and K. thompsonae/coleothrypta.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 07

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3507m

2. **SAMPLE NO:** OT 67 DR 04/2A **TYPE:** dredge **DEPTH:** sea-floor WD 4050+m
   LITHOLOGY: lam., burrowed mudstone **YIELD:** low **PRESERVATION:** poor
   STREW MOUNT CODE: MFP 8870 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

   GEOLOGIC AGE: Campanian
   ZONE (SPORE-POLLEN): T. lilliei **CONFID. RATING:** 1
   ZONE (DINOFLAGELLATE) I. korojongense **CONFID. RATING:** 0

   INDEX SPP: Tricolporites lilliei, Tricolpites waiparensis, Proteacidites wahooensis ms, Isabelidinium pellucidum

4. **AGE RANGE**

   MAXIMUM AGE: Campanian **based on:** T. lilliei, I. pellucidum

   MINIMUM AGE: Maastrichtian **based on:** I. pellucidum

5. **RECYCLED SPP:** none noted

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:**

8. **COMMENTS:** The negligible recovery of dinoflagellates is consistent with deposition in a low energy environment subject to a low degree of marine influence.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 08

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3508

2. **SAMPLE NO:** OT 67 DR 22/2 **TYPE:** dredge **DEPTH:** sea-floor WD 3900+m
LITHOLOGY: similith. mud **YIELD:** high **PRESERVATION:** fair
STREW MOUNT CODE: MFP 8871 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Maastrichtian	
ZONE (SPORE-POLLEN):	Upper _T._ _longus_	**CONFID. RATING:** 1
ZONE (DINOFLAGELLATE)	_M._ _druggii_	**CONFID. RATING:** 0

INDEX SPP: _Ornamentifera sentosa_, _Tricolporites lilliei_, _Stereisporites_ (_Tripunctisporis_) sp., _Mamumiella druggii_ (abundant).

4. **AGE RANGE**

MAXIMUM AGE:	Upper _T._ _longus_	**based on:**	_M._ _druggii_, _Stereisporites_ (_Tripunctisporis_) sp.
MINIMUM AGE:	as above	**based on:**	as above

5. **RECYCLED SPP:** _Isabelidinium ponticum_?

6. **PALAEOENVIRONMENT:** Restricted marginal marine

7. **REFERENCES:**

8. **COMMENTS:** Despite the abundance of _M._ _druggii_, other dinoflagellate species are rare, indicating a restricted/marginal rather than open marine depositional environment. Analogous modern dinoflagellate 'blooms' occur at the mouths of rivers entering estuaries or in restricted seaways such as the Red Sea.

Based on Gippsland Basin seismic stratigraphy, the sample is likely to come from a condensed section close to, but below, the Cretaceous/Tertiary boundary.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 09

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3508

2. **SAMPLE NO:** OT 67 DR 21/2 **TYPE:** dredge **DEPTH:** sea-floor WD 4155+m
LITHOLOGY: lam., carb., ss. **YIELD:** low **PRESERVATION:** good
STREW MOUNT CODE: MFP 8872 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Maastrichtian	
ZONE (SPORE-POLLEN):	Lower _T. longus_	**CONFID. RATING:** 2
ZONE (DINOFLAGELLATE)	-	**CONFID. RATING:** -

INDEX SPP: _Forcipites sabulosus_, _Triporopollenites sectilis_, _Gambierina_ spp. (freq.), _Odontochitona spinosa_ (freq.), _I._ cf _fenestrata_ ms

4. **AGE RANGE**

MAXIMUM AGE: Campanian **based on:** _T. sectilis_

MINIMUM AGE: Maastrichtian **based on:** _F. sabulosus_, _O. spinosa_

5. **RECYCLED SPP:** Early Cretaceous spp. including _Dictyotosporites complex_, _D. speciosus_.

6. **PALAEOENVIRONMENT:** Marginal marine

7. **REFERENCES:** Wilson, G.J. (1984). _N.Z. J. Botany_, 22: 549-556

8. **COMMENTS:** The age-determination is based on Wilson _ibid_, who has recorded a population of _O. spinosa_ in Maastrichtian sediments in New Zealand, and _Forcipites sabulosus_, which ranges no higher than the Lower _T. longus_ zone. The similarity of the assemblage to that described by Wilson is reinforced by the occurrence of a _Microdinium_ sp. cf _M. cassiculatum_.

