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BMR CRUISE 95

TRIASSIC AND JURASSIC SEQUENCES OF THE NORTHERN EXMOUTH PLATEAU AND OFFSHORE CANNING BASIN

Principal Investigators : N.F.Exon & D.C.Ramsay

Division of Marine Geosciences & Petroleum Geology

BMR GEOSCIENCE RESEARCH CRUISE 95

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Principal Investigators

N.F.Exon & D.C.Ramsay

Scientific Staff

T.Graham, D.Lynch[1], H.Miller, P.Petkovic, S.Shafik, B.West

Technical Support Staff

J.Bedford, N.Clark, P.Davis, C.Dyke, C.Green, D.Holdway, A.Hunter, C.Lawson, A.Radley, D.Sewter, J.Stratton, J.Whatman

[1] Geology Department, University of Western Australia, Perth

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ABSTRACT

R.V. *Rig Seismic* left Darwin to start this cruise at midday on 28 April 1990, and berthed in Fremantle early on 29 May. The cruise successfully carried out most of the Cruise Plan and should enable the objectives specified to be met during the term of this project.

Specifically, experimental seismic work in the Vulcan Sub-basin gave rise to 110 km of high-resolution seismic data shot as four lines near and across the Challis oilfield. The monitor records indicated that the key Base Cretaceous unconformity had been reached.

Conventional seismic tie lines were provided more or less as planned, except that two long tie lines in the Canning Basin were cut out of the program for logistic reasons. Nevertheless, the 1750 km of regional seismic lines does not fall far short of the planned 2100 km, and meets most of our scientific objectives. Data quality appears to be good, and recording was 36-fold or better.

The dredging program on the outer Rowley Terrace went very well indeed. A great variety of Jurassic, and probably Triassic, rocks were obtained, as well as Cretaceous and Cainozoic sediments, and the results will be used to constrain geological interpretations of the Rowley Sub-basin previously based on shelf wells and seismic profiles. 13 locations were dredged in 7 days; three Cainozoic cores were also obtained at various locations.

The high-resolution seismic survey across ODP Sites 761 and 764 on the Wombat Plateau was constrained, by bad weather and lack of time, to less than the planned 400 km, but nevertheless 255 km of reasonable quality data were obtained over a little more than two days. The monitors show that the objective of detailing the Triassic reef complexes was fully attained.

The full scientific significance of the cruise must await processing of the multichannel seismic profiles, and further work on the rock samples, especially palynological studies of the non-marine samples. Nevertheless, preliminary appraisal of the data collected indicates that :

- High-quality multichannel seismic tie lines now link Barcoo No 1 well and East Mermaid No 1 well to the Argo Abyssal Plain. The two lines show markedly different character.

- A multichannel seismic tie line now links East Mermaid No 1 well to the northern Exmouth Plateau. This line also contrasts the quite different characters of the Canning Basin and the northern Exmouth Plateau.

- A multichannel seismic tie line, from Delambre No 1 well on the northern Exmouth Plateau to ODP Site 764 on the Wombat Plateau, shows a marked change in geological character from south to north. The Wombat Plateau is a high block with a massive fault on its southern side, and a greatly uplifted Triassic sequence.

- A large number of buildups, largely of Jurassic age, have been identified on seismic profiles in the northern Exmouth Plateau. These sit on Triassic horst blocks, and commonly are 500 m thick, 2000 m wide, and more than 10 km long. We believe them to be

reefal complexes; they clearly are of interest as potential petroleum reservoirs. Follow-up dredging, on BMR Survey 96, has since recovered hard, iron-stained, mollusc-rich skeletal limestones and limestone breccias from an outcrop of an interpreted buildup.

- The rock types dredged from the Rowley Sub-basin include proven Jurassic marine and non-marine detrital sediments, some bearing ammonites; proven Jurassic shelf carbonates, and Triassic-Jurassic volcanics. Undated rocks include coral and algal boundstones, other shelfal carbonates with varied shelly faunas, and many marine and non-marine detrital sediments. A large proportion of these rocks may prove to be Triassic, the remainder Jurassic.

- The character of the Rhaetian reefal and lagoonal carbonates drilled on the Wombat Plateau in ODP Sites 761 and 764 is now determined seismically. Reefs are widely distributed, and generally of moderate size. They amalgamate to form a larger barrier reef along the northern margin of the plateau.

1. INTRODUCTION

The northern Exmouth Plateau and the western Canning Basin (the Rowley Terrace) both lie in water depths largely in the range 1000-3000 m (Fig. 3). They flank the Argo Abyssal Plain where the water is about 5500 m deep and merge landward into the North West Shelf. The two areas are contiguous areas of continental crust and have similar geological histories, their Mesozoic history being of most interest. Both have steep outer margins which are heavily faulted and cut by canyons, and hence are ideal sites for dredging the thick Triassic and Jurassic sequences known from earlier work.

The Exmouth Plateau is a marginal plateau lying off northwest Australia (Fig. 1). Water depths range from 800 m to 4000 m, and the area shallower than 2000 m is approximately 150,000 square kilometres. The plateau consists of rifted and deeply subsided continental crust, with a Phanerozoic sedimentary sequence about 10 km thick. It is separated from the North West Shelf by the Kangaroo Syncline, and is bounded to the north, west, and south by oceanic crust.

The plateau was first studied by BMR in the period 1974-1979, using 18,000 km of seismic profiles and some sample information, and results of the study were published, starting with Willcox and Exon (1976) and ending with von Rad and Exon (1983). The large fault blocks in the rifted Triassic and earliest Jurassic sequences, and the very large areal closures in the overlying Jurassic and Cretaceous sequences, encouraged petroleum exploration in the late 1970s and early 1980s. Some 30,000 km of high-quality multichannel seismic data were collected, and 14 exploration wells were drilled. The rifted section was shown to be largely gas-prone, and the overlying section to be largely immature. These results and the deep water over the plateau caused relinquishment of permits, except in the area surrounding the large Scarborough gas field discovered by Esso-BHP.

Because of the need to increase knowledge of this huge plateau, and to attempt to stimulate a second round of petroleum exploration over it, BMR's Marine Division designed a three-phase research program for the plateau. The first phase was a short heatflow cruise, designed to ascertain present-day thermal gradients and hence maturation levels (Choi, Stagg, and others, 1987). The second phase was a two-ship crustal structure study carried out with Lamont-Doherty Geological Observatory (Williamson, Falvey and others, 1988). The third phase was a study of the northern and western margins of the plateau, using conventional geophysical and sampling methods, and included site surveys for proposed Ocean Drilling Program (ODP) drill holes (Exon, Williamson, and others, 1988).

ODP Leg 122 drilled six holes on the plateau (von Rad and others, 1989; Haq, von Rad, and others, 1990). Leg 123 drilled 2 holes: one on the Argo Abyssal Plain, and one on the lower slope of the western Exmouth Plateau (Gradstein, Ludden, and others, 1990). The ODP Sites are located in Figure 1. A major discovery was that Triassic reefs are present in Rhaetian shelf carbonates on the Wombat Plateau (Williamson and others, 1988; Exon and others, 1989). This is the first time reefs of this age have been found in Australia, and potentially it adds a new petroleum exploration play on the North West Shelf. A recent BMR assessment of the petroleum potential of such reefs suggests that there is a 50% chance of there being 60 million barrels of undiscovered oil in Triassic reefs on the North West Shelf (BMR Research Newsletter 11).

The outer Canning Basin has received far less attention in recent years than the Exmouth Plateau, with the last major review being that of Stagg and Exon (1981). The area of interest for the present study is the Rowley Sub-basin, beneath the morphological Rowley Terrace, which lies between the Rowley Shoals and the Argo Abyssal Plain (Fig. 3). We regard the Rowley Terrace as limited to the north by the latitude of Bowers Canyon, to the southeast by the 400-m isobath, and to the southwest by the Swan Canyon. Most studies of the offshore Canning Basin by petroleum exploration companies have mentioned the deepwater and only gently structured Rowley Sub-basin only in passing (eg. Challinor, 1970; Warris, 1976; Powell, 1976). The sub-basin is known to contain thick Jurassic, Cretaceous, and Cainozoic sequences, believed to be underlain by a thick Triassic sequence. These sequences are believed to be generally similar to those found on the northern Exmouth Plateau, suggesting a similar geological history for both margins of the Argo Abyssal Plain.

The aim of the present study was to better define the geological development of both the northern Exmouth Plateau and the Rowley Sub-basin. In particular it was to assess the extent of the Triassic and Jurassic carbonates known from company drilling and scientific dredging in the region, and especially whether reefal bodies like that drilled in ODP Site 764 could be identified in shallower water along the continental margin.

1.1 Crew of RV *Rig Seismic*

Master	H. Foreman
Chief Officer	R. Hardinge
2nd Officer	W. McKay
Chief Engineer	R. Wade
2nd Engineer	T. Ireland
Electrical Officer	W. Hanson
EA/Seaman	L. Clarke
Chief Steward/Cook	H. Dekker
Cook	W. Leary
Steward	J. Caminiti
Steward/Seaman	S. O'Rourke
AB	J. Fraser
AB	D. Kane
AB	T. Dale

1.2 Acknowledgements

The enthusiasm, skill, and cooperation of the master and crew of the *Rig Seismic* are gratefully acknowledged. They have made a major contribution to the success of the cruise. The contribution of AUSLIG personnel in manning the HIFIX navigation stations for this program is most gratefully acknowledged.

Permission from Woodside Offshore Petroleum to use logs of their wells Delambre No 1 and Barcoo No 1, and permission from Shell Petroleum to use logs of their well East Mermaid No 1 is gratefully acknowledged. We thank BHP Petroleum in Darwin for helpful discussions prior to the commencement of the cruise, and especially for logistic assistance during the early part of the cruise.

1.3 Scientific Responsibilities

N. Exon and D. Ramsay were responsible for overall planning.
While doing geophysical operations, D. Ramsay and T. Graham were responsible for data quality control.
While doing geological operations, N. Exon and T. Graham were responsible for the recovery or otherwise of goodies from the deep.
P. Petkovic and H. Miller were responsible for the upkeep of the various computer acquisition systems.
J. Stratton was Senior Technical Officer (Science), responsible for geological support activities.
D. Holdway was Senior Technical Officer (Electronics), responsible mainly for systems hardware; he was also the nominated Safety Officer.
C. Green was (the only) Technical Officer (Mechanical), responsible for most things mechanical, notably compressors, guns, and coring winch/power pack.

2. OBJECTIVES

(i) Map the extent of and facies changes within the Triassic/Jurassic carbonates in and south of Wombat Plateau, and in the Rowley Sub-basin of the southwestern Canning Basin, using seismic profiling and dredging techniques.

(ii) Define the extent, character and petroleum potential of any Triassic or Jurassic reefs found.

(iii) Use the cruise results, along with other data, to help assess the petroleum prospects of Mesozoic reef plays elsewhere on the North West Shelf.

(iv) Better define the geological history of the northern Exmouth Plateau and the adjacent southwest Canning Basin.

3. CRUISE PLAN

The cruise was scheduled for 34 days, Darwin - Perth, starting in April 1990. Excluding transit time and some work in the Vulcan Sub-basin, this left 25 working days in the Exmouth-Canning area. Figure 3 is a pre-cruise summary track map. The scientific activities have four components:

1. Experimental seismic lines in Vulcan Sub-basin
(Estimated working time 2 days)

An experimental high-resolution watergun seismic survey totalling about 70 km was to be run NW to SE across the Vulcan Sub-graben, as a test for the proposed high-resolution seismic survey there later in 1990. Location is about 275 km northwest of Cape Leveque.

2. Conventional seismic tie lines
(Estimated working time 13 days)

It was intended to use a conventional 2400 m, 96 channel seismic cable and a single airgun array to provide critical tie lines between our areas of detailed study (outer Canning Basin/Rowley Terrace, and northwest Exmouth Plateau/Wombat Plateau) and key exploration company wells in shelf water depths. These data will also be useful in mapping the shoreward extension of Triassic/Jurassic shelf carbonates and reefal buildups from their known development in deep water.

The total amount of profiling was planned to be about 2160 km, which would take about 10 days at a constant ship speed of 5 knots. Allowing two to three days for deployment and retrieval of equipment, and minor breakdowns, 13 days of working time was allowed. The layout of the proposed tracks is detailed in Figure 3.

The tracks in the Rowley Sub-basin provided for tie lines (A & D-G) from Barcoo No 1 and East Mermaid No 1 wells and the JNOC seismic grid to the lower continental slope in the outer part of the sub-basin, where Triassic and Jurassic rocks are believed to be exposed. They also provided one along-slope line (C) to complete the tie, and also to help delineate sample sites.

Water depths along the seismic lines in the Rowley Sub-basin would range from 720 m at Barcoo No 1 and 400 m at East Mermaid No 1, to 5500 m on the Argo Abyssal Plain. The top of the middle Jurassic (E reflector) lies at 3.02 s (TWT) at Barcoo No 1 and 2.19 s at East Mermaid No 1; the top Triassic reflector (F) lies at 3.57 s at Barcoo No 1.

A long line (H) was planned to extend westward from East Mermaid No 1 to the northern Exmouth Plateau (Fig. 3) to tie the two regions together in an area of shallow Triassic subcrop (along the North Exmouth Hinge Zone). A final regional line (J) would tie ODP sites 764 and 761 to the regional GSI data grid and Delambre No 1, and complete the regional tie to the Rowley Sub-basin.

3. Dredging and coring on outer Rowley Terrace
(Estimated time 7-8 days)

It was proposed to extensively dredge (and perhaps core) the walls of the canyons which cut the outer margin of the Rowley Terrace (Fig. 3) in an endeavour to recover the Triassic, Jurassic and basement rocks that appeared to crop out, on the evidence of existing seismic profiles. There are three major canyons and several subsidiary ones, and the structure is complex. About 14 dredge hauls would be needed to address the known problems, which would take about 7 days in these water depths with some preliminary surveying.

4. High-resolution seismic lines across ODP sites
(Estimated working time 3-4 days)

It was proposed to run about 400 km of detailed high-resolution seismic profiles, using a 1200 m, 96 channel seismic cable and a watergun array, in the vicinity of ODP sites 761 and 764, to delineate the shape and extent of the Triassic reefs found in site 764. The detailed survey was to consist of an initial grid spaced 4 km apart, with a follow-up grid in areas where reefs were clearly widespread, to reduce the line spacing to 2 km. Including deployment and retrieval, and assuming a ship speed of 4.5 knots, 400 line-km plus all the necessary turns should have taken 3 to 4 days.

4. BACKGROUND

4.1 Previous Scientific Studies

Key studies of the region were carried out by :

1. BMR, in the period 1974-1980, used regional seismic data and well ties (Willcox & Exon 1976; Exon & Willcox, 1978, 1980; Stagg & Exon, 1981).

2. The German Geological Survey (BGR) and BMR, in the period 1979-1983, used new dredge and core information gathered by R.V. *Sonne* to upgrade the earlier interpretations (von Stackelberg and others, 1980; Exon and others, 1982; von Rad & Exon, 1983)

3. A variety of scientific institutions concentrated on the history of the Argo Abyssal Plain as revealed by magnetic lineations.

4. BMR, in 1986-1988, used new dredge and multichannel seismic data gathered by R.V. *Rig Seismic* in 1986 (Exon, Williamson, and others, 1988).

5. The Ocean Drilling Program (ODP), drilled Leg 122 on the Exmouth Plateau (Haq, von Rad, O'Connell, and others, 1990), and Leg 123 on the Argo Abyssal Plain (Gradstein, Ludden, and others, 1990)

These studies have led to a basic understanding of the stratigraphy of the region, and its relationship to regional seismic reflectors (Figs. 6 & 7). They have shown that adjacent to the northern margin of the Exmouth Plateau is a complex of horsts and grabens produced by vertical movements along northeast- and east-striking faults. Displacements on individual faults of either trend exceed 1000 m in places. Closely-spaced faults have caused a total displacement of the order of 2500 m down the lower continental slope. Gravity modelling indicates that the crust thins abruptly under the lower continental slope, which is consistent with the interpretation that it developed by transform faulting.

Several small subplateaux in water depths of 1600 to 2300 m coincide with the horst blocks and were once part of the Exmouth Plateau. The largest, the Wombat Plateau (Fig. 1), covers an area of about 3500 km^2. Identification of seismic horizons in the northern area is impeded by lack of continuity between the subplateaux across the grabens which separate them, and between the subplateaux and the Exmouth Plateau proper.

In general, the northern margin of the plateau is downwarped along the extensively faulted North Exmouth Hinge Zone, which is made up of numerous blocks down-faulted northward or northwestward into a series of half-grabens. The subplateaux which separate the half-grabens from the Argo Abyssal Plain are composed largely of west-dipping Triassic and Jurassic strata, beneath nearly horizontal Mesozoic and Cainozoic strata, and buttressed against collapse by igneous intrusions along their northern edges.

The deepest reflector identified on the seismic profiles, Horizon G, is correlated with an intra-Triassic unconformity (Fig. 9). It is an extensively faulted horizon which on Echidna Spur lies 4000 m below sea level beneath an overburden of about 1800 m, and in the adjacent graben lies 6600 m below sea level beneath an overburden of about 3600 m.

On Emu and Echidna Spurs, west of the Swan Canyon, Mesozoic strata lie beneath a wavecut platform upon which Cainozoic carbonates had been deposited. A well-defined magnetic anomaly trough corresponds with the half-graben south of the Wombat Plateau and extends eastwards along the northern margin of the Exmouth Plateau. The trough is due in part to the negative anomalies of large dipolar fields associated with elevated basement blocks to the north, but its linearity suggests that there may also be a contribution from a deepseated structural trough. This trough could be a westerly extension of the Fitzroy Trough in the northern Canning Basin. North-south offsets of the trough on meridians 115°30', 116°30', and 117°00'E are reminiscent of transcurrent faults.

The Rowley Sub-basin also is composed largely of Triassic and Jurassic rocks. There is far less faulting than that beneath the Exmouth Plateau, except along the outer continental slope, where canyons cut down along northwest to west trending faults which may be related to fracture zones on the Argo Abyssal Plain (Stagg & Exon, 1981).

The spreading history of the Argo Abyssal Plain has ben studied by Falvey (1972a); Larson (1975); Heirtzler and others (1978); Powell, Roots and Veevers (1988); and Fullerton, Sagor and Handschumacher (1989). The latest study (Fullerton and others, 1989) used both marine magnetic and aeromagnetic data to arrive at the magnetic isochrons shown in Figure 8. The authors concluded that the spreading history of the abyssal plain covered 18 Ma (144 - 162 Ma), and took place from the late Oxfordian (early Late Jurassic) until the Berriasian (earliest Cretaceous). The assumption is that a continental mass filled the abyssal plain until breakup, and this fractured into various microcontinents, now incorporated into Southeast Asia and the Himalayas.

The studies of von Stackelberg and others (1980); Exon and others (1982); and von Rad and Exon (1983), based on a cruise by R.V. *Sonne*, and those of Exon, Williamson and others (1988), and von Rad and others (1990) based on a cruise of R.V. *Rig Seismic*, led to further increases in our understanding of the northern Exmouth margin (see Figs. 9-11). Von Stackelberg and others (1980) reported the results of 18 dredge hauls from the outer slopes of the northern margin. More than half contained Jurassic and Triassic pre-breakup shallow-water sediments. Four dredges from the north also contained intermediate to acid volcanics dated at about the time of rift onset (Triassic-Jurassic boundary). This suggests limited continental crustal anatexis very near to the incipient continent-ocean boundary. These data also indicate that it is not valid to interpret the occurrence of volcanics on a marginal plateau slope as definitive evidence of non-continental crustal structure, either in whole or in part (Falvey & Mutter, 1981).

The main results of these studies were to provide the vital rocks with which the interpretations of seismic profiles could be controlled, and a firmly-based geological history was developed. In the Swan Canyon area in the northeast (Figs. 9 & 10), the *Sonne* results showed that a thick, dipping Jurassic sequence underlies the almost planar main unconformity in the Emu Spur and Echidna Spur regions. This consisted largely of Early and Middle Jurassic shelf carbonates and coal measures. A thin sequence of younger rocks rested on the unconformity, and thin Cretaceous rocks were probably below it in places.

In the Wombat Plateau region (Figs. 9 & 11), the same main unconformity was underlain by thick Late Triassic detrital sediments, Early Jurassic shelf carbonates, and Triassic/Jurassic volcanics. Von Stackelberg and others (1980) assumed that a thick Jurassic sequence rested on the Triassic sequence (as was indeed the case in the Emu and Echidna Spurs), and that a Cretaceous sequence also underlaid the main unconformity in places. A thin Cainozoic sequence rested on the unconformity.

The studies of Exon, Williamson and others (1988) built on the earlier results. In the northern part of the plateau a series of regional multichannel seismic profiles were run by *Rig Seismic*, as well as ODP site surveys, and 16 dredge hauls were obtained from the Wombat Plateau (Figs. 9 & 11).

During ODP Leg 122 in 1988, four continuously cored holes were drilled on the Wombat Plateau, a northern subplateau of the Exmouth Plateau: Sites 759, 760, 761 and 764 (Figs. 1, 9, 11 & 12). These four holes all intersected Late Triassic sediments directly beneath the main unconformity, with a composite thickness of 750 m (Fig. 13), of which 30% are carbonates, and the remainder low-energy paralic to fluviodeltaic facies. Haq, von Rad, and others (1990) stated that carbonate rocks were first deposited on the Wombat Plateau during late Carnian time, in a southern embayment of a shallow Tethys sea where marginal marine clastics were succeeded by alternating shallow-water carbonates and deltaic siliciclastics. In the Norian, a more than 300 m thick, shallowing-upwards sequence began to be deposited, resulting in shallow-marine limestones interbedded with fluviodeltaic silty claystone, grading upwards to a deltaic coastal plain facies with algal mats, coal seams and root-mottled zones that indicate periodic emergence. The Wombat Plateau developed a fully marine carbonate platform sequence in the Rhaetian, with a deeper water shelf limestone/marlstone section, overlaid by an over 200 m thick reef complex and related perireefal facies. These carbonates resemble their coeval strata in the western Tethys region of the Alps. Jurassic northward tilting and uplift of the Wombat Plateau resulted in emergence, and subaerial erosion that removed Jurassic sequences at the onset of Argo Abyssal Plain seafloor spreading. During early Neocomian time the Wombat Plateau sank below sea level and, coupled with the adjacent cooling crust of the Argo Abyssal Plain, subsided to bathyal water depths. A condensed sequence of upper Berriasian to lower Valanginian sandstone, belemnite sand, and hemipelagic calcisphere/nannofossil chalk, interbedded with bentonite layers, documents rapid subsidence from littoral to bathyal depths during the 'juvenile ocean stage'. The Turonian marks the onset of the 'mature ocean stage' and purely pelagic carbonate sedimentation.

The Rhaetian carbonate rocks drilled in ODP sites 761 and 764 are of particular interest. The Rhaetian sequence consists predominantly of shelf carbonates, including reef complexes. In Site 764 (Figs. 13 & 14) a reef complex was drilled, and there the sequence was 300 m thick. It consists of outer shelf mudstone, overlain by cycles of outer shelf limestone and marl, overlain by a thick sequence of alternating reefal, peri-reefal and back-reefal deposits including oolite shoals and fore-reef talus, and capped by shallow open-marine limestone and marl.

Williamson and others (1989) reviewed existing well data and came to the conclusion that Triassic shelf carbonates were widespread on the outer North West Shelf (Fig. 15). The belief that Triassic and Jurassic reef complexes could be widespread in the region led to the present study (BMR Cruise 95).

4.2 Tectonic Framework

The geological development of the Exmouth Plateau and/or Rowley Sub-basin has been discussed by Falvey and Veevers (1974); Veevers and Johnstone (1974); Exon and others (1975), Veevers and Cotterill (1976); Powell (1976); Willcox and Exon (1976); Exon and Willcox (1978, 1980); Wright and Wheatley (1979); von Stackelberg and others (1980); Stagg and Exon (1981); von Rad and Exon (1983); Barber (1982, 1988); Exon, Williamson, and others (1988); and Haq, von Rad, and others (1990). The Exmouth Plateau margins abutting oceanic crust were compared and contrasted by Exon and others (1982).

The present structural configuration of the Exmouth Plateau and Rowley Sub-basin regions was initiated by rifting in Triassic to Middle Jurassic times prior to seafloor spreading. The western Exmouth margin and the Rowley Sub-basin margin have a normal rifted structure, and the southern Exmouth margin has a transform-dominated structure. The complex northern Exmouth rifted margin contains at least one crustal block of pre-breakup igneous origin.

The northern Exmouth/Wombat Plateau/Rowley area experienced major deep crustal extension and thinning during the Permian (Williamson and others, 1990), and this was followed by rifting in the Triassic (Carnian/Norian; ODP Sites 759, 760) and Jurassic time. Igneous intrusions and extrusions accompanied pre-Norian and post-Rhaetian deposition, and Jurassic block faulting separated the Wombat Plateau from the Exmouth Plateau by formation of steep south-facing escarpments. The results of ODP Leg 123 (Gradstein, Ludden and others, 1990) suggest that the margin formed in the Tithonian, when seafloor spreading commenced in the Argo Abyssal Plain.

Throughout the Triassic and Jurassic, pre-breakup rift tectonics affected the entire Australian western margin (Falvey & Mutter, 1981). Steady subsidence along the incipient northern Exmouth margin, north of an east-west hinge line, allowed several thousand metres of Upper Triassic deltaic sediments, Rhaetian carbonates, and Lower and Middle Jurassic carbonates and coal measures to accumulate before breakup (Exon and others, 1982; von Rad and others, 1990; Haq, von Rad and others, 1990). Breakup occurred along a series of rifted and sheared margin segments, complicated by northeast trending Jurassic horsts and grabens. The horsts were planed off in Late Jurassic and Early Cretaceous times, and the whole northern margin was covered by a few hundred metres of Upper Cretaceous and Cainozoic pelagic carbonates as it subsided steadily to its present average depth of 2000-5000 m. The history of the Rowley Sub-basin, east of the Swan Canyon, appears to have been very similar to that of the northern Exmouth margin, but with less widespread faulting.

4.3 Stratigraphy

The stratigraphy of the Exmouth Plateau is sketched in Figure 6. Sediment starvation has led to a greatly reduced post-breakup sequence. Thus, seismic profiling and drilling have been able to penetrate well into the pre-breakup sequence and resolve early stages of margin evolution (von Rad & Exon, 1983). Fourteen petroleum wells have been drilled and results from Phillips Jupiter No 1, Saturn No 1 and Mercury No 1 have been published (Barber, 1982). Stratigraphic studies have been carried out by von Stackelberg and others (1980); Colwell and von Stackelberg (1981); Barber (1988); and von Rad and Exon (1983), and palaeontological studies by Quilty (1980a, 1981, 1990) and Zobel (1984). Seismic control consists of 12,000 km of data from the 1972 BMR continental margin survey, 9300 km of GSI seismic data collected in 1976 and 1977 (Wright & Wheatley, 1979), 30,000 km of subsequent petroleum industry seismic data, 1450 km of wide angle common-depth-point data (Williamson, Falvey, and others, 1988), and 2100 km of 1986 BMR conventional seismic data (Exon, Williamson, and others, 1988).