As with sample OT 67 DR 04/2A (Campanian), the marine-influence, at the time of deposition of this sediment in a low energy environment, was slight.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO: 10**

1\. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3530

2\. **SAMPLE NO:** 78 DR 09B **TYPE:** dredge **DEPTH:** sea-floor WD 3700+m
LITHOLOGY: grey mudstone **YIELD:** high **PRESERVATION:** fair
STREW MOUNT CODE: MFP 9123 **NO. OF MOUNTS WORKED:** 2

3\. **AGE DETERMINATION**

GEOLOGIC AGE: Paleocene
ZONE (SPORE-POLLEN): Lower L. balmei **CONFID. RATING:** 1
ZONE (DINOFLAGELLATE) E. crassitabulata **CONFID. RATING:** 0

INDEX SPP: Eisenackia crassitabulata, Paleocystodinium golzowense, Deflanderea medcalfii/dartmooria, Glaphracysta retiintexta Haloragacidites harrisii, Tetracolporites multistrixus ms

4\. **AGE RANGE**

MAXIMUM AGE: Early Paleocene **based on:** E. crassitabulata

MINIMUM AGE: Late Paleocene **based on:** Lygistepollenites balmei, Gambierina rudata.

5\. **RECYCLED SPP:** taeniate bisaccate (Permian)

6\. **PALAEOENVIRONMENT:** Restricted marine based on the relative abundance of spore-pollen (very high) to dinoflagellates (high).

7\. **REFERENCES:**

8\. **COMMENTS:** A single specimen of the Middle Eocene-Pliocene species Nothofagidites falcatus was recorded. This is more likely to be a contaminant (introduced via bioturbation?) than indicating any significant reworking of a Paleocene sediment during the late Tertiary.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 11

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3530

2. **SAMPLE NO:** 78 DR 06A **TYPE:** dredge **DEPTH:** sea-floor WD 3760+m
LITHOLOGY: grey mudstone **YIELD:** low **PRESERVATION:** fair
STREW MOUNT CODE: MFP 9124 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Santonian	
ZONE (SPORE-POLLEN):	T. apoxyexinus	**CONFID. RATING:** 2
ZONE (DINOFLAGELLATE)	O. porifera	**CONFID. RATING:** 1

INDEX SPP: Cyatheacidites tectifera, Forcipites cf stipulatus, Amosopollis cruciformis (freq.), Odontochitona porifera, *Chatangiella tripartita, Heterosphaeridium heterocanthum

4. **AGE RANGE**

MAXIMUM AGE:	Santonian	**based on:**	C. tectifera, O. porifera, *C. tripartita
MINIMUM AGE:	Campanian	**based on:**	possible occurrence of Isabelidinium korojongense

5. **RECYCLED SPP:** none noted

6. **PALAEOENVIRONMENT:** Marginal marine

7. **REFERENCES:**

8. **COMMENTS:** *Some uncertainty exists about the identification of Chatangiella tripartita. The majority of specimens are intermediate between this species and Isabelidium korojongense.
The presence of Cyatheacidites tectifera is more consistent with a Santonian rather than a Campanian date, as is a possible specimen of Hoegisporis and the absence of distinctive Late Cretaceous Proteacidites, Tricolpites and Tricolporites spp.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 12

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3531

2. **SAMPLE NO:** 78 GC 05A **TYPE:** core catcher **DEPTH:** sea-floor WD 3530m
LITHOLOGY: grey mudstone **YIELD:** high **PRESERVATION:** fair
STREW MOUNT CODE: MFP 9125 **NO. OF MOUNTS WORKED:** 2

3. **AGE DETERMINATION**

GEOLOGIC AGE:	Early Eocene	
ZONE (SPORE-POLLEN):	Lower M. diversus	**CONFID. RATING:** 2
ZONE (DINOFLAGELLATE)	-	**CONFID. RATING:** -

INDEX SPP: Deflandrea dartmooria, Cyathidites gigantis, Bysmapollis emaciatus, Proteacidites grandis (freq.).