Interpretation of seismic profiles indicates that up to 5000 m of Palaeozoic strata and 5000 m of younger strata overlie basement. The sediments have been gently folded, and the pre-breakup section is affected by northeast trending faults.

The sediments beneath the Exmouth Plateau are considered to have been deposited in an extension of the Carnarvon Basin, part of the Westralian Superbasin (Yeates and others, 1987). This formed a north-facing Tethyan embayment in Gondwanaland and received detrital sediments from the south until early Cretaceous time. In the central Plateau region, at least 3000 m of mainly paralic and shallow marine detrital sediments were deposited from Permian to Middle Jurassic times. After the Late Triassic rifting, about 1000 m of shallow marine and deltaic detrital sediments, derived from the south and east, covered the block-faulted surface in Early Cretaceous times. About 200 m of terrigenous marine sediment was deposited in the Middle Cretaceous, and 500 to 1000 m of carbonate sediment in the Late Cretaceous and Cainozoic. The Exmouth Plateau Arch and Kangaroo Syncline probably warped to their present form in the Miocene (Exon & Willcox, 1978, 1980), by which time the central Plateau had subsided to bathyal depths (Barber, 1982, 1988). On the northern margin there are Early to Middle Jurassic shelf carbonates and Middle Jurassic coal measure sequences in the Swan Canyon region, perhaps 2000-3000 m thick in total (von Stackelberg and others, 1981; Exon and others, 1989; von Rad and others, 1990; Quilty, 1990). On the Wombat Plateau, ODP drilling showed that there is a thick Late Triassic deltaic and carbonate sequence (Haq, von Rad, and others, 1990).

The Rowley Sub-basin is an ENE trending, mainly Mesozoic basin connecting with the Beagle Sub-basin to the southwest (Stagg & Exon, 1981). It is separated from the Bedout Sub-basin to the southeast by the Bedout High. The sub-basin contains thick Cainozoic, Cretaceous, Jurassic and Triassic sedimentary sequences, with major unconformities of latest Triassic and approximately Callovian age (Fig. 7). The central part of the sub-basin is structurally simple but its margins are complex, being both faulted and gently folded - especially beneath the Cretaceous sequence.

4.4 Petroleum Exploration

In the mid 1970s the Exmouth Plateau was regarded as having considerable petroleum potential. Reconnaissance surveys shot in the 1970s revealed the presence of large fault-bounded structures (Willcox & Exon, 1976; Exon & Willcox, 1978; Wright & Wheatley, 1979) and the close proximity of major hydrocarbon accumulations on the North West Shelf and at

Barrow Island in the Carnarvon Basin encouraged optimism. Five exploration permits divided up the plateau in 1977, much seismic data was recorded, and 14 exploration wells were drilled in the central and southern areas. Several non-commercial gas shows were encountered as well as the Scarborough gas discovery that has been retained by Esso-BHP. The nearest exploration well to the northern Exmouth Plateau study area is Woodside Delambre No 1 (Figs. 5 & 16), which contains thick Triassic and Jurassic sequences.

Early exploration concepts involved generation of oil from Upper Jurassic and Neocomian shales in the Kangaroo Syncline and subsequent migration into the Jurassic and Triassic tilted fault blocks on the Exmouth Plateau Arch. The lack of liquid hydrocarbons was attributed to unfavourable source rocks, unsuitable burial history and a low palaeothermal gradient. For three wells (Phillips Saturn No 1, Jupiter No 1 and Mercury No 1) Upper Triasssic, Jurassic and Cretaceous sections were found to be immature and incapable of generating hydrocarbons. Most hydrocarbons so far encountered on the Exmouth Plateau are thought to have originated from deep (5 km or more) overmature gas source rocks, probably Lower Triassic and Permian shales, by tapping of source beds along faults bounding the tilted block structures, enabling the gas to migrate upwards (Barber, 1982).

Shelf carbonates of Triassic and Jurassic age are common on the Exmouth Plateau. Barber (1988) stated that in the central plateau, a shallow sea transgressed over the fluvio-deltaic sequence of the Mungaroo Formation during late Rhaetian to Hettangian time, depositing an interbedded sequence of calcareous sands, siltstones and occasional limestones. The total thickness of this sequence is about 100-300 m. Further shoreward to the southeast, at the intersection of the prograding fluvial-deltaic regime with the marine transgressive front, a north-northeast-trending beach-barrier bar and back-lagoonal complex developed. As deltaic input diminished, carbonate deposition predominated, and the base of the Jurassic Dingo Claystone is largely carbonate.

The lack of success in finding oil in the major Exmouth Plateau structures has resulted in the dropping of all except part of one permit and the cessation of petroleum exploration on the plateau. Future petroleum exploration interest would appear to depend on demonstrating a marine oil-prone source at mature depths, either in Jurassic graben-fill sediments in the Kangaroo Syncline or local grabens, or in Triassic and Permian pre-rift sediments on the western or northern margins of the plateau, along with suitably located trapping structures.

There has been little petroleum exploration in the Rowley Sub-basin, and the deepwater part of the sub-basin (northwest of the Rowley Shoals) is covered only sparsely by seismic surveys. Two wells have been drilled in the deepwater sub-basin: Shell East Mermaid No 1 in 1973, and Woodside Barcoo No 1 in 1980. East Mermaid No 1 (Fig. 17) penetrated about 1250 m of Cainozoic carbonates, 120 m of Senonian-Maastrichtian shelf carbonates, 180 m of Albian-Cenomanian shelf mudstone and marl, 1000 m of Neocomian-Aptian shelf mudstone, and more than 1200 m of Jurassic deltaic mudstone and sandstone. Minor gas indications were present in the Jurassic sequence.

Barcoo No 1 (Fig. 18) penetrated nearly 1600 m of Cainozoic carbonates, 300 m of Turonian-Maastrichtian shelf carbonates, 800 m of Neocomian to Cenomanian shelf mudstone, 950 m of Jurassic deltaic mudstone, 100 m of Rhaetian deltaic mudstone, and 260 m of Rhaetian shelf limestone and mudstone. Minor gas indications were found in the Cretaceous, Jurassic and Triassic sequences. The well found several sandstone sequences with good porosity and permeability in the Mesozoic sequence, and thick Lower Jurassic claystones that are potential source rocks.

In 1987 and 1988, the Japanese National Oil Corporation carried out regional seismic surveys in the Canning Basin, shoreward of the Rowley Shoals (Fig. 2), recording more than 11,000 km of seismic reflection profiles. These profiles tied most of the offshore wells in the Canning Basin, but not Barcoo No 1.

5. CRUISE NARRATIVE

This is an overview of cruise operations, including external factors which significantly influenced those operations.

Ship's Departure

The original cruise plan proposed that the ship would depart from Darwin on 25 April 1990, and berth in Fremantle on 28 May 1990. Ten days prior to this sailing date the departure date was postponed to the 27th April because of the delayed arrival of the ship's reconditioned shaft generator. The shaft generator had been repaired in Newcastle and was due to arrive in Darwin at the time of the vessel's arrival there, but an industrial dispute in Newcastle delayed its arrival until 1200 hrs, 24 April. This postponement also facilitated work on computer and navigational systems being carried out on board. These system modifications were as follows:

i. the installation and interfacing of a Trimble 4000S G.P.S. receiver (which arrived on 23 April).

ii. incorporation of new Hifix smoothing techniques into the radio navigation software, in order that further testing would have minimal effect on navigation while at sea.

iii. preparation of the seismic system software to handle the watergun array.

A delay in the completion of these system changes led to a further postponement of the sailing date to 28 April. The ship departed the wharf at Darwin at 1200 hrs 28th April (0400 hrs Day 118).

Cruise Diary

118.0400 Depart Darwin - commence transit to the Vulcan Graben/Sub Basin.

119.0025 Shaft generator found to be out of balance and replaced by auxiliary generators. (This would have implications on the ship's fuel usage - refer to later report on fuel).

119.1400 Lat 11°54', Long 124°56'. Commence deploying the 1200 m high-resolution seismic cable. The first phase of the cruise operations was designed to provide a series of high resolution seismic lines across regional strike in the sector of the Vulcan Graben where the Challis Oilfield has been developed.

119.2330 Cable deployed - commence system and cable testing, plus correct navigational disparities.

120.1123 Commence the first of four NW-SE orientated lines crossing Challis Oilfield (refer Fig. 19). Cable and guns were set at 5 m depth, and early indications were that only four of the five waterguns were firing.

120.1537 Commence the second line of the Vulcan Graben lines (95/002).

120.1849 Having failed to isolate the cause of the gun firing problem it was decided to retrieve the array at the end of line 95/002 for checking. During this retrieval the guns became entangled in the seismic cable tow leader. This problem was rectified by letting out the tow leader, causing it to sink and shake free of the guns.

120.2120 Started line 95/003, the third of the Vulcan Graben lines. In a further attempt to solve the gun firing problem, which appeared to have been isolated to the gun contoller, the micro control card was exchanged. This proved unsuccessful.

121.0059 Commenced line 95/004 (Vulcan Graben).

121.0423 Line 95/004 completed. It was decided to overshoot line 95/001 using an airgun array. The water gun array was retrieved and the air gun array was deployed suspended from Norwegian buoys by short chains (ie. rather than the usual longer ropes), in order to hold the array at the five metre depth more suited to a high resolution configuration. The line (95/005) was abandoned after approx. 50 minutes of shooting when one of the Norwegian buoys was lost, and the loss of further buoys appeared imminent. The gun array and 1200 m seismic cable were retrieved, marking the successful completion of the first phase of operations, marred partially by the gun firing problem.

The ship transited from the Vulcan Graben to the site of the Barcoo Well on the outer North West Shelf to commence the next phase of operations - a series of regional air gun lines tying well sites off the shelf edge and onto the Argo Abyssal Plain. The stratigraphy of the continental slope was to become the subject of an intensive dredging program later in the cruise.

123.1100 Deployment of the 2400 m seismic cable was completed after 14 hrs of operational time.

123.2118 After completion of extensive cable and gun testing the first production shot was recorded on line 95/006. The objective of this line was to tie the stratigraphy from Barcoo west to the Argo Abyssal Plain (~135 n miles). Recording on line 95/006 proceeded quite well through almost an entire day, interrupted only briefly on two occasions by system crashes. At 124.2055 the system crashed (for no apparent reason other than a delay change in the CHAOS program). The program failed to reboot on the first two attempts and the computer had to be powered down before rebooting. This loss of time (and therefore fold) required the ship to be directed to loop.

124.2241 Back on line and ready to commence overlap.

125.0000 System crashed and ship directed to loop again.

125.0334 After an extended loop to try and solve the system problem the overlap had recommenced but another system crash occurred, and it became apparent from symptoms such as the gun logger printing chaotically that major systems problems were occurring. These problems deteriorated to the extent that the system would not reboot, and it was decided after extended attempts to solve the problem to abandon seismic work and move directly to the geological sampling planned for later in the cruise. The problems with the seismic computer were compounded by the Data Acquisition System (DAS - which records and processes navigational data), crashing also on a regular basis.

125.1109 Proceed toward the first dredge sampling site.

Geological Sampling

The objective of this phase of operations was to sample primarily Triassic and Jurassic stratigraphy (as well as some Cretaceous and Cenozoic stratigraphy), identified from earlier seismic lines which crossed deep canyons extending from the shelf break down to the Argo Abyssal Plain. More detailed descriptions of actual dredge sites and results are given in section CANNING BASIN STUDY : Geological Sampling.

125.2100 On site at the base of Taipan Canyon (15°1.92', 118°57.53') for the first dredge (95DR/001) after a brief bathymetric survey of the proposed dredging slope. The first dredge targeted Triassic volcanics plus some Cz section identified in Shell seismic line N206 on the northern slope of the canyon. The depth range of the target slope was 4650 m to 3480 m. The winch developed a problem with only 170 m of cable spooled out. A faulty contact causing the safety lock system to engage was isolated as the problem. Spooling resumed at 126.0105 and a successful dredging operation continued over the next 10 hrs resulting in a variety of rocks of volcanic origin, and claystones.

126.1306 Dredge 95DR/002 commenced on a northern slope further toward the head of Taipan Canyon (14°57.91', 119°06.33') targeting a sequence identified in BMR seismic line 17/086. After a dredging operation lasting ~7 hrs, two lithologies were recovered.

126.2340 Dredge 95DR/003 on the southern slope of Copperhead Canyon (which joins Taipan downslope) commenced. The target was a 4900 m to 4400 m deep sequence identified in Shell line N206. The only recovery in this operation was soft sediment from the pipe dredge (ie. attached to the main dredge), and palaeontological investigations suggest that this material may be from a Cretaceous slump deposit.

127.0806 The dredge was deployed for 95DR/004 which again targeted the lower part of a sequence in Copperhead Canyon, as identified in Shell line N206 (15°22.0', 118°57.9' at 4200 - 3750 m). This dredge was the first of a series of dredges in which the recovered samples filled the dredge bag to its capacity. In this case some 400 kg of Triassic and Jurassic sandstones and siltstones were recovered.

127.1547 The target for 95DR/005 was the upper part of the same slope targeted in the previous dredge. This was expected to be primarily Jurassic stratigraphy moving perhaps into Cenozoic toward the top of the slope. After ~8 hrs of almost constant tension peaks, another full dredge bag of primarily sandstone, mudstone and siltstone samples was recovered.

128.0452 Dredging commenced on 95DR/006 at the head of Tortoise Canyon some 30 n miles south of the previous sites. Again this sequence was identified in Shell seismic line N206 and was interpreted as including Cenozoic, possibly Cretaceous, and Jurassic stratigraphy, plus some volcanics. Dredging commenced at 16°0.65', 118°46.57' in 3400 m water depth and covered a southerly slope to 16°0.0', 118°36.50' in water depth of 3100 m. The dredge recovered ~150 kg of samples including mudstones, ironstone boxstones, and tuffaceous samples.

128.1353 95DR/007 targeted the lower part of a northwest facing slope in Mermaid Canyon. This sequence was interpreted from BMR seismic line 17/091 as Triassic and early to mid-Jurassic. At 1756 hrs the dredge became 'hung up' (ie. snagged on the bottom) and tension loads of up to

~12.5 t were applied in an attempt to break the dredge free. This applies approximately 7 t of pull at the seabed which is approaching the limit that can be applied without equipment damage in this water depth. The dredge could not be broken free, and the slow retrieval process of cutting the ship's power and dragging it back over the location of the dredge on the slope commenced at 1820 hrs. At 1852 hrs the hydraulic power pack for the winch overheated from the prolonged loading it had received, necessitating its being shut down until 2006 hrs. At 2037 hrs, some 2.5 hrs after becoming hung up, the dredge was pulled free by a near vertical pull. The dredge was returned to the seabed and dredging resumed. At 2057 hrs further problems were experienced with the winch. It was determined that this was not an overheating problem with the power pack, and other potential causes of winch power loss were investigated. Attempts to rectify this problem continued until 129.0146, when the winch began to operate again after repairing a hydraulic valve in the hydraulic power pack. Dredging then recommenced upslope until 129.0233 when the dredge became hung up again. The ship was directed to a reciprocal course and the dredge was recovered some 10 hrs after deployment, filled to capacity with a range of lithologies including quartz sandstones, ferruginous boxstones, calcareous mudstones and sandstones, coralline boundstone with hexacorals, and chert.

129.1508 The dredge was deployed for the commencement of 95DR/008 which attempted to overlap the top of the previous dredge and sample the middle section of the same slope in Mermaid Canyon. At 1735 hrs the dredge was on the bottom and the ship began to move on course laying out cable. The first major tension peak registered at 1932 hrs followed by a series of very substantial tension peaks until 2042 hrs when the dredge became hung up. After 15 min of maximum tension the dredge could not be freed and the tedious process of pulling the ship back over the dredge was pursued. Maximum tension was applied for 20 min while the ship manoeuvred around a near vertical position before the dredge broke free. The dredge was returned to the seabed and cable laid out to recommence dredging the slope. However, after only two tension peaks the dredge once again hung up and the retrieval process was repeated. Three minutes after the dredge was freed at 130.0046 hrs it hung up again. For the next three hours the ship moved in different directions, through arc, while tension was applied before the dredge was freed. At 130.0450 hrs, more than 13 hrs after the dredge was deployed, it returned to the vessel with ~70 kg of samples covering a range of lithologies.

130.0543 Dredge 95DR/009 commenced, targeting the top of the same slope sampled by the two previous dredges. This dredging operation took ~8 hrs with one 'hang up', and recovered a full dredge bag of samples covering a range of fossiliferous mudstones and siltstones, plus very fine sandstones. The water depth range of this dredge was 4200 m to 3350 m.

130.1536 Dredge 95DR/010 moved to a northwest facing slope of Mermaid Canyon, targeting a Triassic and early Jurassic section identified in Shell seismic line N207. During an approximately nine and a half hour operation, with an almost constant register of tension peaks and two 'hang ups', a full dredge bag was recovered. Samples ranged through three varieties of sandstone, two mudstsone types, ferruginous boxstones, calcarenite, fossiliferous wackestones, volcanic breccia, andesite, two varieties of basalt, a cherty volcanic rock, plus ooze. Water depth range was 5325 m to 4090 m.

131.0400 The next dredge, 95DR/011, attempted to overlap with the top of the previous dredge and continue to sample the upper part of that slope. This dredge, conducted over ~7 hrs, recovered a full bag of samples covering a range of lithologies including mudstones and claystones, a very fine sandstone, ferruginous boxstones, and an early to mid Miocene chalk. Water depth was 4000 m to 3300 m.

131.1435 Dredge 95DR/012 targeted a ridge west of Clerke Canyon, in which the section identified in a Gulf seismic line (Au 26) suggested exposed Triassic and Jurassic stratigraphy. In the course of this dredge, which experienced almost constant tension peaks, the dredge hung up four times requiring the ship to be pulled back to free the dredge. The dredge covered the slope between 4470 m and 3625 m water depths and through fifteen and a half hours of persistence produced a full bag of samples ranging through seventeen different rock types, a clay, and two varieties of ooze. A full description of these rocks is given in the geological section, but they are generally consistent with the Late Triassic, and the Jurassic coal measures.

132.0633 Dredge 95DR/013 targeted a west facing slope at the head of a subsidiary canyon of Mermaid Canyon and again identified in Gulf seismic line Au 26. The dredging pattern produced a constant series of moderate tension peaks and occasional higher tension peaks, which is indicative generally of softer lithologies and a less rugged bottom topography. This dredge proceeded without incident and was completed in approximately 6 hrs, producing ~2/3rds of a bag of primarily siltstones and mudstones, plus some ferruginous boxstones.

In summary, the quantity and variety of samples recovered from dredging operations lead to the conclusion that this part of the cruise was an unqualified success. Dredging in the generally deep water depths encountered in this region, and being repeatedly snagged by rough bottom terrain, is time consuming and taxing on personnel. However, this effort was compensated for on this occasion by the results. After the initial winch problems the equipment worked well. The dredge used in this operation, which was a revised design with a hardened cutting edge, operated throughout with no loss of components and minimal distortion. The fact that in four consecutive dredges the shear pins were found to have undergone mild distortion, testifies to the accurate functioning of the shear mechanisms, and to the fact that we pushed the shear pins to their limits. Successful dredging operations rely heavily on good echo sounding records (especially in these water depths), and considering the currently less-than-optimal condition of the ship's echo sounders, the excellent sea and weather conditions were a great assistance to the operation. Variations in weather conditions were recorded for parts of the cruise and are shown in Figure 4.

132.1417 A gravity core (95GC/01) was deployed to target a terrace at 3300 m water depth to the west of Mermaid Canyon (16°29.5', 118°10.1'). The first attempt was not successful and the corer was redeployed at the same location at 132.1702 hrs. On the second attempt a 2.73 m core was recovered.

Computer systems work had been constantly underway during the geological sampling, and toward the end of the geological program it appeared that the seismic system could be operated with some reliability. The seismic program had been curtailed because of the systems problems and, with the start point of the next seismic line in close proximity to the last geological site, redeployment of the 2400 m seismic cable commenced immediately.

134.0214 The first production shot was collected on line 95/007 running northeast along the top of the continental slope in the Rowley Sub-Basin area. Shortly after commencement of this line (0256 hrs), a gun firing problem was experienced due to a pulse not being sent to the guns. This required the ship to be looped while the seismic computer was powered down and rebooted to reinitialise the gun controller. With the firing problem solved, shooting on line 95/007 recommenced at 134.0703. A strategy was developed at this stage to establish balance between record length and delay, in order to give the seismic system adequate write-time to deal with minor aberrations that had been causing crashes. It was decided to reduce fold from 48 to 36, to allow the seismic system more time for recording each shot, and this proved a successful decision. Fortunately the Triassic boundary shallows toward the seabed in areas where long delays are required, and shortened record lengths in these deep water areas did not disadvantage the survey greatly. Line 95/007 was completed with only one minor incident when the computer was put through a forced crash as it would not allow the operator to come out of the operator intervention program (CHAOS).

134.2213 Line 95/008 was a short line connecting the end of line 007 to the location on line 006 where acquisition had been brought to a halt by systems problems on day 125. This line was completed without incident at 135.0327.

135.0505 Shooting commenced on line 95/009 (the continuation of line 95/006 - the long tie line from Barcoo Well to the Argo Abyssal Plain). Up to this point of the survey the air gun seismic lines had been shot at 5.5 knots in near perfect sea conditions. However, the noise test prior to commencing line 95/009 confirmed observations that sea conditions were deteriorating, and the overall speed was reduced to 5 knots. Line 95/009 was shot without incident, and a new milestone was achieved in gun performance with the starboard array having fired for 19.5 hrs before a gun went down. The ship passed through the intended end of line at 135.1110 hrs but was directed to continue further onto the abyssal plain due to interesting features in the seismic record.

135.1345 Line 95/010, a line tying from the abyssal plain back up the shelf slope to line 95/007, commenced. At 1622 hrs it was determined that the ship could again achieve a speed of 5.5 knots and the firing rate was adjusted accordingly to take advantage of this. After six hours of incident-free shooting an auto-fire problem caused the array to go out of specifications. On the exchange of gun arrays a problem was identified with the starboard array about to be deployed, and it became necessary to loop the ship while repairs were undertaken. Shooting resumed and the line was completed at 136.0025 hrs. At 136.0100, while progressing toward a standard butterfly tie to commence line 95/011, a dual problem of broken equipment in the starboard array and electronic problems in the port gun controller was identified. A further two hours was specified for the turn.

136.0319 An unidentified firing problem interrupted the commencement of line 95/011, and three guns in the starboard array were switched out in rapid succession. Line 95/011, moving off the upper slope onto the Argo Abyssal Plain, was completed at 136.1140 hrs.

136.1305 Line 95/012, a long (115 n mile) line from the Argo Abyssal Plain, doglegging around the northern end of Rowley Shoals to tie to East Mermaid Well, commenced. Shooting on this line continued well, interrupted briefly by an auto-fire problem in a non-activated gun which was isolated and eliminated. At 137.0743, for no explainable reason, the system wrote an additional 3 shots to tape beyond the low tape warning before attempting the tape change. Although aquiring data, the system refused to write to either tape drive and had to be powered down and rebooted. This was achieved without substantial loss of fold and a loop was not instigated. The line was completed with the ship having towed the streamer 2 n mile through E. Mermaid Well site at 137.1116.

137.1300 On the approach to the way point for the start of line 95/013, the shot interval was experimentally reduced to 8.8 sec. This appeared to be beyond the capability of the computer and it was returned to 13.3 sec. Line 95/013 was a short (30 n mile) line running parallel to Rowley Shoals and was completed at 137.1912.

137.2024 This saw the start of line 95/014, a long (225 n mile) line extending from the Rowley Shoals on the Rowley Terrace onto the Exmouth Plateau, more than 4.5 degrees of longitude to the west. Over the following 21 hours shooting continued in near optimal conditions, with 6 sec records being collected at 5.5 knots. At 138.1731 the log entry notes that the front of the cable was rising as wind and sea conditions begin to deteriorate. At 138.1813 the bridge advised they had increased the propellor pitch to >70% and any further necessity to increase pitch would require a reduction in the speed and consequently the firing rate. This occurred approximately an hour later, with the propellor pitch at a high 76% to maintain 5.2 knots. An increase in ship's speed was gradually achieved as conditions allowed, and 5.5 knots was again available at 139.0002. Line 95/014 was completed at 139.1419.

On day 139 the cruise chief was informed by the captain of a possible fuel shortage. The *Rig Seismic* has substantial fuel capacity, however prior to this cruise the captain had been instructed to minimise the fuel on board with the ship due to drydock immediately after. The captain's calculations were based on the normal fuel usage during recent seismic trips plus a safety margin. However, on this cruise the shaft generator failure resulted in the constant running of two large auxiliary generators, and the majority of seismic collection had been at 5.5 knots which is 1 knot faster than has been customary.

139.1517 With the long regional line 95/014 complete, a series of short lines (95/015, 95/016, 95/017 and the first section of 95/018) was run to investigate features believed to be reefs occupying the tops of blocks identified in previous seismic records. Although data quality was diminished by deteriorating sea conditions, several of the target features were recorded. After we completed this seismic 'box', line 95/018 doglegged and continued on to tie with Delambre Well. This line once again was shot at a reduced speed due to sea conditions and was completed at 140.1314 hrs.

140.1418 A 'butterfly' turn was executed with no delays and line 95/019 commenced with the objective of tying back through Delambre Well across the long regional line 95/014, and continuing on through ODP sites 761 and 764 on the Wombat Plateau. The port array continued for approx. 15 hrs on line 95/019, a total of ~35 hrs since deployment. Line 95/019 was completed after ~26 hrs of continuous recording marred only by one system crash (apparently triggered by a gain change), and deteriorating sea conditions. The end of line 95/019 at 141.1602 marked the end of a total of ~1760 km of air gun seismic, which despite persistent and unpredictable system problems, and some reduction in data quality in the deteriorating sea conditons toward the end, was of a high quality.

The objective of the next phase of operations was to run a high-resolution watergun seismic survey grid over the structures on which Triassic reefs had been drilled by ODP, on the edge of the Wombat Plateau.

Within 5.5 hrs, the 2.4 km seismic cable had been retrieved and modified to a 1200 m high-resolution cable. Noise tests confirmed that the cable was noisy, which was to be expected with the weather now deteriorated to the worst it had been for the voyage, driven by 40 knot winds from the east.

142.0427 Shooting on line 95/020 at 4.5 knots commenced. During this line the seismic cable was quite unstable and the system crashed once. At the end of line (142.0739), the water gun array became entangled in the tow leader during the turn. This caused substantial downtime and was further compounded by damage to the tugger cable during retrieval, requiring it to be reterminated. It was determined that it would not be possible to shoot lines in the opposite (ie. northerly) direction, and the ship was obliged to travel back in this direction with the guns inboard so that the next line could be shot to the south. The unusual situation that prevented shooting was that the cable was being forced toward the starboard (ie. watergun array side) direction by current, while the gun array was being heaved in the opposite direction as the Norwegian buoys rode the swell, leaving an imminent danger of the guns lifting over the tow leader of the seismic cable.
142.1738 Line 95/021 commenced after a computer crash. The weather was logged at 142.1805 as follows: wind speed - 32 knots, seas - very rough, swell - mod. from the S.E. The line was shot in these conditions and completed at 142.2053.

The gun array was brought close to the stern for the turn and a further assessment of the risk in shooting toward the north soon led to the conclusion that the ship would again have to travel to the other end of the line and shoot going south. With the prospect of these sea conditions persisting and causing unacceptable time losses, the operations supervisors met with engineering staff and decided to change the gun array tow point to the end of the starboard magnetometer boom.
143.0349 Line 95/022 commenced and was completed at 143.0728.

143.0821 Line 95/023 was the first line attempted in a northerly direction since the array tow point had been adjusted, and verified the success of that strategy. It was completed at 143.1133. A series of grid lines was shot systematically after this, with the difficult sea conditions persisting. Acquisition was finally halted after line 95/028 at 0825 hrs on day 144 to mark the end of seismic acquistion for the survey. It was not possible to complete the entire planned high-resolution seismic grid because of the fuel situation discussed previously, which led to a 3 day curtailment of the cruise. The seismic cable was retrieved and the ship started the long (>4 day) transit to Fremantle, after taking Quaternary Core GC03, 7.13 m long, at the location of ODP Site 760.

148.0100 After three days of transit it was determined that the fuel and time situation would allow for a gravity core (GC04) to be taken on the continental slope for palaeoclimatic purposes. Although the weather had improved substantially, the ship was still affected by large rolling swells which made this operation marginal. The corer entered the water at 148.0127 hrs and returned to the stern at 148.0328 hrs. The lower part of the coring barrel was badly bent, and a core of 1.54 m of Pleistocene ooze overlying Paleocene or earliest Eocene chalk was recovered.

The ship berthed in Fremantle at 0630 hrs local time Tuesday, 29 May 1990.

6. VULCAN SUB-BASIN SEISMIC SURVEY

Following discussions with BHP personnel in Darwin, it was decided to site the Vulcan Graben lines across the Challis oilfield (Fig. 19). The oilfield occurs in a low relief, fault dependent closure with a maximum vertical relief of only 55 m, and appears on seismic records at 1.1 seconds TWT; water depth is about 100 m (Wormald, 1988). Typical fault throws at reservoir level, and typical reservoir sand thickness are each of the order of 20 m, thus making this site a very exacting test of a high-resolution seismic system. BHP also has proprietary 3-D seismic coverage over this area, so that comparison with existing data will be possible.

For this sort of target, a short cable with short group lengths, at a small offset from a high-frequency source, and a high shot repetition rate, is the general recipe. We employed a 1200 m, 96 channel streamer with an offset of 101 m from a four watergun array. The shot distance was set at 18.75 m, every third CDP, which will yield a stack profile with 32 fold coverage. A record length of 2 seconds and a sample interval of 2 ms was deemed sufficient. Both streamer and array were run at a depth of 5 metres to enhance the high-frequency end of the spectrum of the returning energy. Because of problems with the acquisition system, it appears that no firing delays were applied to the four working waterguns; this would have the effect of spreading or smearing the output pulse and will probably detract from the final processed section.

Part of the seismic monitor of profile 95/01 is shown in Figure 20. Although masked by water-bottom multiples, there appear to be real events at about 1 second TWT. Proper evaluation of these data will have to await processing.

7. CANNING BASIN STUDY

This work was done in three phases: an early period of geophysical surveying when profile 95/06 was recorded; a period of seven days of sampling, during which 13 dredge stations and one core station were occupied; and a final period of geophysical surveying when profiles 95/07 to 95/12 were recorded. For convenience, all geophysical surveying will be treated in one section, and all sampling in another.

7.1 Geophysical Survey Lines

This geophysical work was done using a seismic system consisting of a single airgun array and a 96 channel 2400 m seismic cable, and in general was shot at a rate allowing later 32 fold processing. The profiles recorded (Figs. 5 & 21) gave the first high-quality multichannel seismic profiles extending east-west from petroleum exploration wells on the outer North West Shelf through the Rowley Sub-basin to the Argo Abyssal Plain (95/06-09 from Barcoo No 1 well, and 95/12 from East Mermaid No 1 well). They included a mid-slope north-south tie line (95/07-08) in water about 3000 m deep, and two short lines from the abyssal plain to the mid-slope (95/10 & 11).

BMR profile 95/06-9 extends from Woodside Barcoo No 1 well (Fig. 18) westward to the abyssal plain. The monitor record (Fig. 22) shows the sequence down to and below the E unconformity ("main unconformity" of Callovian age - see Fig. 7) across most of the Rowley Sub-basin. The Neogene carbonate sequence (seabed-A) consists of calcarenite in the well, and forms a wedge up to 1500 m thick which progrades about 150 km westward across the sub-basin, before thinning to a bathyal sequence a few hundred metres thick. The Paleogene carbonate sequence (A-B) consists of calcilutite and marl in the well, and forms a well-bedded sequence 300-350 m thick across the sub-basin. The Late Cretaceous carbonate sequence (B-C) is well-bedded with small scale diffractions common, consists of calcilutite and marl in the well, and is generally about 200 m thick. The Early Cretaceous claystone sequence (C-E) is well-bedded and generally 500-800 m thick.

The Jurassic, largely claystone, sequence beneath the E unconformity is generally not visible to any great depth on the monitor records. From 124.0600 to 124.1420 (an extent of about 80 km) it is underlain by a rough surface, which probably marks the top of a Triassic/Jurassic continental volcanic sequence. From 124.1600 to 124.2000 (about 40 km) it is underlain by a faulted and folded sequence, probably consisting of Triassic sedimentary rocks. Beyond 135.0520 is the steep continental slope down to the abyssal plain, most of which is underlain by volcanics, and on which there is little sediment cover. The abyssal plain has sedimentary cover about 500 m thick on this line.

BMR profile 95/07-8 ties profiles 95/06-9 and 95/07-8 together along the top of the steep continental slope (Fig. 21). It crosses the heads of a number of canyons and the carbonate sequences (seabed-A, A-B, and B-C) are thin and disturbed along most of its length (Fig. 23). At its northern end they are similar in character to their equivalents in the tied profile 95/06-9. The "main unconformity" E extends almost flat along the profile at 4.0-4.3 seconds. Beneath it flat-lying Triassic/Jurassic sediments extend north as far as the Turtle canyons. The canyons appear to correspond with a zone of steeply dipping faults which brings the F (top Triassic) unconformity up from about 5 seconds to 4.2 seconds. North of the Turtle canyons there is a zone of probable volcanics beneath the E unconformity for 40 km, corresponding to a magnetic high, and beyond that faulted and folded probably Triassic sediments underlie it. Another magnetic high above Mermaid Canyon cannot be explained using the seismic monitor records.

BMR profiles 95/10 & 95/11 are very similar (Figs. 24 & 25), showing a small amount of normal sedimentary sequence on the upper slope cut by canyons, a steep slope of diffracting volcanics, and a 500-1000 m thick abyssal plain sequence above oceanic crust. The slope corresponds to a magnetic high and a gravity low.

BMR profile 95/12 extends from Shell East Mermaid No 1 well (Fig. 17) westward to the abyssal plain. The seismic monitor record (Fig. 26) shows, like profile 95/06-9, a wedge of Neogene sediments (seabed-A), a relatively thin Paleogene sequence (A-B) (here it is part of the prograding wedge) and a fairly consistent and thin Late Cretaceous sequence (B-C). The Late Jurassic deltaic detrital sequence and the Early Cretaceous shelf mudstone sequence (C-E) total about 1650 m thick in East Mermaid No 1, twice as thick as in Barcoo No 1, and thin westward as a prograding wedge downlapping the E unconformity. The Early and Middle Jurassic (E-F) sequence consists of shelf and deltaic shale and sandstone in the well, and downlaps the F (top Triassic) unconformity westward. A possible carbonate buildup occurs between 126.1900 and 126.2000 near the outer end of the profile. There are no signs of the continental volcanics or the deformed Triassic sediments visible in the outer part of line 95/06-9. Normal faults, of less than 100 m displacement, occur in the well-bedded Triassic sequence.

BMR profiles 95/13 and 95/14 provide a major transect from the western margin of the Canning Basin, across the Rowley Terrace and into the Exmouth Plateau (Fig. 37). The lines tie East Mermaid No 1 well to the 1976 GSI regional seismic lines (see Appendix A). Profile 95/13 joined to 95/14 (part 1 to 138.0400) crosses the western margin of the Canning Basin, and shows a fairly uniform thickness of Neogene sediment (seabed-A), overlying a westward thickening, prograding wedge of Paleogene sediment (A-B) (Fig. 38). A uniform thin Late Cretaceous sequence (B-C) underlies the Paleogene, which in turn is underlain by a thick (approx 1650 m) sequence of flat or slightly westward dipping Early to Middle Jurassic sediments (C-F), consisting of shelf and deltaic shales and sandstones in East Mermaid No 1 well (Fig. 17). The section is cut by numerous normal faults, many of which extend from below the top Triassic horizon (F) to the base Neogene horizon (A). Several of the faults extend right through to the sea bottom.

From 138.0400 to 138.1400, the profile corresponds with the Rowley Terrace. The Neogene (seabed-A) and Paleogene (A-B) sequences show a large degree of slumping related to the progradation of the Paleogene wedge. The Cretaceous sequence (B-C) becomes less distinct westwards towards the margin of the Swan Canyon at 138.1400, and below horizon C there is a zone of disrupted and diffused reflectors where no interpretation was possible.

The Swan Canyon, between 138.1400 and 138.1600 on profile 95/14, marks the boundary between the Rowley Terrace and the Exmouth Plateau. This and other canyons in the same general area may be related to northwest trending strike slip movement. The remainder of profile 95/14 is described under "Exmouth Plateau Regional Study".

7.2 Geological Sampling

The Canning Basin geological sampling program was designed to provide geological information which could be tied directly into the regional seismic grid. Our original intention was to run an additional seismic survey before sampling began, so that it could be used to define additional sampling targets. However, the failure of the seismic system at the end of profile 95/06 brought the geological sampling program forward, and meant that we had to use pre-existing seismic lines for our dredge targets. All 13 dredge targets were on the slopes of canyons and all recovered some material. The single core target was on a terrace in a canyon wall, and succeeded in recovering sediment at the second attempt (95/GC02).

The dredge locations are related to bathymetry in Figure 27, the seismic lines on which they were taken in Figure 28, and the new BMR lines in Figure 29. The bathymetric map shows how the continental slope falls gently northwestward to the 3000 m isobath, and then precipitously down to the edge of the Argo Abyssal Plain at 5000 m. The margin is cut by seven major canyon systems (new names in Figure 27) and several minor ones, all roughly normal to the slope, although some structural control may be indicated by westerly trends in Taipan, Seasnake, and Tortoise canyons in the north. The amount of canyon downcutting is variable, reaching a maximum of about 3000 m in Taipan canyon in the north and Swan canyon in the south.

The dredge results are summarised in Table 1, which shows that a great variety of rocks was recovered. The equipment used was a large chain-bag dredge with a smaller pipe dedge attached behind. The rock types were generally similar to those known from the northern Exmouth Plateau, so the lithofacies association scheme used for that area (von Stackelberg and others, 1980; von Rad & Exon, 1983; Exon, Williamson and others, 1988; von Rad and others, 1990) has been adopted, and our rocks assigned in Table 1 to the various associations listed below. The major lithofacies and their probable ages are:

A. Delta plain/coal measure association -- Late Triassic to Middle Jurassic
B. Ferruginous association -- Late Jurassic
C. Shallow water carbonate association -- Late Triassic to Middle Jurassic
D. Deltaic/marine mudstone association -- Late Triassic to mid Cretaceous
E. Pelagic marls and chalks -- Early Cretaceous to Pliocene
F. Chert and orthoquartzite association -- Jurassic to Early Cretaceous
G. Fe/Mn crusts -- Neogene
H. Volcanic and volcaniclastic rocks -- Late Triassic to Middle Jurassic
I. Evaporitic association -- Middle Jurassic

The dredge material was studied aboard ship in hand specimen, including sawn material, and classified into various groups for each dredge haul. Any foraminiferal or nannofossil determinatons made aboard ship (see later sections) were taken account of in this initial classification. Note that we had no means of dating the abundant non-marine rocks, many of which may be Triassic, aboard ship. Each group in each dredge was assigned a number, and individual samples were assigned a subsidiary letter. Thus a typical number for an individual sample from group 3, from dredge 2 might be 95/DR02/3A. Individual dredge hauls are described briefly below.

<u>Dredge 95/DR01</u> was taken from the northern slope of Taipan canyon in water depths of 4650-3800 m (Table 1). It is located on Shell seismic profile N206 which suggests it should largely have sampled pre-Oxfordian rocks (Fig. 30). It recovered a large quantity of basaltic to trachytic continental volcanic and volcaniclastic rocks, some claystone of probable Jurassic age, late Miocene and younger chalks and oozes, and one piece of red, hard, calcite-veined claystone which may be of Triassic age.

<u>Dredge 95/DR02</u> was taken from the western slope of the northern arm of Taipan canyon in water depths of 4000-3100 m (Table 1). It is located on BMR profile 17/086, which suggests it should have dredged similar pre-Oxfordian rocks to DR01 (Fig. 31). A limited haul of rocks was recov-

ered: largely shallow marine Oxfordian volcaniclastic grits with shelly fossil remains, and subsidiary volcanic rock, probably andesitic tuff, and a little foram ooze.

Dredge 95/DR03 was taken from the southern slope of Copperhead canyon in water depths of 4900-4400 m, on Shell line N206, probably in a slump consisting largely of Cretaceous mudstones (Fig. 30). None of the material was hard enough to survive in the chain-bag dredge, but the pipe dredge recovered a little dark grey probably Mesozoic mudstone, and various Miocene and younger oozes and muds (Table 1).

Dredge 95/DR04 was taken from the southwest slope of Copperhead canyon on Shell line N206, in water 4200-3750 m deep, probably across rocks which are Triassic to Middle Jurassic in age (Fig. 32). It recovered a large haul of varied rocks, including Middle Jurassic marine clastic rocks, softer Neocomian marine clastic sediments, Late Cretaceous chalk, and younger chalk, mud, and ooze (Table 1). No macrofossils were seen.

Dredge 95/DR05 was at the same locality (Fig. 32), but in shallower water (3850-3330 m). It probably dredged a terrain dominated by Jurassic and Cretaceous rocks. All the large volume of older rocks recovered appeared to be non-marine, and were dominantly clastic sedimentary rocks, often heavily ferruginized and probably Jurassic in age (Table 1). A little altered ?tuff and some Neogene ooze made up this dredge haul.

Dredge 95/DR06 was taken on the southwestern slope of Tortoise canyon in water 3400-3100 m deep, on Shell line N206, across a sequence where Triassic, Jurassic, and Cretaceous rocks should be present (Fig. 33). This large haul (Table 1) is dominated by welded tuff and lapillistone, but also contains abundant calcareous and non-calcareous marine mudstones, free of macrofossils but with Early and Middle Jurassic foraminifera and nannofossils. One piece of grey Middle Jurassic mudstone with laminae of fibrous calcite is believed to be evaporitic. Ooze of Pliocene and younger age is also present.

Dredge 95/DR07 was a large haul taken up a northwest facing slope of Mermaid canyon on BMR line 17/091 (Fig. 34) in water depths of 4530-3900 m, across a terrain of Late Triassic to Middle Jurassic rocks. It is largely non-marine quartzose sandstone (Table 1), but is of great interest in that it contains various shelf carbonates containing macrofossils, including crinoids, corals, and bivalve fragments. Among these carbonates is a coral boundstone containing branching hexacorals which may well be reefal. Massive chert beds and nodules contain shell debris and appear to be altered carbonate mudstone. Some Middle Jurassic clay and young ooze is present.

Dredge 95/DR08 was taken in the same general location, but over only the lower part (4400-4230 m) of the scarp dredged at 95/DR06 (Fig. 34). It comprised abundant marine rocks containing shelly fossils which are as yet undated, but are certainly Late Triassic to Middle Jurassic in age (Table 1). Shallow-water marine carbonates include calcareous quartz-bearing sandstone with bivalve fragments, and ooids of two types: calcareous and ferruginous (?chamosite). True calcarenites and calcisiltites contain calcareous ooids and pectenoid shelly fossils. Hard, angular recrystallized limestone may represent a hard ground. Abundant carbonaceous mudstone contains a probable brachiopod, and in places is encased in ferruginous boxstone. Pliocene and younger ooze makes up the remainder of the sample.

Dredge 95/DR09 is at the same location as the two previous dredges (Fig. 34), but probably dredged a Jurassic sequence in generally shallower water (4200-3350 m). A large haul is dominantly undated marine mudstone and siltstone, both calcareous and non-calcareous, containing common shelly fossils including well-preserved ammonites (Table 1). One calcareous sandstone is dated as Jurassic on foraminifera. Minor calcareous ooid grainstone is present. Younger material includes ooze and mud.

Dredge 95/DR10 was taken on the eastern slope of Clerke canyon, on Shell profile N207 in water depths of 5325-4090 m, largely across an apparently Late Triassic sequence (Fig. 35). It was a large, undated and varied haul containing marine detrital sediments, shallow marine carbonates, and volcanic rocks (Table 1). The marine sandstone, siltstone and mudstone is generally bioturbated, but only one marine macrofossil, an ammonite, was found. The carbonate rocks are rich in macrofossils (bi valves, crinoids and algae) and include algal boundstone, calcarenite, and carbonate wackestone and mudstone. Some are extensively recrystallized. The volcanic rocks include a volcanic breccia and various basaltic and andesitic lavas. Young ooze completes the haul.

Dredge 95/DR11 was on Shell profile N207 near the previous station (Fig. 35) but dredged a younger (Jurassic) sequence in water 4000-3300 m deep. It provided a large haul of mudstone, siltstone and sandstone, containing no macrofossils but assumed to be marine on the basis of bioturbation, and lesser Miocene and younger claystone, mud, chalk and ooze.

Dredge 95/DR12 sampled a ridge west of Clerke canyon on Gulf profile AU26 in water 4470-3625 m deep (Fig. 36). The profile suggests it traversed a suite of Late Triassic to Middle Jurassic rocks. A large dredge haul included a little black coal, marine and non-marine detrital sediments, shallow marine carbonates and a variety of volcanic rocks. The detrital sediments include carbonaceous mudstone, quartzose sandstone, and poorly sorted lithic sandstone, gritty and pebbly in part. No marine macrofossils were seen, but some bioturbation was present. Ferruginized, silicified sandstone represents a later period of exposure and weathering. The carbonates include calcarenites and calcisiltites with bivalve, crinoid, algal and brachiopod remains, and a chert is probably altered limestone. The volcanics are not very abundant and include acid to basic flows and a weathered volcanic breccia. Younger sediments include clay, marl and ooze.

Dredge 95/DR13 came from the eastern slope of Clerke canyon on Gulf profile AU26 from water depths of 3480-3100 m (Fig. 36). The profile suggests it traversed a Jurassic sequence. It recovered a large haul of marine and non-marine detrital sediments, many of them altered to ferruginous boxstone, and Paleocene and younger chalk, mud and ooze. The non-marine rocks are quartzose sandstone and siltstone. Laminated siltstone and mudstone contain the casts of shelly fossils.

TABLE 1 : BMR CRUISE 95 DREDGE STATIONS

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
STATION 95/DR01			
Northern slope of Taipan Canyon (Dredged to North) 15° 01.92'S 118° 57.53'E to 14° 59.60'S 118° 57.76'E	Shell N206 S.P. 31200 Seismic suggests dredged largely pre-Oxfordian volcanic and volcaniclastic rocks	4650 m to 3800 m 100 kg	Light grey non-calcareous very soft claystone with Mn crust to 5 mm (D). 30% Light green grey to brown volcanic breccia (H). 5% Light olive brown altered tuff (H). 30% Volcanics: grey basaltic to trachytic, some filled vughs, thin Mn veneer (H). 30% Lithified yellow volcanic grits and conglomerates coated with Mn crust up to 1 cm thick (H). 3% White chalky foram/nanno ooze : late Miocene - early Pliocene. Greyish brown foram ooze. Dark brown slightly calcareous mud.
STATION 95/DR02			
Northern slope of Taipan Canyon (Dredged to Northwest) 14° 57.87'S 119° 06.03'E to 14° 55.86'S 119° 05.11'E	BMR 17/086 time 76.1300 Seismic suggests dredged largely pre-Oxfordian volcanic and volcaniclastic rocks	4000 m to 3100 m 20 kg	Dark grey volcanics with fine groundmass and elongate volcanic fragments, probably andesitic (H). 10% Light olive brown calcareous lithic grit, largely volcanic fragments with some quartz, forams, bivalve, crinoid and echinoid fragments. Strongly lithified and variably weathered. Shallow marine Oxfordian forams (C). Black Mn crusts 0.5 - 1 cm thick (G). Greyish brown foram ooze.
STATION 95/DR03			
Southeast slope of Copperhead Canyon (Dredged to Southeast) 15° 08.8'S 118° 57.9'E to 15° 10.1'S 118° 58.5'E	Shell N206 S.P. 31400 Seismic suggests may have dredged a Cretaceous slump	4900 m to 4400 m 5 kg	Pipe dredge only: Light olive brown calcareous ooze with forams, radiolarians and one fish tooth. Benthic and planktic forams, early Pliocene to Recent (E). Dark grey non-calcareous mudstone. Zeolitic with some quartz (D). Light olive grey calcareous mud. Some foram, radiolarian and mollusc fragments. Miocene or younger forams (E). Dark reddish grey ooze.

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
STATION 95/DR04			
Southwest	Shell N206	4200 m	Light grey calcareous mud with forams, ostracods and
slope of	S.P. 31900	to	Hauterivian nannos.
Copperhead		3750 m	White Middle Miocene chalk
Canyon	Seismic		White Pliocene foram/nanno ooze
(Dredged to	suggests	400 kg	White to light grey foram/nanno chalk, some small
Southwest)	Triassic and		bivalves, planktonic forams, latest Campanian (E). 2%
	Early to		Dark brown unconsolidated very fine sandstone/siltstone
15° 22.0'S	Middle Jurassic		ferruginous (D). 15%
118° 58.9'E	rocks		Light olive grey soft mudstone. Calcareous, laminated,
to	predominate		burrowings, Neocomian nannos (D). 5%
15° 22.5'S			Dark grey brown medium to very fine quartz sandstone,
118° 57.9'E			partly ferruginised, abundant burrowing (D). 15%
			Pale olive medium to very fine quartz sandstone, bored.
			Sparse forams suggest Jurassic (D). 1%
			Light to dark grey granular to medium quartz sandstone,
			thin shaley partings, possible cross bedding (A). 5%
			Dark brown to grey brown ferruginous siltstone to medium
			sandstone. Micaceous, well sorted subangular to well
			rounded grains. Common Fe crust up to 1 cm, Bajocian and
			Barremian nannos (D/B). 30%
			Dark grey very fine sandstone to siltstone, very hard and
			brittle, thin carbonaceous laminae.
			Fe cover to 5 mm (A/D). 20%
			Grey to black very fine sandstone to siltstone, soft,
			laminated and carbonaceous (A/D). 5%
			Brown plastic silty mud, late Miocene.
STATION 95/DR05			
Southwest	Shell N206	3850 m	Yellow to brown very coarse to very fine ferruginous
slope of	S.P. 31900	to	sandstone and ironstone breccias (A/B). 40%
Copperhead		3330 m	Pyrite (very fine) concretions in clayey sandstone (A). 2%
Canyon	Seismic		Grey to black mudstone to sandstone;black carbonaceous
(Dredged to	suggests	400 kg	partings and coaly laminae (A). 15%
Southeast)	Jurassic and		Grey well laminated labile sandstone (A) 10%
	Cretaceous		Soft grey to brown micaceous siltstone to very fine
15° 22.53'S	rocks should		sandstone, some burrowing evident (A). 20%
118° 57.91'E	predominate		Grey very fine hard slightly calcareous ? tuffaceous
to			sansdtone (A). 1%
15° 24.21'S			Grey, hard well bedded siltstone and labile
118° 58.38'E			Various minor mudstone and siltstone types.
			sandstone (A). 10%
			Minor brown altered ?tuff.

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
STATION 95/DR06			
Southwest slope of Tortoise Canyon (Dredged to South) 16° 01.33'S 118° 46.39'E to 16° 00.00'S 118° 46.50'E	Shell N206 S.P. 33450 Seismic suggests Late Triassic, Jurassic and Cretaceous rocks should predominate	3400 m to 3100 m 150 kg	Dark grey carbonaceous mudstone massive; with Middle Jurassic forams and nannos (A). 20% Ironstone boxstones with grey mudstone cores (B). 20% Grey to dark grey welded tuff to lapillistone. Thin to medium bedded with angular clasts of acid and intermediate volcanics set in a fine grained quartz - feldspar matrix; shows some grading, clasts are not flattened (H). 60% Grey green (Late Triassic to Toarcian) calcareous mudstone. Brown silty mudstone with late Toarcian forams Grey evaporitic Middle Jurassic mudstone with laminae of fibrous calcite (replacing earlier minerals (J). Pale brown foram/nanno ooze, Pliocene to Recent.
STATION 95/DR07			
Northeast side of Mermaid Canyon (Dredged to East) 16° 18.9'S 118° 22.2'E to 16° 18.2'S 118° 24.3'E	BMR 17/091 time 81.1300 Seismic suggests Late Triassic, Early and Middle Jurassic rocks should predominate	4530 m to 3900 m 400 kg	Olive grey to grey brown very fine to fine quartz sandstone; commonly micaceous and carbonaceous; poorly bedded to partly laminated. Abundant carbonaceous partings and probable rootlets, some coarse yellow quartz sandstone; sands are generally well sorted, fluvial (A). 64% Ferruginous boxstones (B). 2% Small amount of grey to black puggy clay with Bajocian-Callovian (Middle Jurassic) forams and nannos. Dark grey to light grey and brown calcareous mudstones and sandstones; well bedded or laminated; slightly bioturbated and containing crinoid and other shelly fragments (C). 15% Grey coralline boundstone with crinoid hexacorals; possibly reefal (C). 2% Grey chert as nodules with calcite veining (F). 15% Greyish brown nanno ooze.
STATION 95/DR08			
Northeast side of Mermaid Canyon (Dredged to East) 16° 19.1'S 118° 22.9'E to 16° 18.9'S 118° 23.2'E	BMR 17/091 time 81.1320 Seismic suggests Late Triassic rocks should predominate	4400 m to 4230 m 70 kg	Grey carbonaceoue mudstone with shelly fossils (D). 25% Ferruginous boxstones with cherty and clayey cores (B). 5% Olive calcareous sandstone, fine to coarse, well sorted, with carbonate, quartz, (?)glauconite and ooids (C). 35% Interbedded brownish yellow calcarenite and greyish brown calcisiltite; contains pelecypods and ooids (C). 10% Greyish brown Pliocene to Recent foram nanno ooze (E) White Pliocene to Recent Foram sand.