4. **AGE RANGE**

MAXIMUM AGE: Late Paleocene **based on:** Lygistepollenites balmei, Proteacidites incurvatus

MINIMUM AGE: Early Eocene **based on:** C. gigantis, D. dartmooria

5. **RECYCLED SPP:** Late Cretaceous spp. including Appendicisporites distocarinatus; Early Cretaceous spp. including Pilosisporites notensis, Trilobosporites tribotrys and Dictyotosporites speciosus; and Permo-Triassic taxa including Plicatpollenites spp.

6. **PALAEOENVIRONMENT:** Marginal marine.

7. **REFERENCES:**

8. **COMMENTS:** The dinoflagellate flora includes Samlandia reticulifera, a species ranging up to (restricted to?) the Late Eocene. What weight should be attached to this record is unclear since no other Middle-Late Eocene dinoflagellate species were recorded.

The Early Eocene, Lower M. diversus Zone age for this core sample is inconsistent with an Upper M. diversus Zone age for sediments some 2 cm lower in the same core. The samples may have been mis-labelled, or there may have been contamination of the lowermost material (in the core catcher) during withdrawal from the sediment.

CLIENT ID: N. Exon, BMR **DATE:** 7/2/89 **RECORD NO:** 13

1. **BASIN:** Otway **WELL/LOCALITY:** offshore WLT 3531

2. **SAMPLE NO:** 78 GC 05 CC **TYPE:** core catcher **DEPTH:** sea-floor WD 3530m
LITHOLOGY: grey mudstone **YIELD:** low **PRESERVATION:** poor
STREW MOUNT CODE: MFP 9126 **NO. OF MOUNTS WORKED:** 1

3. **AGE DETERMINATION**

GEOLOGIC AGE: Early Eocene
ZONE (SPORE-POLLEN): Upper M. diversus **CONFID. RATING:** 2
ZONE (DINOFLAGELLATE) - **CONFID. RATING:** -

INDEX SPP: Deflandrea flounderensis, D. truncata, Dryptopollenites semilunatus

4. **AGE RANGE**

MAXIMUM AGE: Paleocene **based on:** Proteacidites grandis, Palaeocystodinium golzowense
MINIMUM AGE: Early Eocene **based on:** D. truncata

5. **RECYCLED SPP:** Dictyotosporites speciosus

6. **PALAEOENVIRONMENT:** Marginal marine

7. **REFERENCES:**

8. **COMMENTS:** Sample badly under-oxidised, leading to clumping and obscuring of virtually all of the palynomorphs by plant macerals. No comprehensive listing of the species present was possible. As noted under comments on sample 78 GC 054, the age-determination is inconsistent with an apparently reliable Lower M. diversus Zone age for sediments some 2 cm higher in the same core.

APPENDIX E: PETROGRAPHIC EXAMINATION OF ROCK TYPES IN DREDGE AND GRAB SAMPLES

E. Anne Felton

SUMMARY

Dredge stations DR04, DR14 and DR21, and grab stations GS24 and GS25, were occupied during the BMR 1987 Otway-Tasmania Cruise 67. Thin sections of suites of samples from DR04, DR21, GS24 and GS25 confirm the rock types and sample ages suggested from shipboard examination of hand specimens. The 'tuff suite' of DR14, which was not assigned an age on board, proved to consist of mudrocks and quartz arenites. The suite resembles that of DR04 and a Late Cretaceous/early Tertiary age is suggested, based on lithological affinity with sediments of this age onshore and in wells.

DR04/2A: Mudrock

This mudrock is brown, with abundant fine to very fine quartz silt and black organic material. Lamination is defined by variations in the proportions of quartz silt, and by preferred orientation of elongate organic particles. Discontinuous silty streaks are also present. Occasionally, lamination is disturbed, probably by bioturbation.

Pyrite aggregates (?framboids), replacements of possible fossil fragments, and veinlets, are abundant. Pale yellow-green glauconite is rare. Pellets were also observed, of either coarse quartz silt or very fine amorphous material, and minor fine quartz-pyrite moulds of microplankton tests. Pellets, probably of faecal origin, are common. They mostly consist of amorphous mineral matter, with very fine quartz silt, and are darker than the surrounding rock. They are well rounded and elongate. One small pellet consisting of coarse quartz silt was noted. One opaline ?spicule present.