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
STATION 95/DR09			
Northeast side of Mermaid Canyon (Dredged to East)	BMR 17/091 time 81.1310	4200 m to 3350 m	Dark brown to yellow brown soft laminated mud (E). 15%
16° 19.0'S 118° 23.8'E to 16° 18.5'S 118° 25.6'E	Seismic suggests Early and Middle Jurassic rocks should predominate	400 kg	Dark grey to dark brown micaceous siltstone to mudstone, bioturbated, burrows and shell fragments including ammonites (D). 35%
			Dark brown silty laminated mudstone (D). 10%
			Dark grey to brown micaceous siltstone to very fine sandstone; carbonaceous?, bioturbated, shelly fragments including ammonites (D). 15%
			Grey brown to yellow brown calcareous very fine quartz sandstone (C). 5%
			Very fine ooid grainstone (C). 1%
			Dark grey brown Jurassic calcareous siltstone, bioturbated with abundant shelly fragments including brachiopods (C). 20%
			Ferruginous boxstones (F). 5%
			Very dark greyish brown nanno ooze.
STATION 95/DR010			
Northeast side of Clerke Canyon (Dredged to Southeast)	Shell N207 S.P.38250	5325 m to 4090 m	Grey hard crossbedded coarse to very coarse quartzose sandstone (A). 2%
16° 23.34'S 118° 09.66'E to 16° 24.36'S 118° 10.75'E	Seismic suggests Late Triassic rocks should predominate	400 kg	Grey fine to medium quartzose sandstone, thin bedded and cross-laminated; bioturbated (D). 23%
			Greyish brown very fine quartzose sandstone and interbedded carbonaceous siltstone; moderately bedded, bioturbated (D). 7%
			Dark grey well bedded carbonaceous silty mudstone; contains an ammonite (D). 7%
			Dark brown weathered silty mudstone (D).
			Ferruginous boxstones about cores of chert or clay (F). 5%
			Yellow and brownish grey algal boundstone containing pelecypods and other shell fragments (C). 7%
			Grey medium bedded, fine to medium quartz rich calcarenite (C). 12%
			Grey carbonate wackestones and mudstones with crinoids and bivalves (C).
			Grey volcanic breccia with clasts in sandsized matrix (H). 3%
			Dark grey ?andesite with K feldspar phenocrysts (H). 5%
			Dark grey vesicular basalt (H). 7%
			Dark grey cryptocrystalline basalt (H). 15%
			Light grey cherty acid volcanic rock (H). 15%
			Dark greyish brown ooze

STATION 95/DR011

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
Northeast	Shell N207	4000 m	Brown to black laminated and bioturbated silty
slope	S.P.38200	to	mudstone (D). 40%
of		3300 m	Dark brown laminated and bioturbated siltstone (D). 2%
Clerke	Seismic		Black, hard, thin bedded mudstone (D). 8%
Canyon	suggests	400 kg	Dark brown very fine quartzose sandstone well sorted (D).
(Dredged to	Early to		Pale olive calcareous claystone with early to middle
Southeast)	Middle		Miocene nannos (D).
	Jurassic		Ferruginous boxstones about cores of chert or clay (F). 10%
16° 25.1'S	rocks		Pale yellow early to middle Miocene chalk (E).
118° 10.6'E	should		Dark brown noncalcareous mud.
to	predominate		Greyish brown foram ooze.
16° 26.3'S			
118° 11.85'E			

STATION 95/DR012

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
Ridge west	Gulf Au 26	4470 m	Black vitreous coal (A).
of Clerke	time 151.1620	to	Dark grey bioturbated carbonaceous mudstone (D).
Canyon		3625 m	Dark grey laminated carbonaceous mudstone (A).
(Dredged to	Seismic		Greyish brown fine to medium well bedded quartzose
East)	suggests	400 kg	sandstone (A). 10%
	Late		Greyish brown, medium to coarse, crossbedded quartzose
16° 29.16'	Triassic and		sandstone (A). 7%
118° 59.55'	Early to		Olive medium bedded hard very fine quartzose
to	Middle Jurassic		sandstone (A). 5%
16° 28.76'S	rocks should		Olive grey poorly sorted lithic sandstone and gritty and
118° 03.64'E	predominate		pebbly sandstone (A). 12%
			Pale yellow recrystallized fine to coarse calcarenite
			with molluscan, crinoid, algal and ?brachiopod debris
			and shells (C). 30%
			Pale yellow calcisiltites with rare shelly fossils (C). 5%
			White chert, probably altered limestone (F). 5%
			Light yellow brown silicified sediment (F). 20%
			Brown layered (?)acid volcanic rock (H).
			Grey, variably weathered fine volcanics, probably
			basalts (H).
			Dark grey very fine acid volcanic rock (H). 2%
			Weathered volcanic breccia with volcanic clasts in clay
			matrix (H).
			Soft black claystone (D).
			Black Mn crusts (G).
			Dark grey puggy clay.
			Light brownish grey ooze.
			Dark brown ooze.
			Light grey Pliocene nanno marl.

Location	Seismic Profile	Depth (m) Recovery (kg)	Description of main rock types
STATION 95/DR013			
Northeast	Gulf Au 26	3480 m	White mixed Paleocene and Pliocene marl (E). 1%
slope of	time 151.1515	to	Brown very fine sandstone to siltstone micaceous
Clerke		3100 m	and mottled (A). 15%
Canyon	Seismic		Brown ferruginized quartz siltstone, laminated,
(Dredged to	suggests	250 kg	micaceous (A). 10%
East)	Early to		Dark grey micaceous siltstone, laminated, some with shelly
	Middle Jurassic		fossil casts (D). 25%
16° 29.36'S	rocks should		Grey laminated soft mudstone (D). 10%
118° 09.8' E	predominate		Ferruginous boxstone about chert and mudstone
to			cores (B). 40%
16° 29.41'S			Dark grey soft mud.
118° 10.62'E			White calcareous ooze (E). 1%
			White to pale brown layered mud with Paleocene nannos.
			White firm chalk with Paleocene nannos.
			Light grey mud with middle Miocene nannos.

7.3 BMR Cruise 95 : Nannofossil Biostratigraphy

Samir Shafik

ABSTRACT

Dredging in several submarine canyons and steep slopes in the Rowley Sub-basin (Canning Basin in the northwest of Australia) revealed the occurrence of a number of Mesozoic and Tertiary nannofossil-bearing levels. Among these levels, the mid Jurassic one, being within the pre-breakup sequence, seems most significant. This Jurassic record came from the Tortoise Canyon, and is the first from Australia. It seems to represent a marine ingression within a largely fluviodeltaic to marginal marine sequence. Within the Cretaceous part of the post-breakup sequence, two levels rich with nannofossils were sampled from the vicinity of the Copperhead Canyon. A Lower Cretaceous level is identified by an assemblage with abundant *Vekshienella matalosa*, which is apparently similar to another assemblage recently recovered from ODP site 763 on the Exmouth Plateau. An Upper Cretaceous level had abundant *Quadrum trifidum*, *Q. gothicum*, *Cribrocorona gallica* and *Ceratolithoides aculeus* which collectively suggest that the Rowley Sub-basin was within the Tropical Province during the latest Campanian - Early Maastrichtian interval. Several horizons within the Tertiary were also sampled, the oldest being an Upper Paleocene, whereas the others are from within the Miocene section. Species indicating warm surface-waters are evident among the assemblages extracted from the Paleocene and Miocene horizons sampled.

INTRODUCTION

This study is based on samples obtained during BMR Cruise 95 (onboard the

R/V Rig Seismic, May 1990) when a program of dredging on the offshore southwestern Canning Basin (the Rowley Sub-basin area), off the north-west corner of Australia (Fig. 1), was successfully carried out. Earlier, sediment dredges and cores were recovered from various parts of the nearby Exmouth Plateau, during 1979 by *R/V Sonne* (SO-8 Cruise) and during 1986 by *R/V Rig Seismic* (BMR Cruise 56), but no such dredging occurred previously on the Rowley Sub-basin. Evaluation of the age and depositional environment of the calcareous nannofossil-bearing sediments recovered during SO-8 Cruise has been given by Shafik (*in* von Stackelberg & others, 1980).

The Ocean Drilling Program (ODP) has recently sampled the Exmouth Plateau's section at several sites. During ODP Leg 122, cores were recovered from six holes on the plateau (Haq, von Rad & others, 1988), and ODP Leg 123 drilled two holes, one on the Argo Abyssal Plain, and the other on the lower slope of the western Exmouth Plateau (Gradstein, Ludden & others, 1989).

Oil company wells in the vicinity of BMR Cruise 95 dredge sites on the Rowley Sub-basin are Woodside Barcoo No 1 and Shell East Mermaid No 1. The stratigraphy of these wells is discussed below.

GEOLOGICAL ACCOUNT OF AREAS NEARBY TO DREDGE SITES

Sites dredged are located on the outer reaches of the Rowley Sub-basin (Fig. 27). Areas nearby to these dredge sites, where the stratigraphic sections are known from drilling, are those in the east within the Rowley Sub-basin where the Woodside Barcoo No 1 and Shell East Mermaid No 1 are located, and those to the southwest in the Argo Abyssal Plain and the northern Exmouth Plateau where there are several ODP holes.

Rowley Sub-Basin, Canning Basin

The stratigraphic sequence of the offshore southwest Canning Basin (Rowley Sub-basin area) may be indicated by the lithological successions of Woodside Barcoo No 1 and Shell East Mermaid No 1 wells. Unconformities within the Upper Triassic to Miocene section penetrated at Barcoo No 1 are: (1) between Bajocian and Callovian sandstones and claystone (Bathonian is missing); (2) "?breakup unconformity=Jb seismic event" between Oxfordian and Berriasian claystones (Kimmeridgian, Portlandian, Ryazanian, Valanginian and Hauterivian are missing); (3) "intra-Aptian event" within Aptian claystones; (4) mid-Cretaceous "base Turonian event=seismic horizon", between Middle Cenomanian claystone and Upper Turonian calcilutite; (5) "Early-Middle Maastrichtian disconformity" between Upper Campanian and Upper Maastrichtian marls; (6) at the Cretaceous/Tertiary boundary; (7) "Late Paleocene disconformity" within Upper Paleocene calcilutites; and (8) "Early Oligocene disconformity" between Upper Eocene and Upper Oligocene marls and calcilutites.

The Aptian disconformity in Barcoo No 1 separates a section above with planktic foraminiferids from another containing only benthic forms. However, palynological studies on the Jurassic sequence of the same section pointed out that conditions during the Callovian to Oxfordian were open marine.

Unconformities within the Jurassic - Miocene sequence of East Mermaid No 1 are: (1) within the Lower Jurassic; (2) "?breakup unconformity" between lower Upper Jurassic and Neocomian; (3) within the Aptian; (4) "Turonian disconformity=seismic horizon D" between Cenomanian and Coniacian; (5) between Lower Campanian and Lower Maastrichtian; (6) at the Cretaceous/Tertiary boundary (Upper Maastrichtian and Lower Paleocene are missing); (7) between Paleocene and Lower Eocene (T6-T8 are missing); and (8) (a possible disconformity, a thin silt bed within grey to yellow bioclastic lime packstone) between Lower and Middle Eocene.

Below the major Cretaceous/Jurassic disconformity in East Mermaid No 1, the sequence may lack any calcareous planktic remains as the palynological evidence suggests that it was mainly deposited in deltaic environments.

Two depositional sequences are recognised within the Mesozoic of Barcoo No 1: a pre-breakup sequence of fluviodeltaic to marginal marine sediments of Triassic to Middle Jurassic age (deposited during the rifting of Gondwanaland); and a post-break marine transgressive sequence of Late Jurassic to Cretaceous age. The same is true for the Mesozoic of East Mermaid No 1, although the post-breakup sequence seems to be younger there, being Early Cretaceous at its base.

Remarks

Data from both Barcoo No 1 and East Mermaid No 1 suggest that the nannofossils should be useful for most of the mid Cretaceous-Oligocene section. Limited use is envisaged for the nannofossils regarding the Lower Cretaceous section, and only doubtful use in the Jurassic and Triassic sequence.

Northern Exmouth Plateau

The geological history of the North Exmouth Plateau has been summarised by Exon & Ramsay (1990). A rifting phase characterised by paralic sedimentation probably began during the Late Triassic and continued on until the break-up during the Late Jurassic when erosion exceeded deposition. Mud deposition occurred in a juvenile ocean during most of the Middle Cretaceous, followed by carbonate deposition, suggesting mature ocean, during the Late Cretaceous. Major unconformities (and seismic reflectors) are probably at the Rhaetian/Hettangian (Triassic/Jurassic transition), Bathonian/Neocomian (Middle Jurassic/Lower Cretaceous), Turonian (mid Cretaceous), Maastrichtian/Paleocene (Cretaceous/Tertiary), and Oligocene.

RESULTS OF THE STUDY

Detailed lithological descriptions and other relevant data (eg. foraminiferal results) concerning the samples discussed in this study are given elsewhere in this record.

Rowley Sub-Basin, Canning Basin

For the Mesozoic, this study makes use of the stratigraphic range charts of Jurassic nannofossil species published by Hamilton (1982), and Brown & others (1988), and of the range charts of Lower Cretaceous nannofossil species published by Thierstein (1973), Perch-Nielsen (1979), and Taylor (1982). For the Tertiary, the zones described by Bukry (1973) are used.

Middle Jurassic

(A) Several species of calcareous nannofossils were tentatively identified from a sample of yellowish brown, heavily altered silty mudstone (DR06/3) which was obtained from the southwest slope of the Tortoise Canyon (at Lat. 16°01.33' - Long. 118°46.39' to Lat. 16°00.00' - Long. 118°46.50') in water 3400 to 3100 m deep. These included *Carinolithus superbus*, *Crepidolithus crassus*, *Discorhabdus striatus*, *Biscutum novum*, *Lotharingius contractus* and *L. crucicentralis*. The age is thought to be Middle Jurassic, probably Aalenian to Bajocian. This is based on the co-occurrence of *Lotharingius contractus* and *Carnolithus superbus*, and the absence of *Watznaueria britannica*.

(B) Rare but apparently relatively diversified nannofossils were extracted from a sample of interlaminated grey mudstone and light yellowish brown fibrous calcite (DR06/4) which was dredged from the southwest slope of the Tortoise Canyon (at Lat. 16°01.33' - Long. 118°46.39' to Lat. 16°00.00' - Long. 118°46.50') in water 3400 to 3100 m deep. Most of the forms are small. Identification of species must be considered tentative pending more work (i.e. concentration of the fossils and their SEM examination). Species identified include *Lotharinguis contractus*, *L. crucicentralis*, *Discorhabdus striatus*, *Biscutum novum*, *Mitrolithus elegans* and a possible species of *Carinolithus*. These suggest a Middle Jurassic age.

Remarks. Dredge sample DR06/4 is thought to have probably been formed as evaporite. In other words, the environmental conditions during the deposition of DR06/4 were likely to have been too distressful for calcareous nannoplankton to flourish. This might have contributed to the dwarfness of the nannofossils in the sample.

(C) A poorly preserved assemblage was extracted from a sample of puggy, dark grey, slightly calcareous clay (DR07/8), which was dredged from a slope near Mermaid Canyon (Lat. 16°18.90' - Long. 118°22.18' to Lat. 16°18.20' - Long. 118°24.3') in water 4530 to 3900 m deep. This assemblage is dominated by severely-etched *Watznaueria britannica*. *Cyclagelosphaera margereli*, *Watznaueria barnease*, *Schizosphaerella puntuclata* and to lesser degree *Discorhabdus jungi*. Species of *Carinolithus* (including *C.* cf. *superbus*: small central opening with wider distal rim) are common. Rare species included *Annulithus arkelli*, *Crucirhabdus primulus*, *Tubirhabdus patulus*, *Lotharingius crucicentralis*, *L. contractus*, *Pseudoconus enigma*, *Ansulosphaera helvetica* (or a form very similar to it), *Discorhabdus striatus* and *Annulithus* sp. (with small central opening). The age is Middle Jurassic (possibly Late Bathonian to early Callovian) on the co-occurrence of *Pseudoconus enigma* and *Ansulosphaera helvetica* according to Brown & others (1988). The presence of *Annulithus arkelli* and *Crucirhabdus primulus* suggests some reworking from Upper Triassic/Lower Jurassic source(s). The stratigraphic ranges of these two species are restricted to the Upper Triassic and/or the Lower Jurassic in Great Britain according to Hamilton (1982).

Possible mid Jurassic to Early Cretaceous

A few calcareous nannofossils were extracted from a sample of pale olive quartz sandstone (DR04/7), which was dredged from the Copperhead Canyon (Lat. 15°22.00' - Long. 118°58.90' to Lat. 15° 22.50' - Long. 118°57.90') in water 4200 to 3750 m deep. These fossils evidently represent a single species only, namely *Watznaueria britannica*. This monospecific "assemblage" is unlikely to be a result of dissolution, rather due to some ecological limitation (such as very shallow environment). The stratigraphic range of *W. britannica* is Bajocian to Barremian. The associated foraminiferids, though meagre, tend to support the Jurassic age assignment.

Remarks. Based on their meagre foraminiferal assemblages, samples DR02/2, DR06/1 and DR06/5 from the Taipan and Tortoise Canyons have been assigned a Jurassic age. These same samples were found to lack nannofossils although they came from water depths comparable to, for example, sample DR06/3 which contains frequent to common nannofossils, discussed above. This suggests that conditions in the Rowley Sub-basin during most of the Jurassic were unfavourable for nannoplankton, probably being either deltaic or restricted marine and very shallow environments. The lithologies of the samples support this conclusion: (a) sample DR02/2 is a volcaniclastic rock which apparently was formed in a shallow marine environment, being light olive brown calcareous grit, consisting largely of volcanic granules in a calcareous cement, and containing molluscan and echinoid fragments; (b) similarly sample DR06/5 is of volcanogenic origin (possibly reworked tuffs) being grey green firm calcareous mudstone with minor mica; and (c) sample DR06/1 is a deltaic deposit (coal measure association) being very dark to dark grey, soft, carbonaceous mudstone.

The record of mid Jurassic reasonably rich nannofossil assemblages from near the Mermaid Canyon and from the Tortoise Canyon (samples DR07/8, DR06/3 & DR06/4) is taken to indicate a marine ingression. The presence of only one nannofossil species, *Watznaueria britannica*, in sample DR04/7 from the Copperhead Canyon may suggest a precursor for this mid-Jurassic marine ingression.

Early Cretaceous: pre-Aptian

(A) A fairly well preserved nannofossil assemblage was extracted from a sample of light grey calcareous mud (DR04/1C), which was dredged from the Copperhead Canyon (Lat. 15°22.00' - Long. 118° 58.90' to Lat. 15°22.50' - Long. 118°57.90') in water 4200 to 3750 m deep. The assemblage is dominanted by *Watznaueria barnesae* and *Vekshinella matalosa*, but nannofossil debris abounds. Other species present included *Parhabdolithus embergerii*, *Perissocyclus noelae*, *Axopodorhabdus dietzmanni*, *Chiastozygus* sp. cf. *C. striatus*, *C. tenuis*, *Cretarhabdus conicus*, *C. striatus*, *Stephanolithion laffittei*, *Bidiscus rotatorius*, small *Tranolithus gabalus*, *Rhagodiscus asper*, *Lithraphidites carniolensis*, *Manivitella pemmatoidea*, *Vekshienella crux*, small *Watznaueria ovata* and very rare *Haqius circumradiatus*. The age is Early Cretaceous, possibly pre-Aptian (Hauterivian-Barremian) on account of the presence of *Vekshienella matalosa* and *Haqius circumradiatus* in the absence of the key species *Chiastozygus litterarius*, *Eprolithus floralis* and *Rhagodiscus angustus*. However, similar evidence has been interpreted as Aptian or Albian in age (see below).

(B) A moderately preserved calcareous nannofossil assemblage was extracted from a sample of light olive grey soft mudstone (DR04/4), which was dredged from the Copperhead Canyon (Lat. 15° 22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118°57.90') in water 4200 to 3750 m deep. Dominant among the relatively large, easily identifiable species are *Watznaueria barnesae* and to a much lesser extent *Vekshienella matalosa* and *Parhabdolithus embergerii*. Other species present included *Litharaphites carniolensis*, *Axopodorhabdus dietamanni*, small *Tranolithus gabalus*, small *Cretarhabdus conicus*, *C. striatus*, *C. surrirellus*, *Heterorhabus sinuosus*, *Chiastozygus tenius*, *C.* sp. cf. *C striatus*, questionably *Hemipodorhabus gorkae*, *Rhagodiscus asper*, *Stephanolithion laffittei*, *Ethmolithus galli-*

cus and *Watznaueria ovata*. Potentially useful species for biostratigraphic assessment of the assemblage are difficult to identify mainly because they seem to be among the smaller ones. The age is Early Cretaceous, pre-Late Aptian on account of the presence of *Vekshienella matalosa* and *Cretarhabdus surrirellus*. SEM examination of the assemblage should help identification of more species and thus possibly narrow the age assignment.

Remarks. It is worth noting here that at ODP site 763 on the Exmouth Plateau, the Early Aptian zone NC6 of Roth (1978) was identified, in spite of the absence of the zonal marker *Chiasozygus litterarius*. This was based on common occurrences of *Vekshienella matalosa* (Haq, von Rad, O'Connel & others, 1990, p.310). Thierstein (1973) indicated that *Vekshienella matalosa* has its lowest occurrence in the Lower Albian, and *Rhagodiscus angustus* as well as *Tranolithus gabalus* occur first in the Upper Aptian-Lower Albian. As indicated above, *Vekshienella matalosa* is abundant in both samples from the Copperhead Canyon, also a small form of *Tranolithus gabalus* was encountered in the same samples, without the association of either *Rhagodiscus angustus* or *Chiastozygus litterarius*. Crux (1987) considered that the lowest occurrence of *Vekshienella matalosa* in the Boreal region was Barremian.

Late Cretaceous: *Quadrum trifidum* range interval

A diversified but poorly to moderately preserved assemblage was recovered from a sample of white calcareous mud (DR04/1B), which was dredged from the Copperhead Canyon (Lat. 15°22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118°57.90') in water 4200 to 3750 m deep. Species present included *Quadrum gothicum Q. trifidum*, *P. copulatus*, *Reinhardtites levis*, *Broinsonia parca*, *Micula staurophora*, *Cretatolithoides aculeus*, *Arkhangelskiella specillata*, *Watznaueria barnesae*, *Cribrosphaerella ehrenbergii*, *Cribrocorona gallica*, *Prediscosphaera cretacea*, *P. majungae*, *P. spinosa*, *Eiffellithus turriseiffeli*, *Microrhabdulus belgicus*, *M. decoratus*, *Chiastozygus litterarius*, *Rhagodiscus angustus*, *Cretarhandus conicus*, *Heterorhabdus sinuosus*, *Cylindralithus serratus*, *Manivitella pemmatoidea*, *Lapideacassis* sp. and several species of *Vekshienella*. The age is latest Campanian to Early Maastrichtian, based on the presence of *Quadrum trifidum*. The absence of *Arkhangelskiella cymbiformis* and also *Eiffellithus eximius*, although a negative evidence, may support a Late Campanian age assignment.

Remarks. Based primarily on the distribution and abundance of some key nannofossil species, Shafik (1990) was able to differentiate three biogeographic provinces during the Late Campanian - Early Maastrichtian interval in the Australian region. The association of abundant *Quadrum trifidum*, *Q. gothicum*, *Ceratolithoides aculeus* and *Cribrocorona gallica*, which is noted in the sample from the Copperhead Canyon (DR04/1B), was used to suggest the Tropical Province. Coeval assemblages with similar associations have been reported from the Papuan Basin to the north, but in the coeval assemblages from the Carnarvon Basin to the south, the same key species are much less frequent, particularly *Quadrum trifidum* and *Quadrum gothicum* which occurred there rarely and sporadically, suggesting the Extratropical Province (Shafik, 1990).

The stratigraphic sequence at the Copperhead Canyon (dredge station DR04, Lat. 15°22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118°57.90') in the Rowley Sub-basin includes horizons of Early and Late Cretaceous age. It is interesting to note that the recovered Lower Cretaceous grey mudstone (DR04/4) is about twelve times the amount of the younger Cretaceous white mud (DR04/1B), the former representing about 15% of the weight of the total recovered material in the dredge haul. This may suggest a much thicker and/or better exposed Lower Cretaceous sequence. This speculation is supported by the recovery of another Lower Cretaceous grey calcareous mud (sample DR04/1C) in the same dredge haul.

Late Paleocene: *Discoaster mohleri* zone

(A) A fairly well preserved assemblage was extracted from a sample of firm white calcareous mudstone (DR13/1) which was dredged from a west facing slope east of Mermaid Canyon (Lat. 16°29.36' - Long. 118°09.80' to Lat. 16°29.41' - Long. 118°10.62') where water depths are betweem 3480 and 3100 m. Species identified include *Placozygus sigmoides*, *Ellipsolithus macellus*, *E. distichus*, *Chiasmolithus consuetus*, *Coccolithus robustus*, *Cruciplacolithus frequens*, *Discoaster mohleri*, *Fasciculithus tympaniformis*, *F. involutus*, *Scapholithus rhombiformis*, *Sphenolithus anarrhopus*, *Toweius craticulatus* and *T. eminens*. The age is early Late Paleocene, and the assemblage is assignable to the *Discoaster mohleri* zone of Bukry (1973). This correlates with the foraminiferal early to mid P4 zone.

(B) An assemblage similar to that from DR13/1 was identified from a sample of white layered soft mud (DR13/M1a) which was collected from the mouth of the basket of the same dredge haul as sample DR13/1. In addition to the species listed from DR13/1, *Toweius tovae* and *Pontosphaera plana* were also identified from DR13/M1a. Moreover, Quaternary contaminants (such as species of *Gephyrocapsa* and *Ceratolithus*) were noted.

Remarks. A comparison between the assemblages from DR13/1 and DR13/M1a and coeval assemblages from the offshore South Perth Basin (recorded recently by Shafik *in* Marshall & others, 1989) indicates that surface waters were much warmer in the Rowley Sub-basin than in the South Perth Basin during the early Late Paleocene. The South Perth assemblages included much more abundant and diversified species of the genera *Chiasmolithus* and *Cruciplacolithus*, by far exceeding in abundance the *Discoaster mohleri*, and much fewer *Sphenolithus anarrhopus*. The genera *Chiasmolithus* and *Cruciplacolithus* are generally regarded as having preferred mid- to high-latitude surface water conditions, whereas the genera *Discoaster* and *Sphenolithus* seem to have thrived better in warmer surface waters.

Late Early or early Middle Miocene: *Sphenolithus heteromorphus* range interval

(A) A moderately well-preserved assemblage was extracted from a sample of white calcareous mud (DR04/1E) which was dredged from the Copperhead Canyon (Lat. 15°22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118°57.90') in waters 4200 to 3750 m deep. Dominant species are *Cyclicargolithus floridanus*, *Discoaster deflandrei* and *Sphenolithus heteromophus*. The associated species included *Helicosphaera kamptneri*, *H. recta*, *H. intermedia*, (slightly elliptical without central opening) *Calcidiscus leptoporus*, rare *C. macintyrei*, *Cyclicargolithus abisectus*, severely etched *Pontosphaera multipora*, *Discoaster variabilis*, rare *D.* sp. cf. *D. martinii*, frequent to common *D. formosus*, *D. exilis*, rare *D. moorei*, *Hayaster perplexus*, *Sphenolithus moriformis*, and *Coronocyclus nitescens*. The age is late Early to early Middle Miocene on the presence of the index species *Sphenolithus heteromorphus*.