DR04/1: Mudrock

This is similar to DR04/2A, but lacks quartz silt, and has diffuse lamination, poorly defined by colour changes and discontinuous streaks. Abundant pyrite occurs, mostly as framboidal aggregates, probably replacing organic matter, and partly in association with opal or chalcedony and ?calcite, replacing microplankton tests.

DR04/3: Mudrock, with secondary carbonate

This fine-grained brown mudrock has patchily developed carbonate (calcite). It contains occasional small pellets (darker than the surrounding matrix) and microplankton test moulds of quartz/pyrite/ calcite. There is scattered pyrite throughout, some replacing ?organic matter, which is dispersed throughout.

DR04/4: Quartz arenite

Poorly sorted, well rounded quartz pebbles and coarse sand are set in a matrix of moderately sorted angular quartz cemented by iron oxides/hydroxides.

'Coarse' quartz. The size range is 1-3 mm, and the quartz is well-rounded, mostly monocrystalline with straight to slightly undulose extinction. About 10% is coarsely polycrystalline. The slightly undulose quartz contains abundant ?vacuole trains and some small quartz inclusions. There are rare, rounded, weathered microcline grains.

'Fine' quartz. The size range is 0.1-0.2 mm. The quartz is angular with straight to slightly undulose extinction and rarely polycrystalline as above. Other components of fine grainsize (<5%) are chert and (meta)sedimentary rock fragments.

DR14/4A: Sandy mudstone

This rock type consists of scattered, poorly sorted quartz sand and silt in a brown mud matrix. Larger quartz grains are moderately to well-rounded, to 0.7 mm diameter, mostly equant, but frequently cracked. They have slightly undulose to straight extinction. All are monocrystalline. The smaller grains (0.1 mm to 0.2 mm) have straight extinction, are angular to subangular, and are monocrystalline to rarely polycrystalline. All quartz grains are partly to completely surrounded by birefringent clay/carbonate, which is also present along the cracks in the larger grains. The edges of the grains are seen to be irregular and rough under high (40 x) magnification, possibly due to diagenetic corrosion. Many grains contain trains of inclusions.

Other detrital components include **microplankton** (moulds filled by clay/quartz), **spherical (faecal) pellets** and elongate **organic matter particles**, partly pyritised. The organic matter is moderately abundant (ca. 5%); some particles are several millimetres long. Crude layering is present, although it is often irregular. It is defined by variations in the clay/quartz ratio and by subparallel alignment of organic particles. Rare weathered plagioclase or microcline is also present (to 0.2 mm diam).

DR14/4B: Quartz arenite

The composition of this rock is quartz 85%, feldspar <1%, chert <1% and calcite cement 10%. There is also minor weathered biotite and metamorphic rock fragments. One ?pelecypod shell fragment was seen. There are a few grains of detrital ?epidote or hornblende, and minor pyrite replacements of ?organic matter.

Quartz grains are moderately to poorly sorted, with slight to no undulose extinction. Most are monocrystalline, but a few rounded polycrystalline grains are present. The larger grains (to 3 mm, average 2 mm) are subangular to well-rounded with about 10% of them cracked; smaller detrital grains are mostly angular. The few feldspars present are large (0.3 - 0.6 mm), rounded and somewhat weathered.

DR14/4C: Weathered mudrock

This is a very fine clay/?carbonate rock, non-laminated, with rare pellets. There are scattered poorly to moderately sorted quartz sand grains, fine-grained, generally angular (to 0.3 mm) and rarely rounded, and also sand aggregates comprising about 5% of the rock. Coarser grains (to 0.5 mm) are well-rounded, mono- or polycrystalline; there are some weathered igneous or metamorphic rock fragments (quartz-mica aggregates), rare weathered plagioclase (?albite) and biotite. Limonite is common and secondary after pyrite aggregates.

The sand aggregates are cemented by iron oxides. The sand grains show slightly to moderately undulose extinction, and are angular, rarely rounded and poorly sorted (0.2 - 1 mm); one grain of ?volcanic quartz was seen (rounded bipyramidal, cracked, slightly strained). The aggregates may have been forced into the softer mudrock during dredging/transport, but scattered grains are a primary component.

DR14/5: Quartz arenite

This rock consists of quartz 85%, feldspar (microcline) <1%, chert <1%, sedimentary rock fragments ca. 1%, and pyrite cement 15%. Quartz grains are moderately to poorly sorted, and larger grains (to 1 mm) are rounded, mostly monocrystalline, and unstrained. A few polycrystalline grains are composed of a mosaic of strained quartz. The smaller grains are mostly angular, monocrystalline and unstrained. Many larger grains are cracked, with cracks infilled by pyrite. There are almost no grain-to-grain contacts due to the pyrite cement. Other detrital grains are slightly weathered microcline, and rounded sedimentary rock fragments (mudstone).

DR14/6: Quartz arenite

This rock consists of quartz 90% and clay matrix 10%. Well-rounded quartz granules and small pebbles, mostly of strained polycrystalline (vein) quartz and quartzite, with smaller sand-sized angular quartz, are set in a clay matrix with specks of ?organic matter.

DR21/1: Quartz-lithic arenite

Point counting (Tables 1-3) shows that this arenite consists of quartz 40-50%, metamorphic rock fragments 1-4%, feldspar (orthoclase) 1-2%, feldspar (microcline) 4-7%, feldspar (plagioclase) 3-4%, volcanic rock fragments 10-18%, biotite 3-10%, heavy minerals 8-9%, clay cement 5-15%, and sedimentary rock fragments 1%. Quartz is angular to subangular, rarely subrounded, and moderately to poorly sorted. Some quartz has conspicuous rutile or apatite inclusions. Feldspar is fresh, consisting mostly of large (to 0.7 mm) grains of microcline. Oligoclase is seen as small grains. Quartz cement is clear, and a little calcite is also present.

Heavy minerals consist mostly of muscovite, colourless garnet and zircon. Green and brown biotite are present, but less common. Blue green hornblende is a rare constituent. Two populations of garnets are present: fresh subangular colourless garnet with a rough appearance, and a rounded 'smooth' garnet with red-brown weathered material coating it. Metamorphic rock fragments are mainly quartz-mica schists, with rare possible weathered amphibolite grains. Igneous rock fragments are possible weathered basalt or amphibolite, dacite, glass and gneissic granite or gneiss. Sedimentary rock fragments are minor mudstone and chert.

A mineralogical analysis of a heavy-mineral concentrate (Appendix F, this volume) shows that in the light heavy fraction there are 50% Fe oxides, 25% amphibole, 5-10% each of tourmaline and epidote, 5% biotite and 5% ?andalusite. In the heavy fraction (SG >3.32) the main minerals are 30-35% ilmenite, 15-20% Ti hematite, 30% garnet, 10% kyanite and 5% epidote.

DR21/2: Quartz-lithic fine arenite

This arenite consist of quartz 30%, organic matter 1%, rock fragments 15%, matrix 40%, detrital mica 10%, feldspar (plagioclase) 5%, and opaques 1%. Fine-grained angular quartz, plagioclase (An_{50}) and sedimentary rock fragments (claystones, possibly chloritic) are set in a fine, altered brownish clay matrix, possibly weathered chlorite. Quartz is monocrystalline or rarely polycrystalline, unstrained to slightly strained, and moderately sorted. Feldspars are fresh to slightly altered, and fine-sand-sized. Rock fragments are rounded and composed mostly of clays; they may be either sedimentary claystones or altered glassy igneous rocks. Detrital mica is common and imparts a layered appearance to the rock. Layering is also defined by variation in the ratio of detritus to matrix. Opaque minerals are probably ilmenite; red-brown transparent leucoxene grains are rarely present. Weathered organic particles were observed.

GS24: Olivine basalt

Fresh and slightly altered olivine phenocrysts, mostly euhedral, are set in a groundmass composed of plagioclase microphenocrysts, dark glass and small opaque grains. Plagioclase is lathlike and the laths are aligned in a flow foliation; measurements on twin angles indicate a composition of An_{50}. Patches of greenish chlorite and calcite are scattered throughout.