To account for the presence of *Helicosphaera recta* and to a lesser extent

Cyclicargolithus abisectus, some reworking from Upper Oligocene source(s) is presumed to have occurred. Such a reworking would have contributed to the high abundance of *C. floridanus* and probably also *Discoaster deflandrei*.

(B) A fairly well-preserved assemblage was extracted from a sample of pale olive claystone (DR11/8) which was dredged from a northwest facing slope west of Mermaid Canyon (Lat. 16°25.10'- Long. 118°10.60' to Lat. 16°26.30' - Long. 118°11.85') where water depth ranges between 4000 and 3300 m. Dominant species are *Cyclicargolithus floridanus*, *Discoaster deflandrei* 'group' and *Sphenolithus heteromorphus*. Associated species included *Discoaster* sp. cf. *D. variabilis*, *D. exilis*, *Sphenolithus moriformis*, *Helicosphaera kamptneri*, *H. euphratis*, rare *H. obliqua*, *Coronocyclus nitescens*, *Coccolithus* sp. cf. *C. pelagicus*, rare (small, broadly elliptical with closed central opening) *Calcidiscus leptoporus*, slightly etched and rare *Pontosphaera multipora*, and *Hayaster perplexus*. At least one new species of *Discoaster* is present. The age is late Early to early Middle Miocene on account of the index species *Sphenolithus heteromorphus*.

Very scarce reworked specimens of the Cretaceous *Cretarhabdus surrirellus* were encountered.

(C) A sample of pale yellow soft chalk (DR11/M1b), collected from the top of the basket of the same dredge haul as sample DR11/8, yielded abundant nannofossils. Dominant species are *Sphenolithus heteromorphus*, *Cyclicargolithus floridanus*, *Discoaster deflandrei* and *D. variabilis*. Associated species include *Calcidiscus macintyrei*, *Discoaster exilis*, *D. moorei*, *Coronocyclus nitescens*, *Cornocyclus* sp., *Hayaster preplexus*, *Helicosphaera granulata*, *H. intermedia* and *Sphenolithus moriformis*. Dissolution seems to have severely affected the assemblage as indicated by the exceptionally high abundance of discoasters and sphenoliths. The age is late Early to early Middle Miocene on the presence of the index species *Sphenolithus heteromorphus*.

Middle Miocene: *Coccolithus miopelagicus* subzone

(A) An assemblage comprising several species was identified among abundant nannofossil debris from a sample of white chalk (DR04/5), which was dredged from the Copperhead Canyon (Lat. 15° 22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118°57.90') in water 4200 to 3750 m deep. The species *Reticulofenetra pseudoumbilica*, *Discoaster variabilis*, *D. deflandrei*, *Coccolithus miopelagicus*, *C.* sp. cf. *C. pelagicus* and *Sphenolithus abies* were noted for dominance. Associated species included *Helicosphaera kamptneri*, *H. californiana*, *Calcidiscus leptoporus*, *C. macintyrei*, *Triquetrorhabdus rugosus*, *Discoaster exilis*, *D. moorei*, *Reticulofenetra gelida*, and species of *Scyphosphaera*. The assemblage can be assigned to the Middle Miocene *Coccolithus miopelagicus* subzone of Bukry (1973).

(B) A slightly etched assemblage of nannofossils was extracted from a sample of light grey calcareous soft mud (DR13/M1b) which was obtained from the mouth of the basket of dredge haul DR13 (taken from a slope east of Mermaid Canyon, Lat. 16°29.36' - Long. 118°09.80' to Lat. 16°29.41' - Long. 118°10.62', water depth between 3480 and 3100 m). Dominant species are *Discoaster variabilis*, *D. exilis*, *Reticulofenestra pseudoumbilica*, *Sphenolithus abies* and *Coccolithus miopelagicus*. Associated species included *Calcidiscus leptoporus*, *C. macintyrei*, *Cyclicargolithus floridanus*, *Helicosphaera kamptneri*, *H. granulata*, *Discoaster signus*, *D.* sp. cf. *D. moorei*, *Coronocyclus nitescens*, rare *Pontosphaera multipora*, ?*Trique-*

trorhabdus milowii, *Coccolithus* sp. cf. *C. pelagicus*, *Emiliania annula* species of *Scyphosphaera* and *Scapholithus*. The assemblage is assignable to the Middle Eocene *Coccolithus miopelagicus* subzone of Bukry (1973).

Late Miocene: *Discoaster quinqueramus* range interval

(A) A sample of chalk which was collected from the pipe attached to dredge basket DR01 from the northern slope of Taipan Canyon (Lat. 15°01.92' - Long. 118°57.53' to Lat. 14°59.60' - Long. 118° 57.76' in water 3650 to 3800 m deep) yielded a rich nannofossil assemblage. Several *Discoaster* species including *D. brouweri*, *D. quinqueramus*, *D. decorus*, *D. pentaradiatus* and *D. berggrenii* and *D. variabilis* dominate the assemblage. Associated species included *Minylitha convalis*, *Triquetrorhabdus rugosus*, *Cacidiscus leptoporus*, *Helicosphaera kamptneri*, *Sphenolithus neoabies*, *Discoaster asymmetricus*, *D. challengeri* and a few species of *Scyphosphaera*. The assemblage is assigned to the *Discoaster berggrenii* subzone of Bukry (1973). This probably correlates with the foraminiferal zone late N17 or early N18 according to data in Martini (1971).

(B) A sample of pale brown soft plastic mud obtained from the top of the pipe dredge at station BMR95-DR004 (the Copperhead Canyon, Lat. 15°22.00' - Long. 118°58.90' to Lat. 15°22.50' - Long. 118° 57.90') where water depths range between 4200 and 3750 m, yielded a nannofossil assemblage containing the index species *Discoaster quinqueramus* and *D. berggrenii*. Other species included *Discoaster brouwerii*, *D. decorus*, *D. pentaradiatus*, *Hayaster perplexus*, *Minylitha convalis*, *Calcidiscus macintyrei*, *C. leptoporus*, *Helicosphaera kamptneri*, and species of *Sphenolithus*. The assemblage is assigned to the *Discoaster berggrenii* subzone of Bukry (1973). This probably correlates with the foraminiferal zone late N17 or early N18 according to data in Martini (1971).

Remarks

Species of the genus *Discoaster* are noted among the dominant elements of all the Miocene assemblages examined. This, together with similar abundance of other warm-water indicators (for instance, *Sphenolithus heteromorphus* in samples from the vicinity of Copperhead and Mermaid Canyons, see above), suggest warm surface-water conditions prevailing during the Miocene in the Rowley Sub-basin.

Mixed Miocene and Pliocene

(B) A fairly well-preserved assemblage was extracted from a sample of pale yellow calcareous mud (DR11/M1a) which was collected from the top of the basket. Dredging occurred on a slope west of the Mermaid Canyon (Lat. 16°25.10' - Long. 118°10.6' to Lat. 16° 26.30' - Long. 118°11.85') where water depth ranges between 4000 and 3300 m. The assemblage seems, however, to be an admixture of Miocene and Pliocene fossils. Discoasters are abundant and include rare *Discoaster asymmetricus*, rare *D. bellus*, *D. brouweri*, very rare *D. braardi*, *D. challengeri*, *D. neorectus*, *D. pansus*, *D. pentaradiatus*, *D.* sp. cf. *D. triradiatus* (the tips of the arms are bifurcated), and *D. variabilis*. Other nannofossil species include *Emiliania annula*, *Coccolithus dorincoides*, *Scyphosphaera*, *Minylitha convallis*, and rare *Holodiscus solidus*. Some reworked elements were encountered. These included frequent *Cyclicargolithus floridanus* and very rare *Watznaueria barnesae*. Notable is the absence of species of the genera *Amaurolithus* and *Ceratolithus*. Also absent is *Reticulofenestra pseudoumbilica* in spite of the presence of species of *Sphenolithus* (such as *S. abies* and *S. neoabies*) usually disappearing with *R. pseudoumbilica.*

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7.4 BMR Cruise 95 : Foraminiferal Biostratigraphy

David Lynch
Geology Department, The University of Western Australia, Nedlands, 6009

Dredge and core material obtained on BMR Cruise 95 includes Jurassic, Cretaceous and Neogene (Miocene, Pliocene and Pleistocene) foraminiferal faunas as follows: Rhaetian to Toarcian (DR06/5), Upper Toarcian (DR06/3), Callovian (DR07/8), Oxfordian (DR02/2), Callovian-Oxfordian (DR06/1), undifferentiated Jurassic (DR04/7, DR09/8), Early Cretaceous (DR04/1C, DR04/4), Late Campanian to Early Maastrichtian (DR04/1B), Paleocene (DR13/1 in part), mixed Miocene to Pleistocene (DR04/1A, DR04/5, DR11/M1, DR11/8, DR13/1 in part, DR13/M1a, DRM1b), Pleistocene to Holocene (DR01/PIPE, DR06/PIPE, DR08/PIPE A, DR08/PIPE B, DR12/PIPE B, DR13/PIPE, GRAVITY CORE 04/CC). Of the three gravity cores taken during the cruise, only Gravity Core 2 (273 cm recovered) was studied in detail. It contains Late Pliocene to Holocene foraminiferal faunas.

Shipboard studies of foraminifera were restricted to the microfaunas from lithologies which could be disaggregated easily by soaking in hydrogen peroxide or boiling. Such disaggregated samples were wet-sieved on a 63 μm screen. Strew slides of the >63 μm residues containing abundant foraminifera were made; residues containing only sparse foraminiferal faunas were picked for microfossils. A number of indurated calcareous lithologies were also sampled and thin sections made for post-cruise studies. Selected specimens have been photographed using a scanning electron microscope at the Electron Microscopy Centre, The University of Western Australia, and plates containing the illustrations are included in this report.

Jurassic

Diverse Jurassic foraminifera were recovered from rocks dredged during the cruise. The faunas observed can be assigned to the following ages.

- Triassic to Toarcian

Sample DR06/5 contained a very sparse foraminiferal fauna consisting of the following species.

Paralingulina tenera (Bornemann)
Verneuilinoides sp.

Paralingulina tenera (Bornemann) is known from Rhaetian to Toarcian sediments in Britain (Copestake & Johnson, 1989), and from Pliensbachian sediments in the Grand Banks area (Gradstein, 1978). Quilty (1981) illustrates similar forms which he has placed into *Geinitizina* from the Lower Jurassic of the Exmouth Plateau, Western Australia.

- Upper Toarcian

Sample DR06/3 contained a sparse, moderately preserved foraminiferal fauna consisting of :

Dentalina sp.
Lenticulina dorbignyi (Roemer)
Lenticulina muensteri (Roemer)

Lenticulina sp. A.

This sample is placed in the Upper Toarcian based on the stratigraphic distribution of *Lenticulina dorbignyi* (Roemer) which is known from Upper Toarcian sediments in the North West Shelf area (Apthorpe in: Copestake & Johnson, 1989).

- Bajocian to Callovian

Sample DR07/8 contains diverse and well preserved foraminifera consisting of :

Astacolus sp.
Citharina flabelloides (Terquem)
Dentalina sp.
Epistomina mosquensis Uhlig
Epistomina regularis Terquem
Frondicularia sp.
Lenticulina muensteri (Roemer)
?*Lenticulina* sp. B.
Reinholdella sp.

The concurrent occurrence of *Citharina flabelloides* (Terquem), *Epistomina mosquensis* Uhlig, and *Epistomina regularis* Terquem is consistent with a Bajocian to Callovian age based on the known ranges of these species as given by Gradstein (1978), Morris and Coleman (1989), and M. Apthorpe (pers. comm.). Morris and Coleman (1989) illustrate *Citharina flabellata* (Gümbel) which I regard as a synonym of *Citharina flabelloides* (Terquem). The diverse foraminiferal fauna suggest a fully marine shelf environment, with some fluvial activity in the vicinity of the site of deposition, as shown by the abundant mica seen in the sample.

- Oxfordian

Only one sample that can be placed as Oxfordian was dredged on the cruise. Sample DR02/2 is an olive brown, calcareous lithicarenite with common foraminifera, rare bivalve fragments, internal moulds of a small, high-spired gastropod, unornamented ostracods and echinoid spines. This sample also contained crinoid ossicles which have been tentatively identified as belonging to *Pentacrinites*, and rare fish teeth. An interesting component of this sample is the abundance of double pyramidal quartz crystals previously described from a similar Late Jurassic lithology by Quilty (1990). The crystals contain a variety of inclusions with carbonate and an amorphous substance (?clay) being the most common. A number of prismatic inclusions suspected as being heavy minerals were also noted. The foraminiferal fauna are generally well preserved with only moderate test recrystallization apparent, and is dominated by *Trocholina nodulosa* Seibold & Seibold (over 80%). The other foraminifera noted in the assemblage are listed below.

Ammobaculites agglutians (d'Orbigny)
Ammodiscus sp.
Enantiodentalina sp.
Eoguttulina sp. A.
Lenticulina sp. aff. *wisniowski* (Myatliuk)
?*Opthalmidium* sp.
Planularia spp.
?*Spirillina* sp.
Turrispirrilina sp. (sp. B of Quilty (1990))

The similarities in faunal composition and lithology of this sample to Lithology 1 described in Exon and Williamson (1988) and Quilty (1990) as Callovian suggest that this sample is of similar age. The sample designated as Lithology 1 in Quilty (1990) contains an abundance of *Trocholina conica* (Schlumberger) but the form seen in sample DR02/2 fits the original descriptions of *Trocholina nodulosa* Seibold & Seibold (Seibold & Seibold, 1960). The presence of *Trocholina nodulosa* Seibold & Seibold indicates an Oxfordian age based on the known stratigraphic range of that species in Europe (Shipp, 1989).

The dominance of one species indicates that this sample accumulated in a shallow marine environment, and in moderate to high energy conditions as shown by the coarseness and sorting characteristics of the sediment.

- Other Jurassic material

Two samples contained sparse foraminiferal assemblages of Jurassic character, but lacked age diagnostic forms which would have enabled a more accurate age determination. These samples belong to Lithofacies A which is a brown to grey, variably carbonaceous, micaeous sandy mudstone deposited in a low to moderate energy, pro-delta environment. The composition of the foraminiferal assemblages from each of these samples is listed below.

DR04/7 - *Astacolus* sp., *Dentalina* sp., *Eoguttulina* sp. A., and *Lenticulina muensteri* (Roemer). *Lenticulina muensteri* (Roemer) is a wide-ranging form known throughout Jurassic sediments in Europe (Copestake & Johnson, 1989; Morris & Coleman, 1989; Shipp, 1989).

DR06/1 - *Astacolus* sp., *Dentalina* sp., *Lenticulina muensteri* (Roemer).

DR09/8 - *Eoguttulina* sp.A., and *Lenticulina muensteri* (Roemer).

Cretaceous

All samples assigned to the Cretaceous were obtained from the Copperhead Canyon region in Dredge 4. Samples DR04/1C and DR04/4 do not contain planktonic foraminifera, but contain an abundant and well-preserved benthonic foraminiferal assemblage of Early Cretaceous (pre-Aptian) affinity including :

Astacolus sp.
Dentalina spp.
Dentalinoides sp.
Frondicularia spp.
Guttulina sp.
Lenticulina spp.
Lingulina loryi (Berthelin)
Marginulina sp.
Marginulopsis sp.
Planularia sp.
Lingulonodosaria sp.

The absence of rotaliids and globigerinids, which did not become common until Aptian times, suggests that the sample is of earliest Cretaceous age. Calcareous nannoplankton derived from these samples also indicate an Early Cretaceous age (see section on calcareous nannoplankton biostratigraphy). These samples were deposited in fully marine conditions in an open shelf environment at no greater than middle neritic depths.

Sample DR04/1B is a white foraminiferal/calcareous nannoplankton chalk containing abundant planktonic foraminifera and calcite prisms derived from the pelecypod *Inoceramus*. The foraminiferal assemblage is dominated by *Rugoglobigerina milamensis* Smith & Pessagno, and *Rugoglobigerina rugosa* (Plummer) which make up approximately 80% of the foraminiferal assemblage. Benthonic foraminifera are very rare in the sample with only a few specimens of *Gaudryina*, *Pyramidina*, and *Anomalinoides* seen in the sample. Planktonic foraminifera of Late Campanian to Early Maastrichtian affinity, noted from the sample, include :

Globotruncana arca (Cushman)
Globotruncana fornicata (Plummer)
Globotruncana linneiana (d'Orbigny)
Globotruncana sp. aff. *ventricosa* White
Gublerina sp. aff. *cuvillieri* Kikoine
Hedbergella sp.
Pseudotextularia elegans (Rzehak)
Rugoglobigerina milamensis Smith & Pessagno
Rugoglobigerina rugosa (Plummer)
Ventilabrella glabrata Cushman
Whiteinella sp.

The predominance of *Rugoglobigerina* and the low proportion of keeled forms (ie. *Globotruncana*) suggest a cold water influence on the foraminiferal assemblage at this time. The characteristics of the foraminiferal assemblage indicate that the sample accumulated in upper bathyal depths.

Sample DR13/1 also contains rare *Rugoglobigerina* spp. mixed with Paleogene and Neogene foraminiferal faunas.

Paleogene

Only one sample (DR13/1) contains Paleogene foraminifera. These are mixed with foraminifera of Early Miocene to Pleistocene age. The planktonic fauna include *Acarinina mckannai* (White), *Acarinina* sp., *Morozovella conicotruncata* (Subbotina), *Morozovella* sp., and *Planorotalites pseudomenardii* (Bolli). The presence of *Planorotalites pseudomenardii* (Bolli) indicates a P4 age for the assemblage using the zonation scheme of Blow (1969) as set out in Toumarkine & Luterbacher (1985).

Neogene

The majority of samples that contain foraminifera are of Neogene age and were seen to be of two lithotypes as follows: (a) white or greenish white muds and chalks of Middle Miocene to Late Pliocene age, and (b) brown muds of Pleistocene to Holocene age. In many of the samples, mixing of faunas has occurred through either downslope movement prior to dredging and/or to mixing during the dredging process. This led to some difficulties when comparing the described faunas with the known ranges of some species in order to provide accurate age determinations.

Dissolution of foraminifera varies according to age and the depth from which the sample was dredged. The Miocene foraminifera recovered in Dredges 4 & 11 are less well preserved than Pleistocene and Holocene representatives of the same species.

For this report, the tropical planktonic foraminiferal N-zone classification as set out in Kennett & Srinivisan (1983) is used, and shown here in the Figure. The base of the Quaternary is defined in this report by the first appearance of *Globorotalia (Truncorotalia) truncatulinoides* (d'Orbigny). No further subdivision of the Pleistocene was attempted.

- Oligocene to Holocene Mixed Foraminiferal Faunas

Samples DR04/1A, DR04/5, DR11/M1, DR11/8, DR13/1, DR13/M1a and DR13/M1b were found to contain mixed foraminiferal faunas of generally Miocene to Holocene age (Table A). DR13/1 also contained Late Cretaceous and Paleocene faunas, and samples DR13/M1a and DR13/M1b contained foraminifera of ?Oligocene age (eg. *Catapsydrax* spp.). The mixing of the assemblages was discerned by examining: a) the composition of the assemblage and determining the presence of foraminifera which are known not to have overlapping stratigraphic distributions; b) abundances of certain foraminifera (eg. *Globoquadrina dehiscens* (Chapman, Parr & Collins) ranges throughout the Miocene but is most abundant in the Early and Middle Miocene); c) differing preservation of taxa.

The ages of each foraminiferal assemblage within the samples is given below with the important index species found in the sample for each age shown in brackets.

DR04/1A - Early to Middle Miocene [abundant *G. dehiscens* (Chapman, Parr & Collins)] and Late Pliocene to Holocene.

DR04/5 - Late Miocene to Early Pliocene [*G. (Z.) apertura* Cushman].

DR11/M1 - latest Early to earliest Middle Miocene [*Praeorbulina* sp.], Early to Middle Miocene [*G. dehiscens* (Chapman, Parr & Collins)], Late Miocene [*G. (Z.) nepenthes* Todd; *G. (G.) merotumida* Blow & Banner], and Pliocene to Holocene.

DR11/8 - Early to Middle Miocene [*G. dehiscens* (Chapman, Parr & Collins)], Late Miocene [*G. (Z.) apertura* Cushman; *G. (Z.) nepenthes* Todd; *G. (G.) plesiotumida* Blow & Banner] and Pliocene to Holocene.

DR13/1 - Miocene-Pliocene [*Dentoglobigerina altispira altispira* Cushman & Jarvis], and Pliocene to Holocene.

DR13/M1a and DR13/M1b - Late Oligocene to Early Miocene [*Catapsydrax* sp.], latest Early to earliest Middle Miocene [*G. sicanus* De Stefani; *Praeorbulina* sp.], early Middle Miocene [*G. (F.) peripheroacuta* Blow & Banner; *G. (J.) mayeri* Cushman & Ellisor; *G. dehiscens* (Chapman, Parr & Collins)], Middle Miocene to Pliocene [*G. (Z.) nepenthes* Todd], and Pliocene to Holocene.

- Gravity Core 2 - Late Pliocene to Pleistocene

Gravity Core 2 (Table 2) consisted of 273 cm of brown, pink, yellow and white foraminiferal muds and oozes ranging from Late Pliocene to Pleistocene. The interval from 50-250 cm was found to be younger than Late Pliocene (N21) but did not contain the Pleistocene index foraminifera *Globorotalia (Truncorotalia) truncatulinoides* (d'Orbigny). Calcareous nannoplankton studies showed that Pleistocene nannofossils first appeared in the 200-250 cm interval (see calcareous nannoplankton biostratigraphy). It would appear therefore that during the early Pleistocene interval, oceanographic influences may have excluded *Globorotalia (Truncorotalia) truncatulinoides* (d'Orbigny) from the water column. It is during this interval that *Globorotalia (Globoconella) inflata* d'Orbigny (a cold water form) is most common, and *Globorotalia (Menardella) menardii* (Parker, Jones & Brady), a warm water form, is least abundant, which suggest that water temperatures were cooler. From 50 cm to the top of the core the opposite occurs, suggesting a warming of the water column.

- Pleistocene

Pleistocene sediments examined during the cruise are confined to the brown muds dredged by the pipe dredge (Table C), the upper 50 cm of Gravity Core 02 (Table B), and the Core Catcher sample in Gravity Core 04 consisting of a white, plastic mud (Table C). These muds contain an abundant and well-preserved foraminiferal assemblage with similar benthonic foraminifera to those encountered in Pliocene sediments. The planktonic foraminiferal assemblage in these samples (excepting DR12/PIPE B and GC04/CC) is characterized by :

Candeina nitida d'Orbigny
Globigerina (Globigerina) bulloides d'Orbigny
Globigerinella aequilateralis (Brady) or *Globigerinella obesa* (Bolli)
Globigerinella calida (Parker)
Globigerinoides conglobatus (Brady)
Globigerinoides ruber (d'Orbigny) [many specimens are coloured pink]
Globigerinoides sacculifer (Brady)
Globigerinita glutinata (Egger)
Globorotalia (Globoconella) inflata d'Orbigny
Globorotalia (Globorotalia) tumida tumida (Brady)
Globorotalia (Globorotalia) ungulata Bermúdez
Globorotalia (Hirsutella) scitula (Brady)
Globorotalia (Menardella) menardii (Parker, Jones & Brady)
Globorotalia (Truncorotalia) truncatulinoides (d'Orbigny)
Globorotaloides hexagona (Natland)
Neogloboquadrina dutertrei (d'Orbigny)
Orbulina universa d'Orbigny
Pullentiatina obliquiloculata (Parker & Jones)
Sphaeroidinella dehiscens (Parker & Jones)

Sample GC04/CC was sampled from the offshore Perth Basin and contains abundant *Globorotalia (Globoconella) inflata* d'Orbigny, which is most abundant in cooler water masses. This sample also differs from those listed above because it lacks *Pulleniatina* and *Sphaeroidinella*.

Sample DR12/PIPE B is heavily affected by dissolution, which has selectively removed the thinner-walled specimens from the assemblage.

- Other Neogene Sediments

Sample DR03/3 contained an abundant and diverse radiolarian assemblage of Neogene (possibly Late Miocene or younger) aspect.

Samples lacking foraminifera

A number of samples processed and examined during the cruise failed to yield foraminifera. These samples are: DR01/1A, DR01/1B, DR01/1C, DR01/5, DR01/8, DR04/1D, DR04/1E, DR04/2, DR04/3, DR04/6, DR04/8,

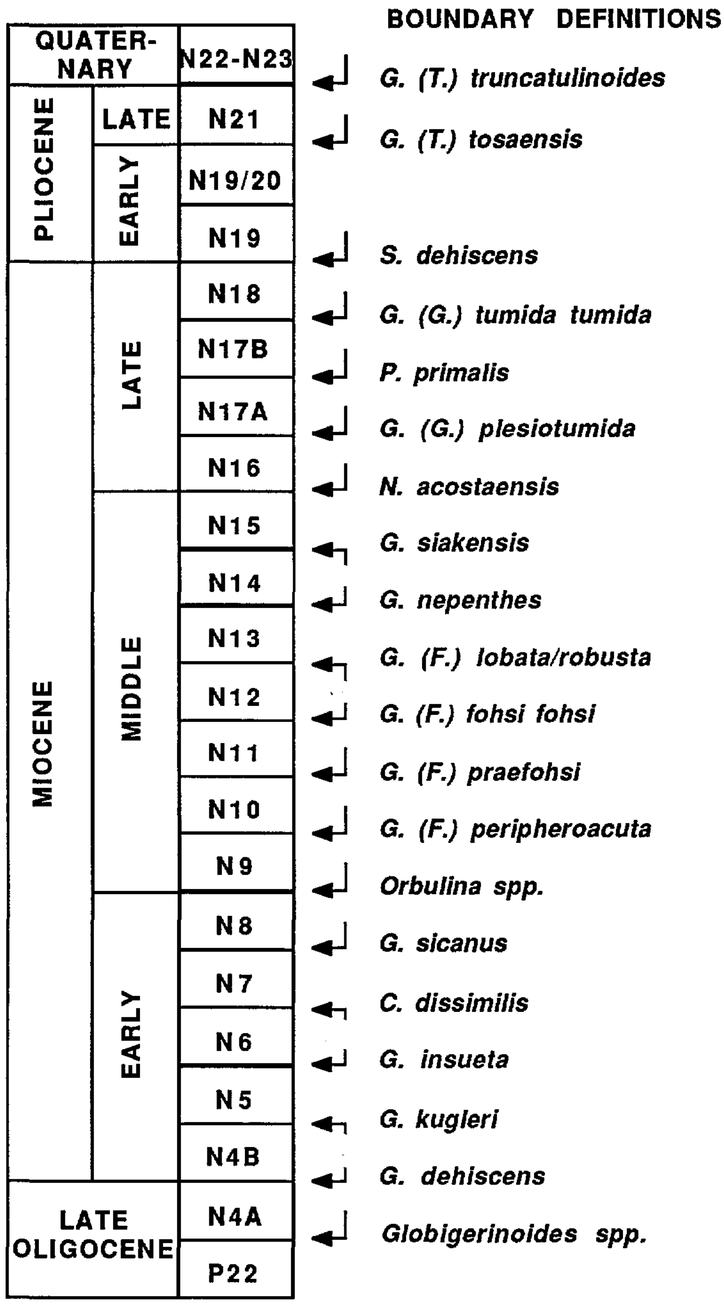


FIGURE Tropical Neogene zonation used in this report (after Kennet and Srinivisan 1983).
[↵ - first appearance, ↰ - last appearance]

Table A. Samples containing mixed foraminiferal faunas encountered on BMR Cruise 95.

Planktonic foraminifera species	Strat. Range	DR04/1A	DR04/5	DR11/M1	DR11/8	DR13/01	DR13/M1a	DR13/M1b
Rugoglobigerina spp.	Late Cret.					x		
Acarinina mckannai	P3B-P5					x		
Acarinina sp.						x		
Morozovella conicotruncata	P3-P4					x		
Morozovella sp.						x		
Planorotalites pseudomenardii	P4					x		
Catapsydrax sp.	Olig-N6					x	x	
Dentoglobigerina altispira altispira	N4B - N19/20	x		x	x	x	x	x
Globigerina (Globigerina) bulloides	N9 - Recent					x	x	
Globigerina (Zeoglob.) apertura	N16 - N19/20		x		x			
G. (Z.) nepenthes	N14 - N19/20	x		x	x		x	x
Globigerinoides conglobatus	N18 - Recent	x				x	x	x
G. immaturus	N5 - Recent				x			
G. quadrilobatus	N5 - Recent			x	x	x		
G. sacculifer	N5 - Recent	x		x	x	x		
G. sicanus	N7- N9						x	x
G. triloba	N4B - Recent				x		x	x
Globoquadrina dehiscens	N4B - N18	x		x	x		x	x
G. venezuelana	Olig. - N19	x	x	x	x			
Globorotalia (Fohsella) peripheroacuta	N10 - N11						x	x
G. (Globorotalia) merotumida	N16 - N18			x				
G. (G.) plesiotumida	N16 - N19				x			
G. (G.) tumida tumida	N18 - Recent	x		x	x	x	x	x
G. (Hirsutella) scitula	N9 - Recent			x		x		
G. (Jenkinsella) mayeri	N4A - N14						x	x
G. (Menardella) menardii	N12 - Recent			x	x	x	x	
G. (Truncorotalia) crassaformis	N19/20 - Rec.					x		
Neogloboquadrina pachyderma	N16 - Recent							x
N. humerosa	N18 - N22			x	x	x	x	x
Orbulina universa / suteralis	N9 - Recent	x	x	x	x			
Praeorbulina sp.	N8 - N9			x			x	
Pullentiatina praecursor	N19 - N21							
P. primalis	N17B - N19/20					x		
P. obliquiloculata	N19/20 - Rec.			x	x	x		
Sphaeroidinella dehiscens	N19 - Recent	x				x		
S. seminulina seminulina	N7 - N21	x	x	x	x		x	x

Table B Planktonic foraminiferal distribution observed in BMR 95 Gravity Core 2
(Samples positions are stated in centimetres from top of core, CC= core catcher)

Planktonic foraminifera species	CC	250	200	150	60	50	0
Bolliella adamsi					v.r		v.r
Globigerinella aequilateralis			r		r	r	r
G. calida		r			v.r	r	r
G. obesa	r			r	r	r	r
Globigerina (Globigerina) bulloides	r	v.r	r		r	r	r
G. (G.) falconensis		r	r	r	r		
Globigerinita glutinata		v.r	r		v.r		r
Globigerinoides conglobatus		r	r		r	r	c
G. quadrilobatus	r		r	r	r		r
G. ruber	r		r		r	r-c	c
G. sacculifer	r-c		r	v.r	v.r	r	c
G. triloba	r	v.r	v.r	v.r	v.r		
Globoquadrina conglomerata						r	r
Globorotalia (Globoconella) inflata		r	v.r	r	r	v.r	
G. (Globorotalia) tumida tumida	c-a	c	c	c	c	c	c
G. (G.) ungulata			v.r	v.r	v.r	r-c	r
G. (Hirsutella) hirsuta							v.r
G. (H.) scitula	r	v.r		v.r	r	r	r
G. (H.) theyeri					v.r		v.r
G. (Menardella) menardii	r	r	v.r	v.r	r	c	c
? G. (M.) multicamerata	v.r						
G. (Truncorotalia) crassaformis	r	r	r	r	r	r	
G. (T.) tosaensis			r	r	r		
G. (T.) truncatulinoides						c	c
Globorotaloides hexagona		r	r		r	r	r
Neogloboquadrina pachyderma	v.r	v.r		r	r	v.r	
N. humerosa	r	v.r	r	v.r	r		
N. dutertrei						r	r
Orbulina universa	a	c-a	c	v.r	r-c	r	r-c
Pullentiatina praecursor	v.r						
P. obliquiloculata	r	r	c	r-c	c	c	c
Sphaeroidinella dehiscens	a	c	a	a	c	r	r
	N21	Pleistocene to Holocene					

Table C Distribution of planktonic foraminifera observed in Quaternary sediments.

Planktonic foraminifera species	DR1/P	DR6/P	DR8/PA	DR8/PB	DR12/PB	DR13/P	GC4/CC
Bolliella adamsi		x				x	
Candeina nitida		x	x			x	
Clavatorella sp.		x	x			x	
Globigerina (Globigerina) bulloides	x	x	x	x		x	x
Globigerina (Zeoglob.) falconesis		x				x	
Globigerinella aequilateralis	x	x	x	x		x	
G. calida	x	x	x	x		x	
G. obesa		x					x
Globigerinoides conglobatus	x	x	x	x	x	x	
G. quadrilobatus	x	x	x	x	x	x	x
G. ruber	x	x	x	x			x
G. sacculifer	x	x	x	x		x	x
G. triloba	x					x	x
Globoquadrina conglomerata		x		x		x	
Globorotalia (Globoconella) inflata	x		x	x	x	x	x
G. (Globorotalia) tumida tumida	x	x	x	x	x	x	x
G. (G.) ungulata	x	x	x	x		x	
G. (Hirsutella) hirsuta							x
G. (H.) scitula	x	x	x	x		x	x
G. (H.) theyeri			x			x	
G. (Menardella) menardii	x	x	x	x	x	x	
G. (Truncorotalia) crassaformis	x	x	x	x		x	
G. (T.) tosaensis	x		x		x	x	x
G. (T.) truncatulinoides	x	x	x	x	x	x	x
Globorotaloides hexagona	x	x	x	x		x	
Neogloboquadrina dutertrei	x	x	x	x		x	x
N. pachyderma	x	x		x	x		x
Orbulina universa	x	x	x	x		x	x
P. obliquiloculata	x	x	x	x	x	x	x
Sphaeroidinella dehiscens	x	x		x	x	x	

PLATE 1

1. *Ammodiscus* sp. [DR 02/2]	x160
2. ?*Spirillina* sp. [DR02/2]	x160
3. *Trocholina nodulosa* Seibold & Seibold [DR 02/2]	x155
4. *Trocholina nodulosa* Seibold & Seibold [DR 02/2]	x165
5. *Verneulinoides* sp. [DR 02/2]	x245
6. *Paralingulina tenera* (Bornemann) [DR 02/2]	x240
7. *Citharina* sp. [DR 07/8]	x52
8. *Citharina flabelloides* (Terquem) [DR 07/8]	x52
9. *Frondicularia* sp. [DR 07/8]	x115
10. *Eoguttulina* sp. A [DR 04/7]	x115
11. *Lenticulina* sp. B. [DR07/8]	x90
12. *Lenticulina dorbignyi* (Roemer) [DR 07/8]	x165
13. *Lenticulina* sp. A. [DR 06/3]	x105
14. *Astacolus* sp. [DR 07/8]	x120
15. *Lenticulina muensteri* (Roemer) [DR 07/8]	x50
16. *Reinholdella* sp. [DR 07/8] spiral view.	x185
17. *Reinholdella* sp. [DR 07/8] apertural view.	x150
18. *Epistomina regularis* Terquem [DR 07/8] umbilical view	x65
19. *Epistomina mosquensis* Uhlig [DR 07/8] umbilical view	x100

PLATE 1

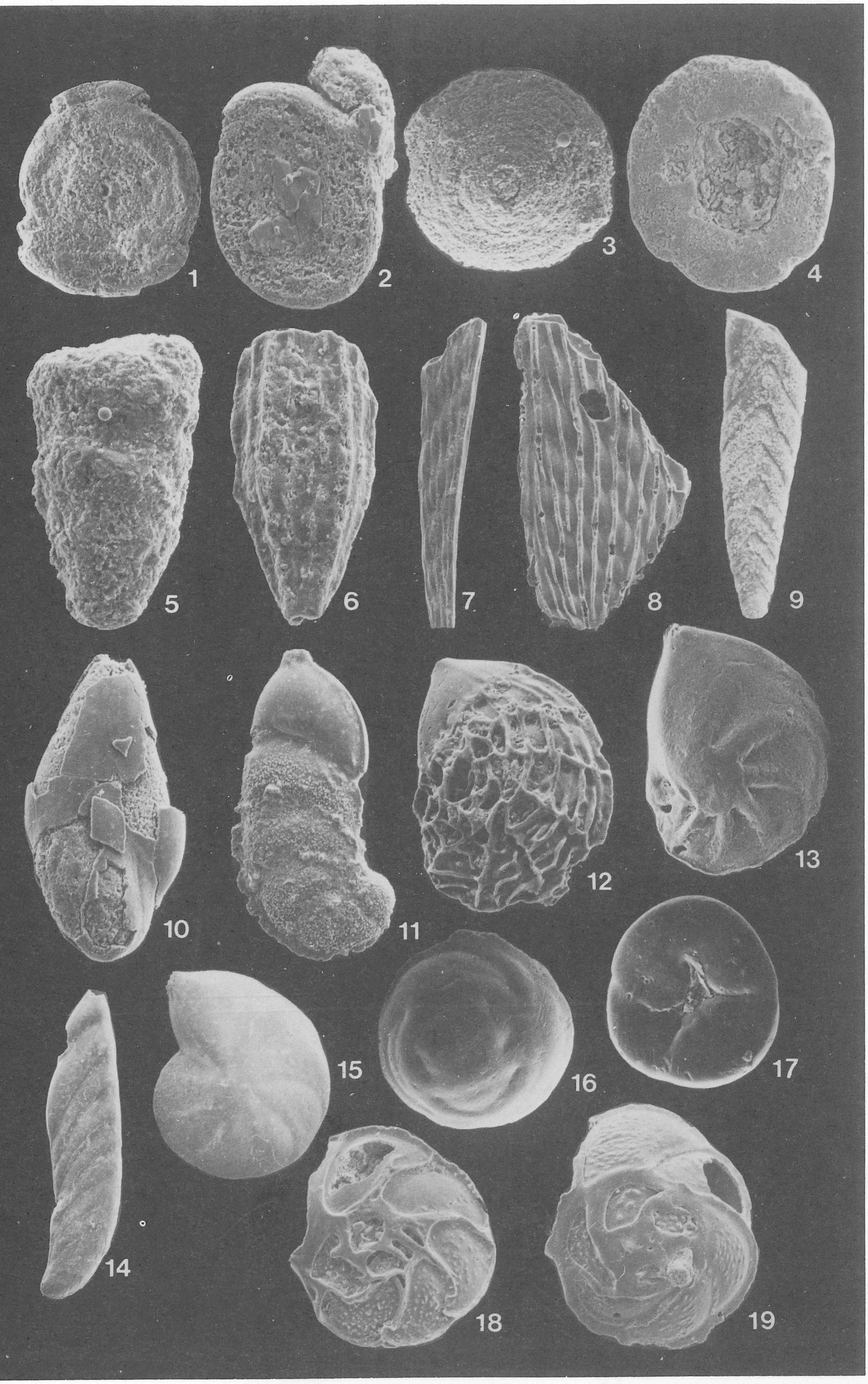


PLATE 2

1. *Rugoglobigerina milamensis* Smith & Pessagno [DR04/1B] spiral view. x115

2. *Gublerina cuvillieri* Kikoine, juvenile form [DR04/1B] x155

3. *Globotruncana arca* (Cushman) [DR04/1B] spiral view. x95

4. *Globotruncana ventricosa* White [DR04/1B] peripheral view. x85

5. *Rugoglobigerina milamensis* Smith & Pessagno [DR04/1B] side view. x135

6. *Dentoglobigerina altispira altispira* (Cushman & Jarvis) [DR04/1A] apertural view. x115

7. *Globigerinella aequilateralis* (Brady) [DR13/PIPE] peripheral view. x85

8. *Orbulina universa* d'Orbigny [DR13/PIPE] x85

9. *Sphaeroidinellopsis seminulina seminulina* (Schwager) [DR04/1A] spiral view. x90

10. *Sphaeroidinella dehiscens* (Parker & Jones) [DR13/PIPE] x95

11. *Pulleniatina obliquiloculata* (Parker & Jones) [DR13/PIPE] peripheral view. x95

12. *Globigerinoides sacculifer* (Brady) [DR13/PIPE] spiral view. x75

13. *Globorotalia (Hirsutella) scitula* (Brady) [DR13/PIPE] spiral view. x90

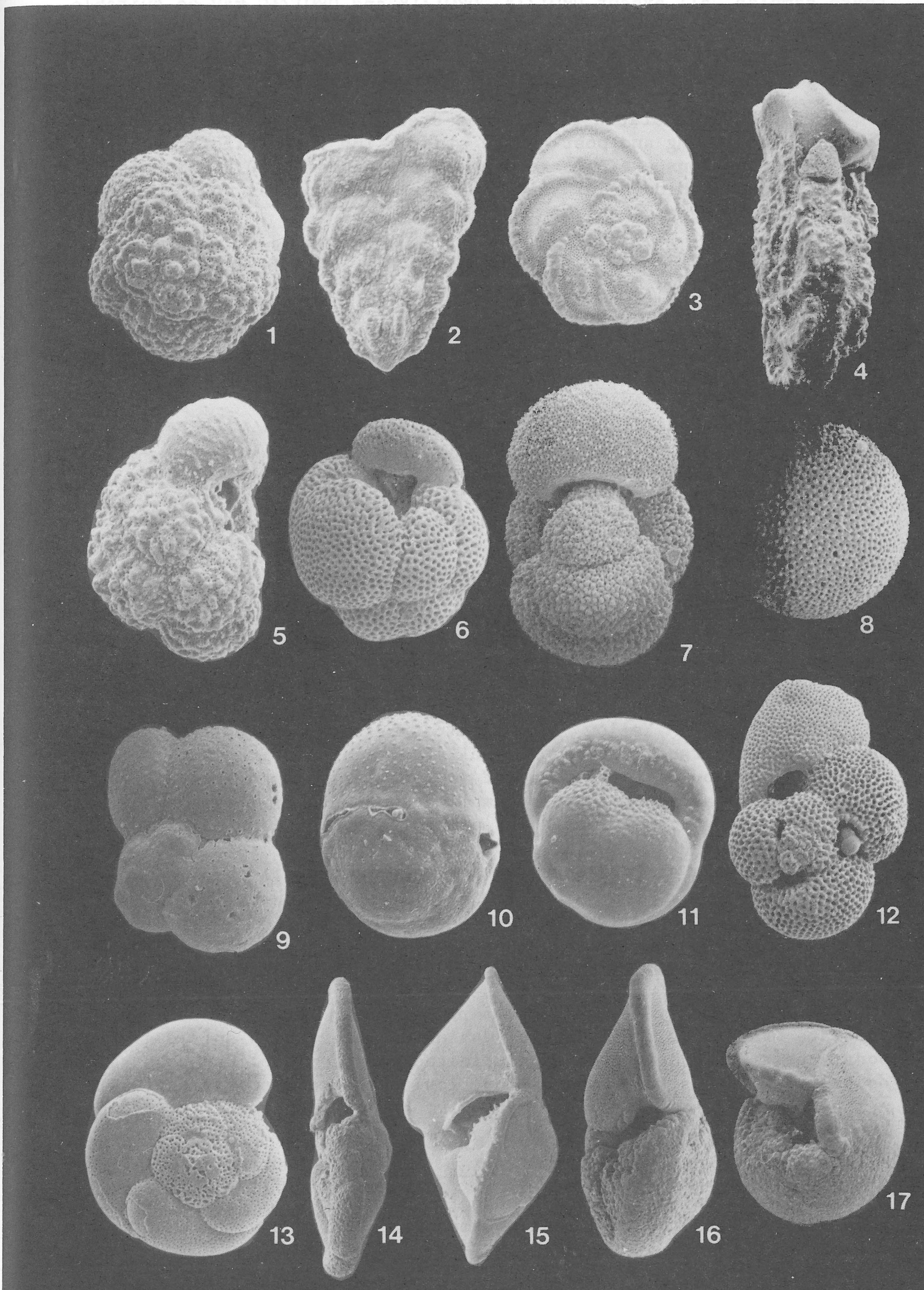
14. *Globorotalia (Menardella) menardii* (Parker, Jones & Brady) [DR13/PIPE] peripheral view. x52

15. *Globorotalia (Globorotalia) ungulata* Bermúdez [DR13/PIPE] peripheral view. x120

16. *Globorotalia (Globorotalia) tumida tumida* (Brady) [DR13/PIPE] peripheral view. x70

17. *Globorotalia (Truncorotalia) truncatulinoides* (d'Orbigny) [DR13/PIPE] peripheral view. x62

PLATE 2



DR04/10, DR04/17, DR05/7, DR07/4, DR07/9, DR07/11, DR07/13, DR07/14, DR08/3, DR09/4, DR11/3A, DR11/4, DR11/5, DR11/6, and DR12/PIPE A. Of these samples, all except DR01/1A, DR01/1B and DR01/1C may be suitable for palynological studies.

Thin section descriptions

A number of indurated lithologies dredged on the cruise were sampled for thin sectioning and post-cruise study. The foraminifera seen in these thin sections are not age diagnostic, except DR10/8 which is tentatively placed as Middle Jurassic, and therefore no ages could be assigned to these lithologies.

Sample DR07/12 - Two differing lithologies were sampled and described as follows :

Light to dark grey, crinoidal packstone and mudstone with common subangular to subrounded, fine quartz grains and minor glauconite. Very rare foraminifera (non-coiled nodosariids) occur in the sample.

Light grey ooid grainstone with sparry calcite cement, with rare foraminifera (non-coiled nodosariids), shelly fragments and echinoid plates. This sample accumulated in a near shore, high energy environment.

Sample DR07/15 - Dark grey to black mudstone, with large colonial hexacorals deposited under low energy conditions.

Sample DR09/6B - This sample consists of two rock types: a dark yellowish-brown calcarenite with common brachiopod and echinoid fragments and rare calcareous algae; and secondly a ferruginized analogue of the first type with some lithic fragments of volcanic origin. Both types have been heavily recrystallized.

Sample DR09/8 - Yellow, fine to medium grained ooid grainstone with calcite cement, rare gastropods, shelly and echinoid fragments. The centre of many ooids is composed of sub-angular to angular quartz, shell fragments and gastropods. This sample accumulated in very shallow water under high energy conditions. The precipitation of carbonate sediments of this type suggests that arid onshore conditions prevailed, as shown by the small amounts of terigenous matter seen in the slide.

Sample DR10/6 - Yellow to brown calcarenite with common calcareous clasts, large bivalve shells, algal and echinoid fragments. This sample was deposited in shallow water under moderate to high energy conditions.

Sample DR10/8 - Grey calcareous packstone and mudstone containing punctate brachiopod shell debris, echinoid plates, high-spired gastropods, and rare foraminifera (agglutinated forms, miliolids and straight nodosariids) deposited in a shallow, low to moderate energy environment. A single specimen of *?Cylindrotrocholina* sp. was observed, suggesting a Middle Jurassic age.

Sample DR12/9 - Pale yellow, recrystallized, fine to coarse calcarenite with bivalve, brachiopod, echinoid, calcareous algae and rare bryzoan clasts deposited in a shallow, moderate energy environment.

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8. EXMOUTH PLATEAU REGIONAL SEISMIC STUDY

The Exmouth Plateau is generally much better surveyed than the offshore Canning Basin, with the best data set being the GSI WA S76 survey, dealt with in Appendix A. However, there was a need for key, high-quality tie lines to link the ODP Sites and dredge stations of the Wombat Plateau with the nearest well, Woodside Delambre No 1, and to link the northern Exmouth Plateau data set to the offshore Canning Basin at Shell East Mermaid No 1 well. As the program developed we realised that there were excellent seismic indications that Jurassic carbonate buildups existed in this area, and they are treated separately below.

8.1 Geophysical Survey Lines

The multichannel seismic profiles shown in Figure 37 were recorded using the same system as were the Canning Basin lines. In general, weather conditions were good and data collection went ahead smoothly. The two key profiles are 95/13-14 from East Mermaid No 1 well along a generally high feature, the North Exmouth Hinge Zone, which ties the northern end of the GSI data set, and 95/19 from Delambre No 1 well to ODP Site 764. Lines 95/16-18 were designed to further investigate the suspected Jurassic carbonate buildups visible on BMR profile 56/13 (Fig. 41). The three regional BMR profiles 95/13-14, 95/18, and 95/19 are dealt with here, and profiles showing suspected carbonate buildups are dealt with later.

BMR Profile 95/14 (parts 3 & 4, from 138.1600 to 139.1400) transects the northwestern part of the Exmouth Plateau near the North Exmouth Hinge Zone, and shows what could be regarded as a typical Exmouth Plateau sequence. We see dipping and folded Triassic and Early to Middle Jurassic rocks cut by numerous normal faults, giving rise to a complex of northeast trending horsts and grabens which terminate either at the Triassic horizon (F), or the top Jurassic (E) and sometimes base Cretaceous horizon (C), with the E or C horizons draping over the fault blocks (Fig. 38). A variable thickness of Cretaceous and post-Cretaceous sediment overlies the Mesozoic sequence.

Several of the fault blocks between 139.1000 and 139.1200 show what are interpreted to be Jurassic carbonate buildups on top of the blocks, draped by the Jurassic (E) horizon. The doming of the sequence on profile 95/14 at 139.0500 and 139.1100 could be a compressional feature related to strike slip movement. The same feature is also seen on BMR profile 95/18 and GSI line WA S76-34.

BMR Profile 95/18 provides a tie between profile 95/14 near the North Exmouth Hinge Zone and Delambre No 1 well, and also cuts across several of the 1976 GSI regional seismic lines discussed in Appendix A. The profile shows a complex series of horsts and grabens containing Triassic and Jurassic sediments (Fig. 39). Most of the faults terminate at either the Triassic horizon (F) or the Jurassic horizon (E).

From a point at about 140.0430 on the profile, the Jurassic sequence dips gently to the northwest with a uniform thickness of about 1700 m, the top Triassic horizon (F) lying at about 3.8 secs (TWT). The underlying Triassic section cannot be picked from this part of the section. Towards the margin of the Exmouth Plateau, between 139.2200 and 140.0430 on profile 95/18, block faulting becomes more intense, with the top Triassic marker rising to about 3.0 secs (TWT), and the overlying Jurassic section being reduced to probably less than 500 m. The Triassic and Jurassic sections on this part of the profile are gently folded in part, and doming occurs between 139.2300 and 140.0000, similar to that seen on BMR profile 95/14 at about the same location.

A number of carbonate buildups have been interpreted to occur on the section between 139.2200 and 140.0500. These features all sit on top of faulted blocks overlying the Triassic (F) horizon, and are draped by either the E or C horizon. Figure 44 shows a diagrammatic interpretation of part of GSI line WA S76-33, with similar possible carbonate buildups at the same stratigraphic position as those identified on BMR profiles 95/14 and 95/18.

Overlying the faulted Mesozoic section is a Cretaceous marine carbonate transgressive sequence of near constant thickness (sequence B-C), which in turn is overlain by a prograding wedge of Paleogene (A-B) and

Neogene (seabed-A) sediment that thins rapidly towards the plateau margin.

BMR profile 95/19 extends northward 260 km from Woodside Delambre No 1, across the outer North West Shelf, down from the North Exmouth Hinge Zone into the Wombat Half-graben and up onto the Wombat Plateau (Figs. 5 & 40). The monitor record shows the sequence down to and below the "Main Unconformity" E, of Callovian age. The Neogene carbonate sequence (seabed-C) consists of claystone and calcilutite in Delambre No 1 and nannofossil ooze in the ODP sites. It forms a well-bedded, northerly prograding wedge up to 1000 m thick on the North West Shelf, but is generally much thinner and more poorly bedded elsewhere.

The Paleogene sequence (A-B) consists of calcilutite and calcisiltite in Delambre No 1 and nanno chalk grading to ooze at the ODP sites. It is well-bedded and parallel bedded, and up to 300 m thick on the North West Shelf, but more disturbed and thinner elsewhere. The Late Cretaceous sequence (B-C) consists of marl and calcilutite in Delambre No 1, and of chalk at the ODP sites. It is well-bedded with small-scale diffractions on the North West Shelf where it is up to 300 m thick, and more disturbed and thinner elewhere. The C unconformity is a major regional feature, which is almost planar on the Wombat Plateau where it immediately overlies the top Triassic unconformity.

The C-E sequence consists entirely of Early Cretaceous claystone and marl in Delambre No 1, and a very thin transgressive marine sand sitting on Triassic rocks and grading rapidly upward to chalk in ODP Site 761. It is very variable in thickness even on the North West Shelf, where it reaches a maximum of 300 m. It is generally well-bedded, but drapes into depressions between Triassic horst blocks. In places it onlaps presumed carbonate buildups which first formed in the E-F sequence.

The Early and Middle Jurassic (E-F) sequence consists of shallow marine sandstone, siltstone, claystone and a little limestone in Delambre No 1 well, and is absent along this line on the Wombat Plateau. Dredging elsewhere on the northern Exmouth Plateau margin shows it to consist of paralic detrital sediments and shelf carbonates. This well-bedded sequence is about 900 m thick in Delambre No 1 well, and probably thickens further northward in depressions in the Triassic surface. It is heavily faulted at and beyond the North Exmouth Hinge Zone. It is host to large presumed carbonate buildups, extending intermittently 100 km northward from 15 km north of Delambre No 1 well to well north of the hinge zone.

The F unconformity is seen only in places, and only on the Wombat Plateau can the pre-F sequence be readily seen on the monitor records, where it is well-bedded and thickening northward. In Delambre No 1 well the pre-F sequence penetrated consists of 1200 m of Late Triassic deltaic claystone, sandstone and siltstone. At the ODP sites it consists of deltaic Carnian and Norian sediments with a few interbedded carbonates, and of Rhaetian carbonates including reefs.

The structural picture along line 95/19 varies considerably. There is only minor Triassic and Jurassic faulting on the North West Shelf, major faulting with some extensional and compressional components between the North Exmouth Hinge Zone and the southern flank of the Wombat Plateau, and a massive fault forming that flank. The top of the Jurassic sequence (E unconformity) falls nearly 2000 m northward into the Wombat Half-graben, and then rises the same amount (as the corresponding F unconformity) onto the Wombat Plateau. The magnetic anomaly reflects the volcanics on the northern flank of the Wombat Plateau, and the gravity anomaly mirrors the sea bed.