GS25: Altered/weathered olivine basalt

Weathered and strongly altered small olivine phenocrysts are present in a fine groundmass composed of thin lathlike plagioclase phenocrysts, yellow-brown altered ?glass and fine opaques. The rock is finer grained and less fresh than GS24, but the plagioclase is fairly fresh and has a composition of An_{50}. Plagioclase laths define a flow texture, as in GS24.

Summary

Station DR04 (four samples)

Three samples of mudrock have pellets, ?microplankton remains, and quartz silt; one sample has patchy secondary carbonate. This is a probable Belfast Mudstone equivalent, of Late Cretaceous age.

One coarse mature quartz arenite is probably Late Cretaceous to early Tertiary in age. No change from shipboard age identification is suggested.

Station DR14 (five samples)

No age suggestion was made from hand specimen examination on board. The 'tuff suite' of sample DR14/4 proved in thin section to be a suite of weathered sandy mudstones and quartz arenites, the sandy mudstones resembling the mudrocks from DR04, but having a coarser quartz component than those. The 'collapsed pumice' was seen in thin section to be closely packed elongate organic matter particles, partly pyritised. The quartz arenites examined were similar in grainsize and detrital composition to the arenite of DR04. A Late Cretaceous to early Tertiary age is suggested for the non-carbonate rocks from DR14.

Station DR21 (two samples)

The samples are fine and medium grained quartz-lithic arenite with common feldspar; they resemble quartz-rich facies of the Otway Group as known from outcrop and wells in Victoria and South Australia. A distinctive heavy-mineral suite, indicating derivation of the detritus from an igneous/metamorphic terrain, is present in the medium-grained sample. The suite was identified as Otway Group on board; thin section examination confirms an Otway Group facies type; but its age is in fact Late Cretaceous (Appendix D).

Stations GS24, 25

Fresh and weathered basalt was obtained from these stations, which correspond with station E of Gill & Segnit (1986). These investigators suggested a Late Pliocene age for the basalts based on thin section examination and chemical analyses; a 'Newer Basalt' affinity was indicated. Their samples were too weathered for dating but our GS24 is probably suitable.

Reference

GILL, E.J., & SEGNIT, E.R., 1986 Submerged volcanoes off Cape Otway, S.E. Australia. Search, 17(5-6), 151-152.

TABLE 1: POINT COUNT RECORDING SHEET 67/DR21/1

Thin section no. 1
Rock no. 67/DR21/1
Counter type. Swift (UW84/5)
Stage interval: H: 2(0.6 mm)
V: 1(0.3 mm)

Rock unit: ?Otway Group
Rock type: sandstone
Grainsize: medium sand, upper

Total points counted: 600

Ocular x 10
Objective x 10

Sorting: moderate to poor
Roundness (quartz): angular to well-rounded.
Compaction: weak

	CONSTITUENT	POINTS	%	
1.	Monocrystalline quartz	225	42.5	(Bubble trains) (Rutilated quartz) (Tourmaline-bearing quartz)
2.	Polycrystalline quartz	33	5.5	
3.	Plagioclase	25	4.1	
4.	Microcline	25	4.1	
5.	Microcline microperthite	9	1.5	
6.	Orthoclase	15	2.5	
7.	Volcanic rock frags.	108	18.0	Mostly altered basalt Altered glassy frags
8.	Sedimentary rock frags.	3	0.5	
9.	Porosity	-	-	Not counted
10.	Metamorphic rock frags.	24	4.0	
11.	Cement	82	13.6	Ferruginous clay and ?zeolite
12.	Other	21	3.5	
	Biotite	10		
	Garnet	1		
	Hornblende	2		
	Opaques	5		
	Organic	3		

Biotite is green and brown-yellow, hornblende colourless to green.
Occasional blue-green tourmaline.
Secondary ?zeolite needles in pore spaces.