8.2 Jurassic Carbonate Buildups

An inspection of multichannel seismic profile BMR 56/13 showed unusual buildups on top of four Triassic horsts, two of which are featured in Figure 41. These features form lenses between the C (mid Cretaceous) and F (top Triassic) unconformities, but the E (Callovian) unconformity pulls up around them, suggesting that they are probably largely Early to Middle Jurassic in age. Structural maps of this area (Exon & Willcox, 1980; Geophysical Services International, 1976; Appendix A) indicate that the horst blocks trend ENE, so that the features probably trend along the blocks in the same directon. On BMR line 56/13, the characteristics of the buildups could be summarised as :

1. Resting on Triassic horst blocks
2. Overlain by mid Cretaceous C unconformity
3. Lens shaped
4. Up to 2.5 km across
5. More than 0.3 seconds (TWT) thick ie. approximately 300 m or more thick
6. Weakly bedded and transitional into surrounding strata
7. Velocity drop-down beneath them, suggesting that they are low-velocity features, probably highly porous and water-filled

To gain more information on the buildups, a small survey was carried out at the end of line 95/14 to better define their distribution, three-dimensional shape, and relationship to the Triassic horst blocks. This survey involved lines 95/14, 15, 16, 17, and 18 (Fig. 37).

BMR profile 95/14 was designed to pass over the southernmost buildup seen on BMR 56/13 (Fig. 41). On BMR 95/14, this buildup is cut almost along its long axis, and extends some 30 km from 139.1100 to 139.1400 (Fig. 42); this contrasts greatly to its width of 2.5 km. The feature is shown on the highly-exaggerated monitor record to rest on a composite Triassic high, trending almost east-west and bounded by faults with a throw of about 500 m at 1045 and 1400. The appearance is of a reefal body about 500 m thick, with its core on the southeastern side, and a wedge of derived talus covering the rest of the block to the northwest.

BMR profiles 95/16 & 95/18 were run parallel to BMR 56/13 about 3 km to either side of it. Both are very similar. The relevant part of the monitor record of BMR 95/18 is shown in Figure 43. Allowing for the very different vertical exaggeration, the section is very like that on BMR 56/13, with buildups associated with horst blocks. It is quite possible to correlate buildups between all three profiles (56/13, 95/14, and 95/18).

Similar buildups are visible on GSI and other data sets in the north Exmouth Plateau area, for example GSI profile WA S76-33 (Fig. 44). A map of the area on which we concentrated is shown in Figure 45. This illustrates how fault blocks can be correlated through the various data sets, and that buildups are very widespread on horsts. Most buildups are 1-3 km across and at least 10 km long.

There is little doubt that these features are carbonate buildups. The only possible alternative is that they are igneous intrusions or extrusions that have made their way up faults. However, such bodies would spread out from the faults in both directions, with no conceivable mechanism confining them to the top of the horsts. Furthermore, they would be dense, and of high velocity, with strong surface reflections and associated velocity pull-ups beneath them.

Our hypothesis is that these buildups are reefal complexes, which started to form on topographic highs (horsts) toward the end of the Triassic, at the same time as the Wombat Plateau reefs formed further north. They continued to grow as the area sank in the Early and Middle Jurassic, a period when shelf carbonates are known to have existed (by dredging) on the northern Exmouth Plateau (von Rad and others, 1990), and shoreline carbonates to be present (by exploration drilling) on the central Exmouth Plateau (Barber, 1982, 1988). In places they continued to grow during the Late Jurassic, and the E unconformity laps around them. Whether growth persisted later requires further study, but they do not appear to exist above the C unconformity of Turonian age.

Follow-up dredging, on BMR Survey 96, has just recovered hard, iron-stained, mollusc-rich skeletal limestones and limestone breccias from an outcrop of a buildup on BMR 56/13, 15 km north of Figure 41 (17°38'S, 115°42'E) in 2250-1950 m water depth (J.B. Colwell, pers. comm.).

9. WOMBAT PLATEAU SEISMIC SURVEY

A high-resolution seismic survey was run over the northeastern corner of the Wombat Plateau, incorporating ODP Sites 761 and 764, in order to map the distribution and define the seismic character of the lagoonal and reefal Rhaetian (latest Triassic) carbonates drilled there (see Haq, von Rad and others, 1990; Williamson and others, 1989). The discovery of a Rhaetian reefal complex in ODP Site 764 was the first of a Late Triassic reef anywhere in Australia. The sequence at this site, summarised in Figure 13, consists of 300 m of outer shelf carbonate mudstone and marl, oolite shoals, and reefal, perireefal, back reef and forereef limestones.

The present survey made use of an array of five 80 cubic inch water-guns, and a 96 channel 1200 m seismic cable. Bad weather hampered data acquisition and degraded data quality, but altogether 255 km of useable data were recorded in water depths of 2000-3000 m on a north-south set of profiles with 2 km spacing (Fig. 45), tied by two east-west profiles. All monitor records show reefal bodies, suggesting that the area was a mass of shoals.

Line drawings of the two north-south lines which cut ODP Sites 761 and 764, indicate the general character of the profiles, and their potentially excellent quality once processed. Both profiles show the Carnian-Norian boundary and the Norian-Rhaetian boundary as mapped by ODP (Haq, von Rad and others, 1990). They also show the shallow, almost horizontal F unconformity which marks the top of the Rhaetian.

The Rhaetian sequence includes a well-bedded sequence of shelf carbonates which is cut by a number of carbonate buildups, including the one proven to be a reefal complex at ODP Site 764. Some of these buildups appear to have originated in Norian times, and some cause displacement of the mid-Cretaceous C unconformity, which immediately overlies the F unconformity. Most of the bodies are less than 2 km across, but some have amalgamated to form reef complexes more than 10 km across, like that shown at the northern end of profile 95/26. Thicknesses of the order of

500 m seem to be present, but we must await the processed data before we can be sure of the distribution, shape, extent and thickness of the buildups.

10. CAINOZOIC CORES

Using a heavy gravity corer, three core stations were successfully occupied during the cruise: one in the Canning Basin, one on the Wombat Plateau, and one in the north Perth Basin on the transit back to Fremantle. Cainozoic sediments were recovered in all three cores and the results are summarised in Table 2.

TABLE 2 : BMR CRUISE 95 CORE STATIONS

Core	Area	Lat (S) Long (E)	Water depth (m)	Recovery (m)	Comments
GC01	S.Rowley	16° 29.8' 118° 10.4'	3300	0	No bottom contact.
GC02	S.Rowley	16° 29.53' 118° 10.43'	3300	2.73	Foram nanno ooze and nanno ooze with forams; Pliocene at base.
GC03	Wombat ODP 760	16° 55.19' 115° 32.44'	1970	7.13	Foram nanno ooze and nanno ooze; mid Pleistocene at base.
GC04	N.Perth	29° 55.1' 113° 56.3'	2100	1.54	Foram nanno ooze grading downward to white and light grey chalk; mostly Pleistocene but latest Paleocene or earliest Eocene at base.

Core GC02 followed the unsuccessful GC01 at the same location in 3300 m of water. It was hoped it would penetrate Late Cretaceous rocks. It recovered 2.73 m - foram nanno ooze to 0.65 m, and nanno ooze with some forams below that to total depth. Pale brown tones predominate, especially near the surface, with some beds of light grey and pale olive colour. Colour changes generally occur at 20-40 cm intervals. There is generally little lamination, and at some levels mottling is common. Molluscan debris is apparent here and there. The base of the core is Pliocene in age on nannnofossil and foraminiferal evidence.

Core GC03 was taken in 1970 m water depth on the Wombat Plateau at ODP Site 760, with the aim of providing material for a higher resolution

Quaternary palaeoclimatic study than is allowable under ODP sampling rules. Recovery was 7.13 m, and the sequence was very similar to that in Core 1 (top 10 m) of ODP Site 760A, drilled with a hydraulic piston corer (Haq, von Rad and others, 1990). The upper 2 m of the core is foram nanno ooze; below that foram nanno ooze predominates, with nanno ooze with some forams present as a subsidiary sediment type.

Pale brown tones predominate to 1.2 m, and persist intermittently to 2.4 m. Light greys and greys dominate most of the core. Colour changes occur at intervals ranging from 10 cm to 50 cm. The bases of some beds are dark, perhaps because of manganese micronodules, and sharp, suggesting a depositional hiatus. Two greenish grey partings may possibly be caused by very fine volcanic ash from Indonesian volcanoes, as recognised in cores from the Scott Plateau further north (Hinz and others, 1978). Bedding laminations and both horizontally and vertically elongated mottles (probably burrows) are intermittently present. Pyritic burrow fillings are particularly common from 4.5 m to 5.7 m. The base of the core is mid Pleistocene on nannofossil evidence (0.9-1.2 Ma).

Core GC04 was taken in 2100 m of water in the north Perth Basin. It has yet to be properly described, but consists of 1.54 m of nannofossil ooze, grading downward to firm chalk, mostly white, but pale grey towards the base. Nannofossils indicate that most of the core is Pleistocene, but it is latest Paleocene or earliest Eocene at the base.

11. SYSTEMS RESULTS

Survey 95 was completed with most of the acquisition objectives achieved. However, numerous problems became manifest in both the seismic and non-seismic data acquisition systems.
-The seismic system was inconsistent in its failures, and hence made trouble-shooting a difficult task. Nevertheless it was brought to a state of near trouble-free performance by the commencement of the Canning Basin seismic work, and remained so to the end of work on the Wombat Plateau.
-The non-seismic acquisition system difficulties probably centred on software modifications in the navigation sub-systems.

One of the cruise objectives was to determine the viability of Hi-Fix. The Hi-Fix navigation system did perform satisfactorily in the context of its basic design, and the fractional lane jump problem of earlier cruises was no longer present. Drift rates were not constant however. The data smoothing for on-line display purposes did not yield obvious advantages, and Hi-Fix was only used as the primary system when the raw data were of high quality. The benefit of feeding smoothed velocities to the DR system to improve the quality of satellite fixes appears promising but yet needs to be fully assessed, and will be detailed in a separate report.

A more complete account of system performance may be found in the Systems Report in the Cruise 95 file (BMR 89/1268).

11.1 Seismic Acquisition System

Since the 1989 refit the seismic system has been plagued with problems. The Maryborough Basin and Arafura Sea cruises both experienced the same type of computer "crashes" consistently and there was doubt about the power supply in the instrument room, the Telex tape drives, and the gun controller. By the end of the Arafura Sea cruise it was believed that all major problems had been identified and solved.

Up to the commencement of work in the Vulcan Sub-Basin, the system ran without failure in test mode. After less than a day of shooting high resolution seismic, 3 crashes had occurred. Acquisition was suspended after 1.5 days work in the Canning Basin as these crashes were similar to those seen on the previous two cruises. Nearly 2 weeks of testing and exhaustive trouble-shooting followed. Following the dredging phase, the system was essentially brought to its original state and proceeded to run smoothly. Appendix E contains the shooting parameters used on this survey.

Except during the last period of high resolution seismic, the seastate and weather were faultless and gun maintenance was minimal. The cable streamed well and was easily controlled by the Syntron birds. During the last phase of acquisition a heavy swell and seastate of up to force 5 created problems for the 1200 m streamer and watergun array. At one stage the cable and guns tangled causing minor damage to the tow leader. This problem was overcome by deploying a chain from the magnetometer boom to the array, to keep it away from the cable.

11.2 Non-Seismic Acquisition System

The Data Acquisition System (DAS) handles the navigation, gravity, magnetic and bathymetric data and was operated from departure at Darwin to arrival at Fremantle.

Prior to sailing, the DAS computer was exchanged, due to system crashes on the Arafura Sea cruise. However these continued to occur, and data loss due to computer down-time amounted to nearly 7 hours. Although the cause of the problems remains uncertain, the crashes were likely related to software modifications in interfacing the hired Trimble GPS receiver, rather than memory parity errors as was the case on Survey 94. Details of changes to the DAS are given in the Systems Report in the Cruise 95 file.

Magnetics

The ship is equipped with Geometrics proton precession magnetometer systems. Magnetic profiles were recorded along the conventional seismic lines only. Typically noise was of the order of 2-3 nT.

Gravity

Gravity data were obtained using a Bodenseewerk KSS-31 Marine Gravimeter. The sensor was levelled twice prior to sailing. The gravity meter caged on at least 6 occasions, even while sea state was low and at least 10 hours of data was lost. Maintenance of the gravity meter is indicated.

Bathymetry

Bathymetric data were obtained from two 2 kW Raytheon echo sounders, operating at 12 kHz and 3.5 kHz. As expected, the 3.5 kHz system performance was poor. Problems and recommendations concerning this are detailed in the Arafura Sea Electronics report. During the geological sampling period of the cruise, the bathymetric data were barely sufficient.

To compound problems, the HADES program, which runs a slave EPC (usually in the winch room) from a master in the instrument room, was not operational. As a solution the 3.5 kHz echo sounder was run directly from the EPC in the winch room and the 12 kHz unit from the instrument room.

See Appendix D for a list of the data set acquired.

11.3 Navigation

Positioning of the ship was derived from three independent systems: Navstar Global Positioning System (GPS), dead reckoning (DR) with updates from the U.S. Navy Navigation Satellite System (Transit system), and radio navigation using BMR modified Hi-Fix/6. The primary positions were obtained from the system judged by the operator as giving the best position accuracy.

GPS data were available for 17 hours per day while Hi-Fix was considered acceptable only during daylight hours. For much of the time, Hi-Fix was the preferred system when both systems were available. On the detailed survey on the Wombat Plateau, the bridge navigated on Hi-Fix 31% of the time. DR was only used when neither of these systems gave acceptable results.

Global Positioning System

The GPS constellation currently consists of 12 of the proposed 18 satellites in functioning orbit. Limited satellite visibility results in GPS positioning being available for up to 20 hours a day, which includes periods of 2 satellite positioning.

For Survey 95, a Trimble 4000S GPS receiver was hired to complement BMR's suspect Magnavox T-Set and to assess the performance of a multichannel receiver with a view to purchasing a replacement for the T-Set in the near future. Experimentation with the T-Set receiver in the past has shown two satellite positioning to be unreliable due to incompatibility between the HP Rubidium frequency standard and the T-Set. There did not appear to be such a problem with the 4000S and 2-satellite data were available for this cruise. For most of the survey, 4000S data were recorded for over 17 hours/day and some 12 hours of this data was better than that from other systems available, and used as primary position data.

Random noise in the position data is in the range 5-15 m generally, though spikes of the order of 100 m are observed. With post-processing, the position accuracy is expected to be 15-30 m. Pre-cruise accuracy checks yielded 18 m RMS with 4 satellites.

Hi-Fix

BMR Marine has been experimenting for some time to extend the effective range of the Hi-Fix system by operating it in circular mode with all stations slaved to their own rubidium frequency standard. Such a system is affected by the individual drifts of the rubidium standards, that is, the drift rate of each station's rubidium standard affects the positioning data derived from the Hi-Fix chain. In order to compensate for this effect, each rubidium standard's drift rate is calculated by comparing observed Hifix ranges to ranges derived from the GPS data.

The Hi-Fix chain was set in place and transmitting by day 128. Data quality was excellent throughout the survey at ranges over 550 km, and night-time noise was not as serious as experienced in earlier surveys in this area. No fractional lane jumps were observed, but the drift rate as measured by comparison with the GPS was not constant. During survey work, an initial estimate of 20 cl/hr was used for navigation, later changed to zero when data on drift rate became available.

Data quality was excellent for most of each day starting at sunrise and ending at sunset. For 9 hours of daylight the noise level was down to 5 cl peak to peak, while at night the signal to noise ratio deteriorated. The high gain antenna was effective, and gave a noticeable improvement in performance in comparison with the standard antenna. Night-time noise was 50-100 cl peak to peak with numerous lane jumps.

The system accuracy depends on non-systematic errors such as noise and lane jumps, and systematic errors in drift, lane-width, and reference position. The random errors appear to have been adequately corrected in the software, while the drift has not been found to be constant. No calibration checks (apart from drift rate determinations) were applied and we don't know the error in the lane width. Our only guide to system accuracy is therefore a statistical analysis of updates and this remains to be done, but indications are that accuracy may be of the order of 100 m.

Dead Reckoning Systems

Two independent systems incorporating a gyro compass, dual axis sonar-doppler and Transit satnav receiver provide basic dead reckoning for periods when the other navigation systems prove inadequate.

The primary dead reckoning system of Sperry gyro, Magnavox MX610D sonar-doppler and MX1107RS dual channel Transit receiver provides one of the best available positioning systems of this type. A lower grade system of Robertson gyro, Raytheon DSN450 sonar-doppler and MX1142 single channel Transit receiver is used as a backup.

Both sonar-dopplers have problems in rough weather or when heading into the sea. Air trapped under the ship's hull combined with turbulence in the water flow along the hull can blank the transmissions of all sonar-doppler systems installed on the ship. This problem is inherent in the ship's design and the placement of the sonar-doppler transducers.

Accuracy of the system is determined by accuracy of Transit fixes and currents. Updates at Transit fixes were of the order of 200 metres. However, pre-updated dead-reckoned positions are current related. Tests in the past have shown most fixes to fall within 200 m. During this survey the 1107RS received speed data from the primary navigation system. It is expected that the error in the fixes was therefore of the order of 100 m when GPS or Hi-Fix was the primary navigation system.

11.4 Geological Sampling

The coring winch used for the coring and dredging operations developed a problem with its braking mechanism early in the survey. While retrieving a dredge, the winch gradually slowed, then came to a complete stop. On investigation, it was discovered the cooling water outlet pipe was unusualy hot. Since the winch hydraulic system shares its cooling water with the air compressors, it was decided to shut off the inlet valves to all compressors, none of which were being used at the time. This diverted all the water through the hydraulic system heat exchanger. The outlet water temperature returned to a reasonable value and the winch was once again operational.

Some time later the problem reappeared. This time the relevant direction control valves were stripped, cleaned and tested before being reinstalled. The filters were changed, and the oil level topped up. This corrected the problem, and no further faults occurred.

The *DYNALUBE* wire-greasing device was cleaned, serviced and repaired prior to being used on the coring winch wire towards the end of the cruise. Because of time constraints, the wire greasing was limited to the first 2000 m.

The spelter sockets on tugger winches 2 & 3 were removed and replaced with a splice and hard eye arrangement on each. This was done to overcome problems experienced on previous cruises when the spelter sockets have broken. The splice proved very successful in respect of its strength, ruggedness and reliability, and is recommended for future use.

No loss of over-the-side hardware occurred, the only damage being slight distortion of the dredge mouth, and bending of a core barrel in the notoriously hard-bottomed Perth Basin.

12. CONCLUSIONS

12.1 General Performance

The cruise successfully carried out most of the Cruise Plan, and should enable the objectives specified to be met during the term of this project. The experimental seismic work in the Vulcan Sub-basin (Fig. 19) gave rise to 110 km of high-resolution seismic data shot as four lines near and across the Challis oilfield. The monitor records indicated that the key Base Cretaceous unconformity (Wormald, 1988) had been reached.

Conventional seismic tie lines were provided as planned, except that computer crashes during the Canning Basin work, and the fear that they might persist indefinitely, impelled us to curtail the Canning Basin profiling. We cut two long tie lines out of the program (compare Figs. 3 & 4). Nevertheless, the 1750 km of regional seismic lines does not fall far short of the planned 2100 km, and meets most of our scientific objectives. We were considering increasing this component of the work late in the cruise, but a shortage of fuel meant we had to return to Perth three days early, so that our planned 34 day cruise bacame a 31 day cruise, preventing any such increase. Data quality appears to be good. The fold of the data was reduced from 48 to 32 to allow the computer more time to handle each shot (more time between shots), and thereafter systems crashes were minimal.

The dredging program on the outer Rowley Terrace went very well indeed, after some initial mechanical problems with the winch. A great variety of Jurassic, and probably Triassic, rocks were obtained, and the results will be used to constrain geological interpretations of the Rowley Sub-basin previously based on shelf wells and seismic profiles. We dredged 13 times in 7 days, almost exactly what we calculated. Three Cainozoic cores were also obtained at various locations.

The high-resolution seismic survey across ODP Sites 761 and 764 on the Wombat Plateau was constrained, by bad weather and lack of time, to less than the planned 400 km, but nevertheless 255 km of reasonable quality data were obtained over a little more than two days. The monitors show that the objective of detailing the Triassic reef complexes was fully obtained.

12.2 Scientific Highlights

The full scientific significance of the cruise must await processing of the multichannel seismic profiles, and further work on the rock samples, especially palynological studies of the non-marine samples. Nonetheless, we can already claim the following highlights :

1. High-quality multichannel seismic tie lines now link Barcoo No 1 well, and East Mermaid No 1 well to the Argo Abyssal Plain. The former line indicates that Triassic sediments are overlain by Triassic-Jurassic continental volcanics in one area, and that the Triassic sequence is highly deformed near the continental margin. In contrast, the latter line shows a virtually undisturbed Triassic sequence persisting to the margin.

2. A multichannel tie line now links East Mermaid No 1 to the northern Exmouth Plateau. This shows the marked change from the undisturbed Canning Basin sequence, through a zone of deformation corresponding to the Swan "graben", to the characteristic fault-block geology of the northern Exmouth Plateau.

3. The multichannel tie line from Delambre No 1 well on the northern Exmouth Plateau to ODP Site 764 on the Wombat Plateau, shows marked changes in geological character from south to north. Near Delambre No 1, layer-cake geology prevails, but from the North Exmouth Hinge Zone down into the Wombat "half-graben", there is very great displacement at the Triassic-Jurassic level on steeply dipping faults. The Wombat Plateau is a high block with a massive fault on its southern side, and a greatly uplifted Triassic sequence.

4. A large number of buildups, largely of Jurassic age, have been identified on seismic profiles in the northern Exmouth Plateau. These sit on Triassic horst blocks, and commonly are up to 500 m thick, 2000 m wide, and more than 10 km long. We believe them to be reefal complexes.

5. The rock types dredged from the Rowley Sub-basin include proven Jurassic marine and non-marine detrital sediments, some bearing ammonites, proven Jurassic shelf carbonates, and Triassic-Jurassic volcanics. Undated rocks include coral and algal boundstones, other shelfal carbonates with varied shelly faunas, and many marine

and non-marine detrital sediments. A large proportion of these rocks may prove to be Triassic, the remainder Jurassic. In addition, Cretaceous and Cainozoic sedimentary rocks were recovered.

6. The character of the Rhaetian (latest Triassic) reefal and lagoonal carbonates drilled on the Wombat Plateau in ODP Sites 761 and 764 is now determined seismically. Reefs are widely distributed, of moderate size, and sometimes amalgamate to form larger complexes.

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APPENDIX A - STUDY OF GSI REGIONAL SEISMIC LINES OVER THE NORTHERN EXMOUTH PLATEAU.

Barry West

A regional interpretation of selected lines from the northern Exmouth Plateau seismic survey WA S76 of Geophysical Service International (GSI) was undertaken to aid tying the regional BMR line 95/14, from East Mermaid No 1 well to the high resolution seismic recorded on the northeast Wombat Plateau in the vicinity of ODP Site 764. The GSI lines used were WA S76-30 to 41 inclusive, and these were tied initially to three wells: Delambre No 1, Brigadier No 1 and Gandara No 1, using the seismic reflectors of Exon and Willcox (1980). Appendix Table 1 summarises the seismic reflectors mapped in the study. The study showed that:

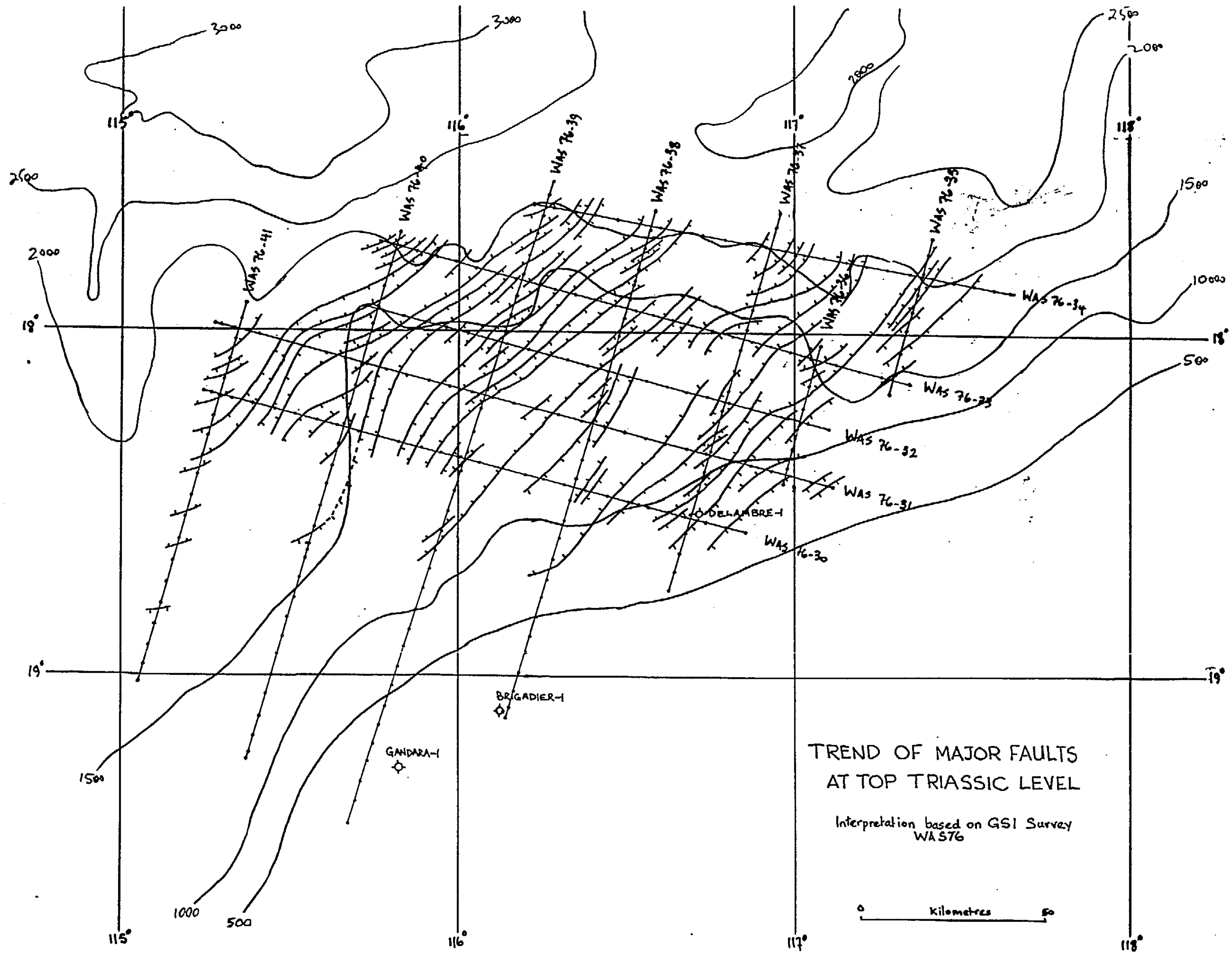
1. At the top Triassic (F) level, the faulting was mainly normal block faulting, dipping slightly to the southeast, and becoming more intense to the north, giving a series of parallel, northeast trending horsts and grabens (Appendix Fig. A).