TABLE 2: POINT COUNT RECORDING SHEET 67/DR21/1

Thin section no. 1 (duplicate)
Rock no. 67/DR21/1
Counter type. Swift (UW84/5)
Stage interval: H: 2
V: 1

Rock unit: ?Otway Group
Rock type: sandstone
Grainsize: medium sand, upper

Total points counted: 600

	CONSTITUENT	POINTS	%	
1.	Monocrystalline quartz	292	48.6	
2.	Polycrystalline quartz	30	5.0	
3.	Plagioclase	26	4.3	
4.	Microcline	41	6.8	
5.	Microcline microperthite	6	1.0	
6.	Orthoclase	7	1.1	V. weathered
7.	Volcanic rock fragments	58	9.6	
8.	Sedimentary rock fragments	6	1.0	
9.	Porosity	15	2.5	
10.	Metamorphic rock fragments	6	1.0	
11.	Cement	91	15.1	Brown clays (?degraded chlorite), zeolite needles
12.	Other	22	3.6	
	Biotite	6		
	Garnet	1		
	Hornblende	2		
	Opaques	2		
	Leucoxene	4		
	Muscovite	1		
	Indeterminate	6		

Probably a more weathered part of section than covered in Table 1. Porosity and cement, plus quartz, increase at the expense of rock fragments and orthoclase.

TABLE 3: POINT COUNT RECORDING SHEET 67/DR21/1

Thin section no. 2
Rock no. 67/DR21/1A
Counter type. Swift (UW84/5) lower
Stage interval: H: 2
V: 1

Rock unit: ?Otway Group
Rock type; sandstone
Grainsize: medium sand,

	CONSTITUENT	POINTS	%	
1.	Monocrystalline quartz	207	34.5	
2.	Polycrystalline quartz	27	4.5	
3.	Plagioclase	16	2.7	
4.	Microcline	28	4.7	Partly dissolved.
5.	Orthoclase	4	0.7	V. weathered
6.	Volcanic rock fragments	86	14.3	(Altered basalt 41 (Dacite 10 (Altered glassy 35
7.	Sedimentary rock fragments	1	0.2	
8.	Porosity	176	29.3	Dissolution of cement and feldspars, also rock fragments
9.	Metamorphic rock fragments	5	0.8	
10.	Cement	28	4.7	Ferruginous clay and ?zeolite
11.	Other	22	3.6	
	Biotite	3		
	Garnet	2		
	Hornblende	2		
	Opaques	3		
	Organic	2		
	?Leucoxene	2		
	?Muscovite	1		
	Indeterminate	7		

Secondary ?zeolite needles in porosity.

APPENDIX F : MINERALOGICAL ANALYSIS OF HEAVY-MINERAL CONCENTRATE FROM DR21/1

Alan W. Webb & Michael J.W. Larrett
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INTRODUCTION

One sample of heavy-mineral concentrate (> 2.96 specific gravity) was received from the Bureau of Mineral Resources with a request to carry out a semi-quantitative mineralogical analysis.

PROCEDURES

The sample was separated centrifugally in heavy liquid at 3.32 sp. gr. and a polished grain mount (PS46585) was prepared from the > 3.32 sp. gr. product. This grain mount was examined by reflected-light microscopy and temporary oil mounts of both products were examined microscopically in transmitted light.

MINERALOGY

The weight distribution of the sample at 3.32 sp. gr. is given below:

Initial weight	Wt. % 2.96-3.32 sp. gr.	Wt. % >3.32 sp. gr.
5.17 g	31.0%	69.0%

Mineralogy of the 2.96-3.32 specific-gravity product

Microscopic examination gives the following percentage estimate of the mineralogical composition:

Brown Fe oxides	50
Amphibole	25
Tourmaline	5-10
Epidote	5-10
Biotite	5
?Andalusite	5
Sillimanite	Trace
Garnet	Trace
Leucoxene	Trace

Mineralogy of the >3.32 specific-gravity product

Microscopic examination in transmitted and reflected light gives the following percentage estimate of the mineralogical composition:

Opaques	Ilmenite	30-35
	Ti-hematite	15-20
	Goethite	2-3
	Leucoxene	2-3
Non-opaques	Garnet	30
	Kyanite	10
	Epidote	5
	Zircon	<5
	Rutile	<1
	Amphibole	Trace

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