2. The mapped top Triassic (F) reflector varies in depth from less than 3.0 secs (TWT) in the southwest to over 6.0 secs (TWT) in the northeast. A simplified time structure map at top Triassic level (Appendix Fig. B) shows a general increase in depth northwards to the North Exmouth Hinge Zone, represented in Figure 2 by the nearly westerly trending contours from 4.2 secs to 5.4 secs (TWT) in the northern part of the area. A southerly trending low ranging from 5.4 secs to 6.6 secs (TWT) in the northeastern corner of the study area probably corresponds with the Swan Canyon at the top Triassic level. The high feature just to the west of the Swan Canyon may be a compressional structure related to strike slip movement.

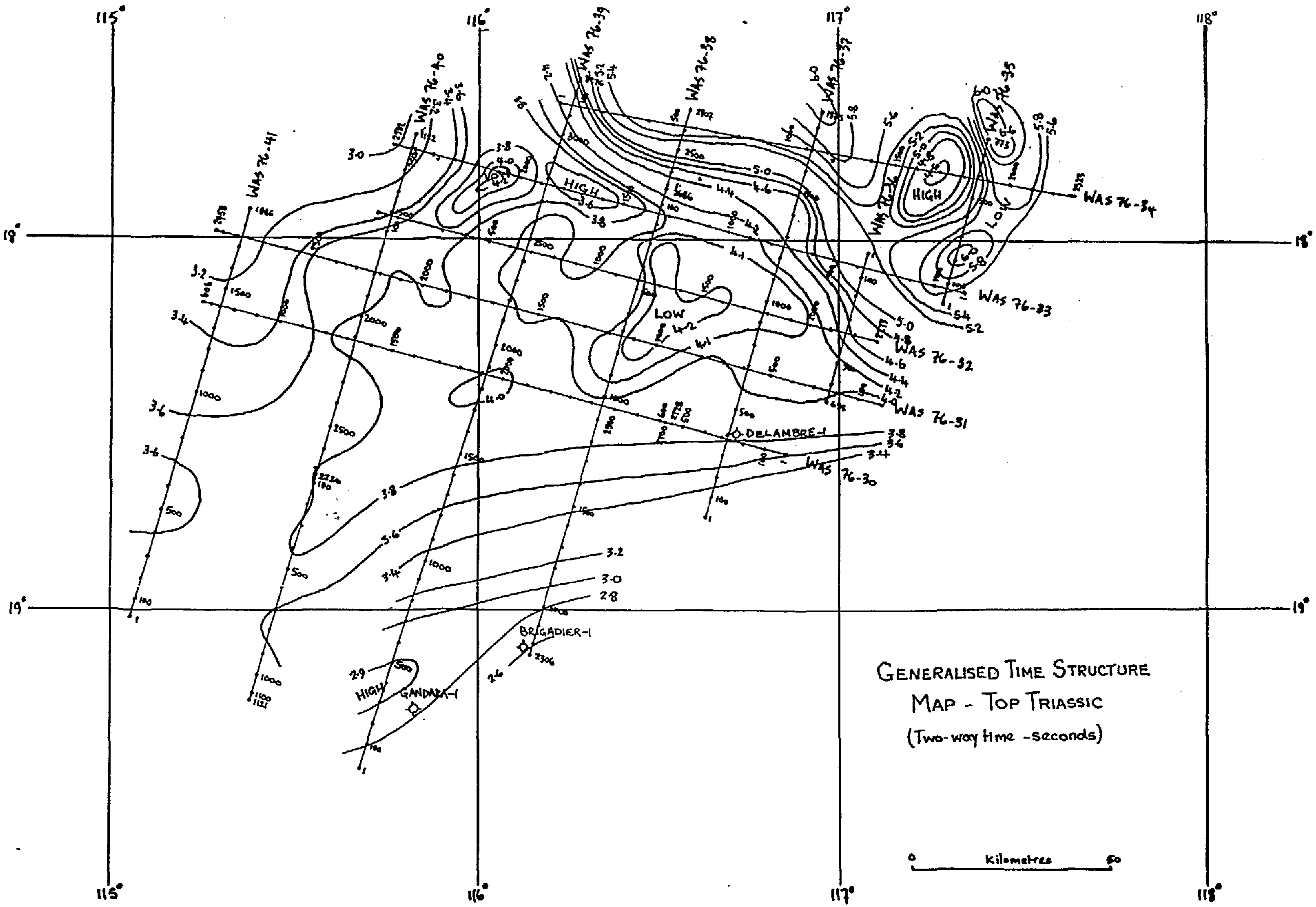
3. The Jurassic section tends to exhibit parallel or only weakly dipping beds, varying in thickness from less than 150 m in the western part of the area, to over 5000 m towards the North Exmouth Hinge Zone and Swan Canyon.

4. A number of seismic anomalies at Jurassic level were identified at the western end of lines WA S76-31 to 33, and the northern end of lines WA S76-39 and 40. These anomalies sit directly on top of fault blocks, and are draped by either the E, D or C horizons (text Fig. 43). When mapped, the anomalies are linearly distributed along the near westerly trending fault blocks. They appear to be similar to those interpreted as carbonate buildups on BMR profiles 95/14-18.

APPENDIX FIGURE A



APPENDIX FIGURE B



GENERALISED TIME STRUCTURE MAP - TOP TRIASSIC

(Two-way time - seconds)

APPENDIX TABLE 1 : Summary of seismic reflectors mapped

Seismic horizon	Probable age	Characteristics
A	Oligocene	Strong reflector separating upper acoustically semi-transparent zone from a lower zone of contorted reflectors. Can be traced throughout the area. Often coalesces or bifurcates.
B	Paleocene	Varies between middle and base of contorted reflectors. Sometimes coalesces or bifurcates.
C	Late Cretaceous	Strong reflector at base of contorted reflectors. Can be mapped throughout the area, and very few faults peneterate the horizon. Some draping occurs over uplifted blocks, and sometimes coincides with horizons D, E and F.
D	Neocomian	Mild unconformity usually less than 0.1 secs (TWT) below the C horizon, and often coincident with C.
E	Middle to Late Jurassic	Weak reflector with mild angular unconformity, usually less than 0.2 secs (TWT) below D horizon. Frequently coincident with D and C horizons, and often drapes over and marks upper limit of block faults.
F	Late Triassic	Strong reflector often with marked angular unconformity. Largely conformable with top or within fault blocks.

APPENDIX B - HI-FIX/6 TRANSMITTER POSITIONS

	AGD84	WGS72
Cape Preston	20° 50.568' S 116° 22.097' E 30.0 m	20° 50.490'S 116° 22.171'E 19.3 m
Point Samson	20° 37.084' S 117° 11.258' E 30.0 m	20° 37.006' S 117° 11.331' E 21.5 m
Port Hedland	20° 18.184' S 118° 32.642' E 30.0 m	20° 18.105' S 118° 32.715' E 25.1 m
Wallal Downs	19° 45.495' S 120° 40.159' E 30.0 m	19° 45.415' S 120° 40.231' E 30.9 m

APPENDIX C - EQUIPMENT LIST

1. GEOPHYSICAL EQUIPMENT

Seismic System

Streamer (2400 m configuration) :

- 2400 m Teledyne hydrophone analogue streamer configured as 96 x 25 m groups
- 10 hydrophones per 12.5 m group
- ~15 microvolts noise, maximum ambient at 5 knots
- Syntron RCL-3 individually addressable cable levellers

Air Gun Source Array :

- 2 x 16-gun arrays; each gun 160 cu. in. (2.6 L) Texas Instruments Pnu-Con Model 3; 10 elements used in each string; one string shooting at a time
- Teledyne gun signature phones, gun depth sensors, and I/O SS-8 shot sensors
- 4 x Price A-300 compressors, each rated at 300 scfm @ 2000 psi

Water Gun Source Array :

- 5 x 80 cu. in. (total 6.6 L) SSI

Recording :

- BMR designed and built seismic acquisition system based on Hewlett-Packard minicomputers
- 96 channel digitally controlled preamp/filters
- bit accuracy:
  12 bit floating point with 4 bit dynamic accuracy
  15 bit integer card
- 6250 bpi Telex tape drives
- data read-after-write in demultiplexed SEG-Y format
- 2 msec sampling with 96 channels
- streamer noise, leakage and individual group QC
- recording oscillator and 4 seismic monitor QC

Bathymetric System

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

Gravity Meter

- Bodenseewerk Geosystem KSS-31 air/sea gravity meter

2. NAVIGATION EQUIPMENT

GPS System

- Magnavox T-Set GPS navigator
- Trimble 4000S GPS surveyor

Prime Transit System

- Magnavox MX1107RS dual channel satellite receiver
- Magnavox MX610D dual-axis sonar doppler speed log
- Sperry Gyro-Compass

Secondary Transit System

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

Radio Navigation

- Decca HI-FIX/6

3. COMPUTER

- data acquisition system built around Hewlett-Packard 2117 F-Series minicomputer, with tape drives, disc drives, 12" and 36" plotters, line printers and interactive terminals.

4. GEOLOGICAL SAMPLING EQUIPMENT

- Australian Winch and Haulage deep-sea winch with 10,000 m of 18 mm wire
- heavy chain-bag dredges with solid bridles: width 89 cm, height 35 cm, length 147 cm
- small pipe-dredges for attachment behind chain-bag dredges
- 5 or 10 m gravity corer to take 90 mm cores

- slabbing saw
- sample preparation equipment
- various microscopes

APPENDIX D - NON-SEISMIC ACQUISITION CHANNELS

The following is a list of channel allocations for the non-seismic data for Survey 95.

The main data set is saved on magnetic tape every minute in blocks of 128 x 6 floating point words. This represents 128 data channels of 6 records per block.

1	Survey and day number (SS.DDD) from RTE clock
2	Acquisition GMT (.HHMMSS) from RTE clock
3	Acquisition GMT (.HHMMSS) from master clock
4	Latitude, best estimate (radians)
5	Longitude, best estimate (radians)
6	Speed, best estimate (knots)
7	Course, best estimate (degrees)
8	Magnetometer # 1 (gammas)
10	Depth from 3.5 kHz (metres)
11	Depth from 12.5 kHz (metres)
12	F/A Magnavox sonar doppler (3840 counts/nm)
13	P/S Magnavox sonar doppler (3840 counts/nm)
14	F/A Raytheon sonar doppler (203 counts/nm)
15	P/S Raytheon sonar doppler (203 counts/nm)
16	Paddle Log (7000 counts/nm)
18	S-G Brown gyro heading (degrees)
19	Robertson gyro heading (degrees)
20	Sperry gyro heading (degrees)
25	Hi-Fix A range (centilanes)
26	Hi-Fix B range (centilanes)
27	Hi-Fix C range (centilanes)
39	T-Set latitude (thousands of minutes)
40	T-Set longitude (thousands of minutes)
41	4000S number of satellites used (x10)
42	4000S GMT of day (seconds)
43	4000S dilution of precision (x10010)
44	4000S latitude (radians)
45	4000S longitude (radians)
46	4000S height above geoid (metres)
47	4000S speed (knots x 10)
48	4000S course (degrees x 10)
49	T-Set speed (knots x 10)

51	Latitude	from	Dead	Reckoning	System 1	(radians)
52	Longitude	"	"	"	"	(radians)
53	Speed	"	"	"	"	(knots)
54	Course	"	"	"	"	(degrees)
55	Latitude	from	Dead	Reckoning	System 2	(radians)
56	Longitude	"	"	"	"	(radians)
57	Speed	"	"	"	"	(knots)
58	Course	"	"	"	"	(degrees)
59	Latitude	from	Dead	Reckoning	System 3	(radians)
60	Longitude	"	"	"	"	(radians)
61	Speed	"	"	"	"	(knots)
62	Course	"	"	"	"	(degrees)
63	Latitude	from	Hi-Fix			(radians)
64	Longitude	"	"			(radians)
65	Speed	"	"			(knots)
66	Course	"	"			(degrees)

67	GMT from Magnavox MX1107 (seconds)
68	Dead reckoned time from MX1107 (seconds)

69	MX1107 latitude (radians)
70	MX1107 longitude (radians)
71	MX1107 speed (knots)
72	MX1107 heading (degrees)
73	GMT from Magnavox MX1142 (seconds)
74	Dead reckoned time from MX1142 (seconds)
75	MX1142 latitude (radians)
76	MX1142 longitude (radians)
77	MX1142 speed (knots)
78	MX1142 heading (degrees)
79	Gravity (mGal x 100)
80	ACX (m/sec^2 x 10000)
81	ACY (m/sec^2 x 10000)
82	Sea state
83	AGRF magnetic anomaly #1
86	Shot time (HHMMSS)
87	Shot point number
88	Northerly set/drift (radians/10 seconds)
89	Easterly set/drift (radians/10 seconds)
94	Hi-Fix A cumulative drift (centilanes)
95	Hi-Fix B cumulative drift (centilanes)
96	Hi-Fix C cumulative drift (centilanes)
104	Hi-Fix A 10 sec drift (centilanes)
105	Hi-Fix B 10 sec drift (centilanes)
106	Hi-Fix C 10 sec drift (centilanes)

Transit Satellite Fixes

The Transit satellite fix information from both the MX1107 and MX1142 is saved in blocks of 20 floating-point words when the fix data becomes available. The data from each satnav is in a similar format, each being identified by the first word.

1	1107 or 1142
2	Day number (1107) or date (1142)
3	GMT
4	Latitude (radians)
5	Longitude (radians)
6	Used flag (0 = not used, 1 = used)
7	Elevation (degrees)
8	Iterations
9	Doppler counts
10	Distance from DR (nautical miles)
11	Direction from DR (degrees)
12	Satellite number
13	Antenna height (metres)
14	Doppler spread flags (1107 only)
.	" " "
.	" " "
20	" " "

APPENDIX E - SHOOTING AND RECORDING PARAMETERS

There was a different set of recording parameters used in each of the 4 areas studied. Each of the following tables refers to two areas. The numbers separated by "/" signify the different parameters used in the respective areas.

Vulcan Sub-Basin/Wombat Plateau

Source:	4 or 5 watergun array
Shot Spacing:	18.75 m
Shot Interval:	7.35 / 8.15 sec
Cable Length:	1200 m
Group Interval:	12.5 m
No. of Channels:	96
Near Offset:	101 / 160 m
Far Offset:	1299 / 1358 m
Cable Depth:	5 / 7 m
Recording Fold:	32
Record Length:	2 sec
Sample Rate:	2 msec
Filter Settings:	8 / 16 Hz low cut; 128 Hz high cut
Amplifier Gain:	Pre-amps variable; IFP used for all lines
Field Tape Density:	6250 bpi
Tape Format:	SEG Y

Canning/Exmouth

Source:	1 x 1600 cubic inch air-gun array
Shot Spacing:	25 / 37.5 m
Shot Interval:	18.8 - 14.65 sec depending on shot spacing, and ship speed
Cable length:	2400 m
Group Interval:	25 m
No. of Channels:	96
Near Offset:	180 - 199 m depending on tow-leader length
Far Offset:	near offset + 2407 m
Cable Depth:	10 m
Recording Fold:	48 or 32 / 32
Record Length:	6 seconds generally
Sample Rate:	2 msec
Filter Settings:	8 Hz low cut; 128 Hz high cut
Amplifier Gain:	Pre-amps variable; IFP used for all lines
Field Tape Density:	6250 bpi
Tape Format:	SEG Y

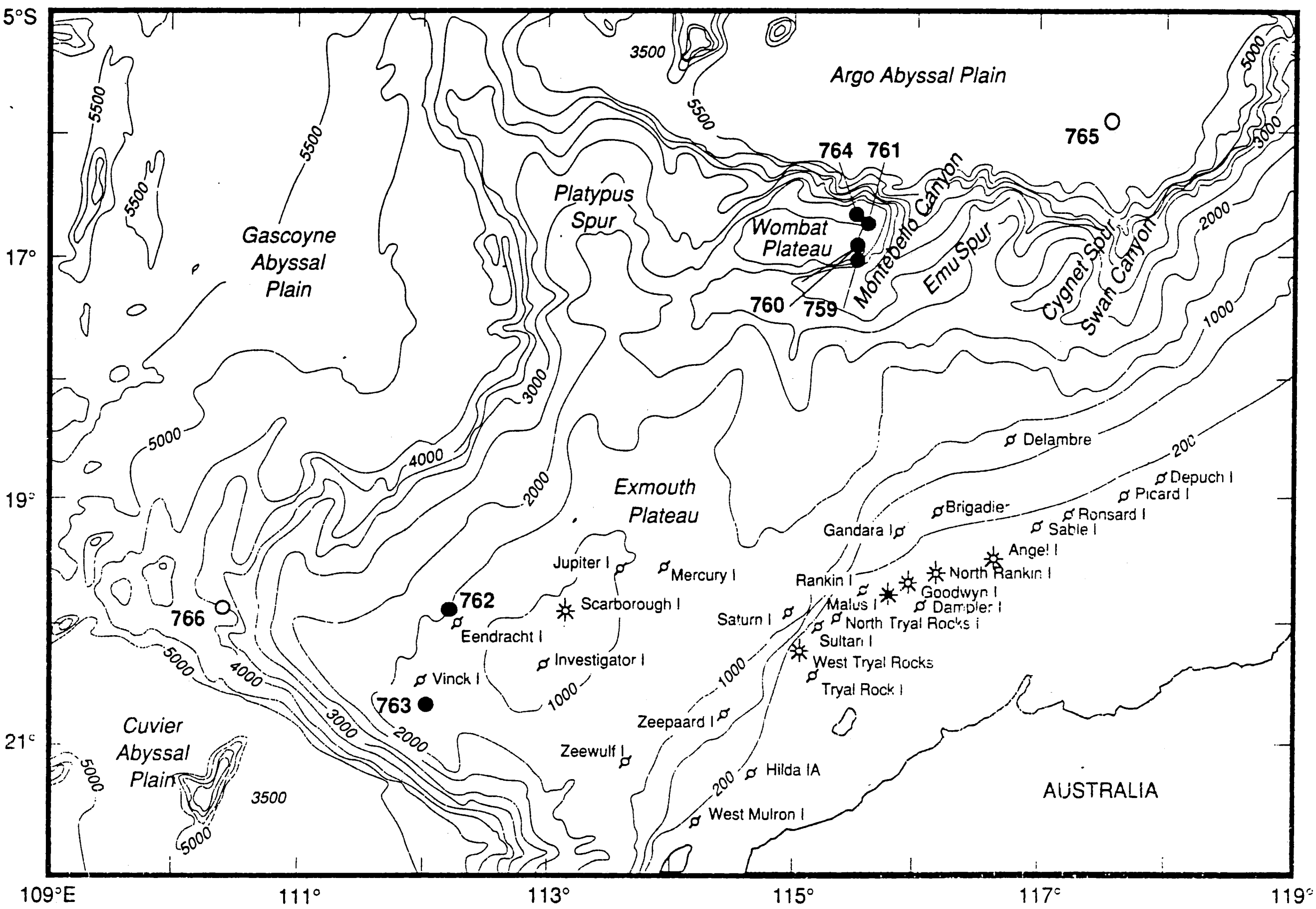
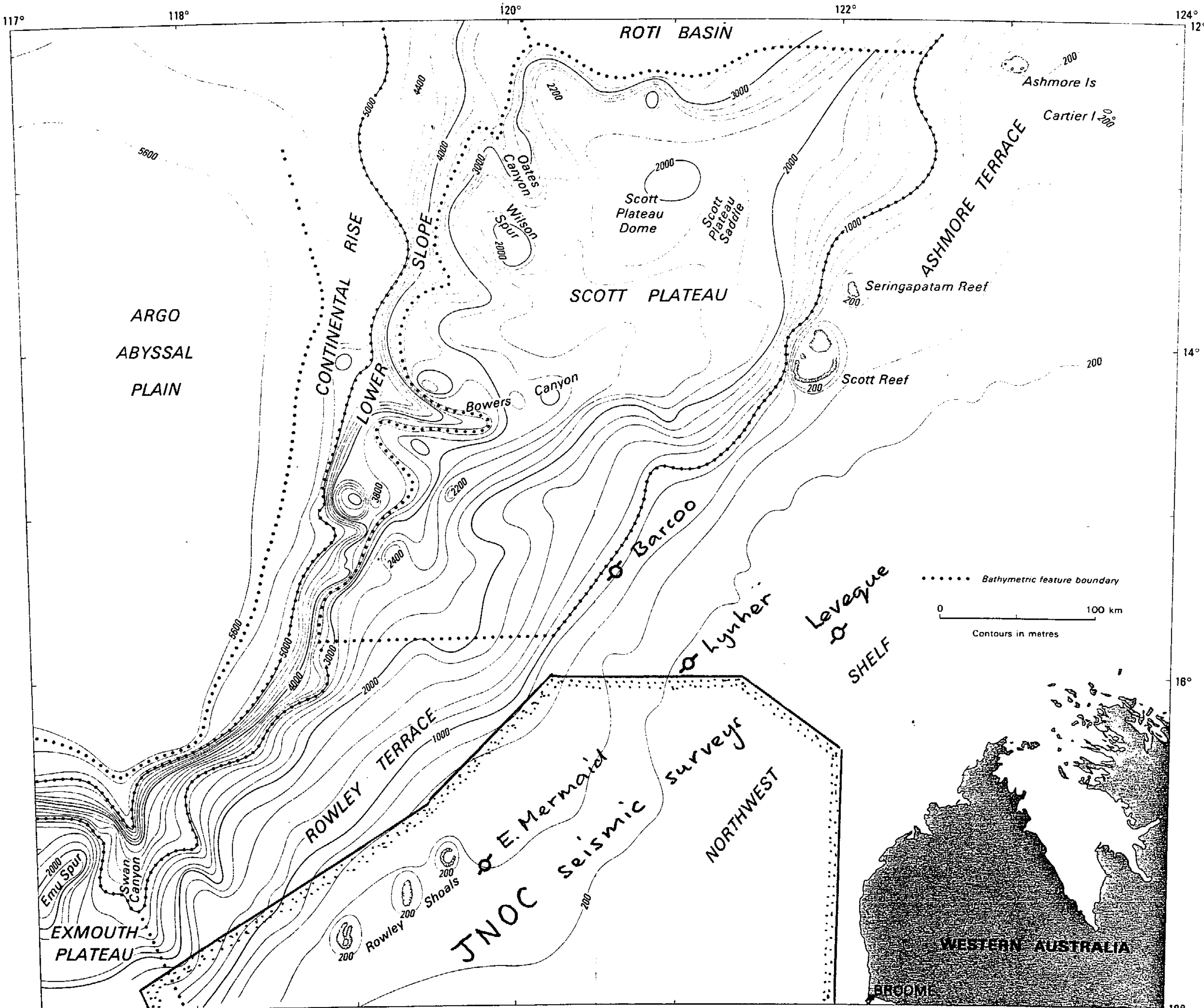


Figure 1. Map of Exmouth Plateau with bathymetry, exploration wells and ODP sites



BATHYMETRIC FEATURES

Figure 2. Map of offshore Canning Basin showing bathymetry, exploration wells and extent of JNOC regional seismic survey

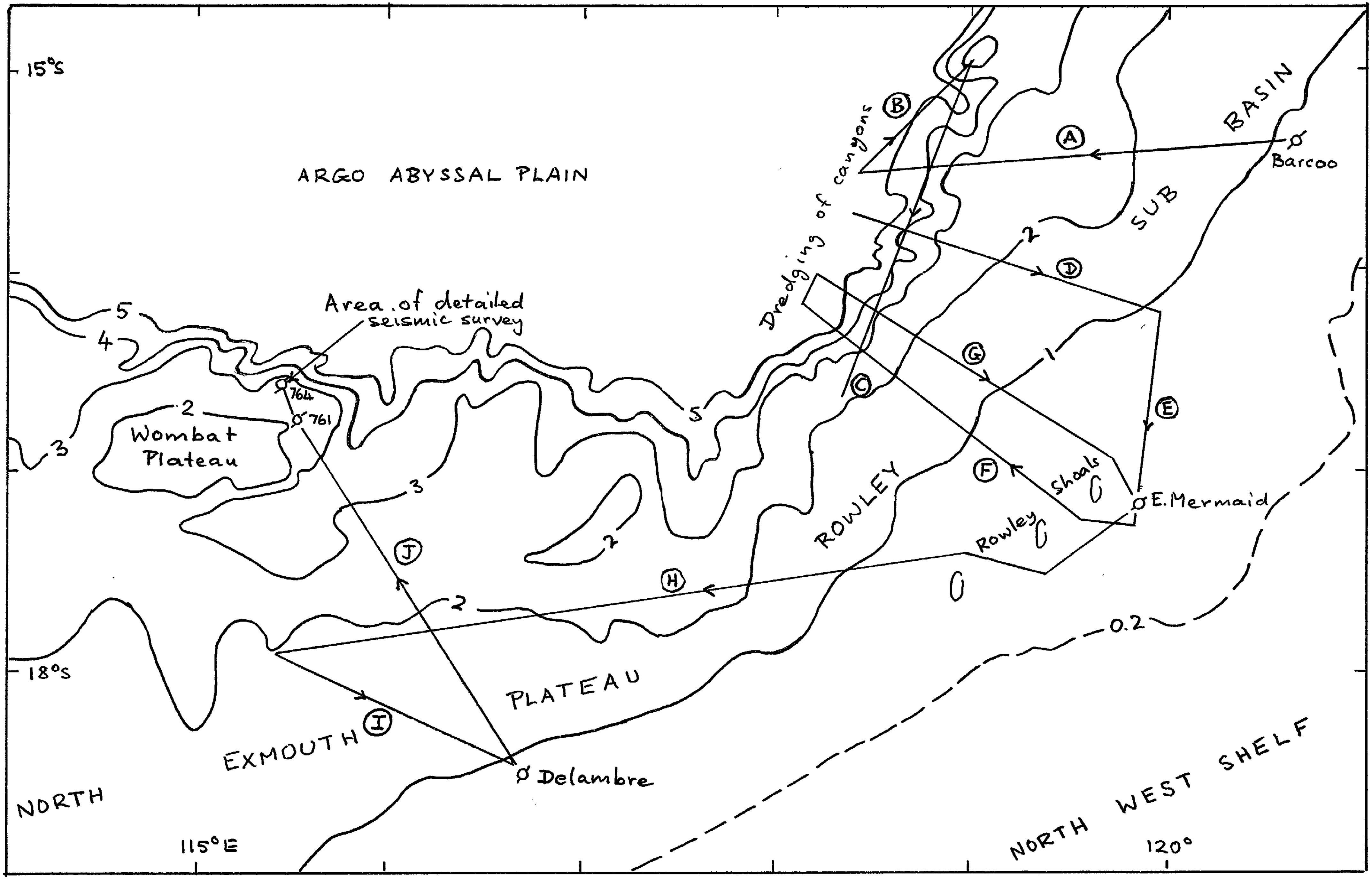


Figure 3. Map showing planned survey activities

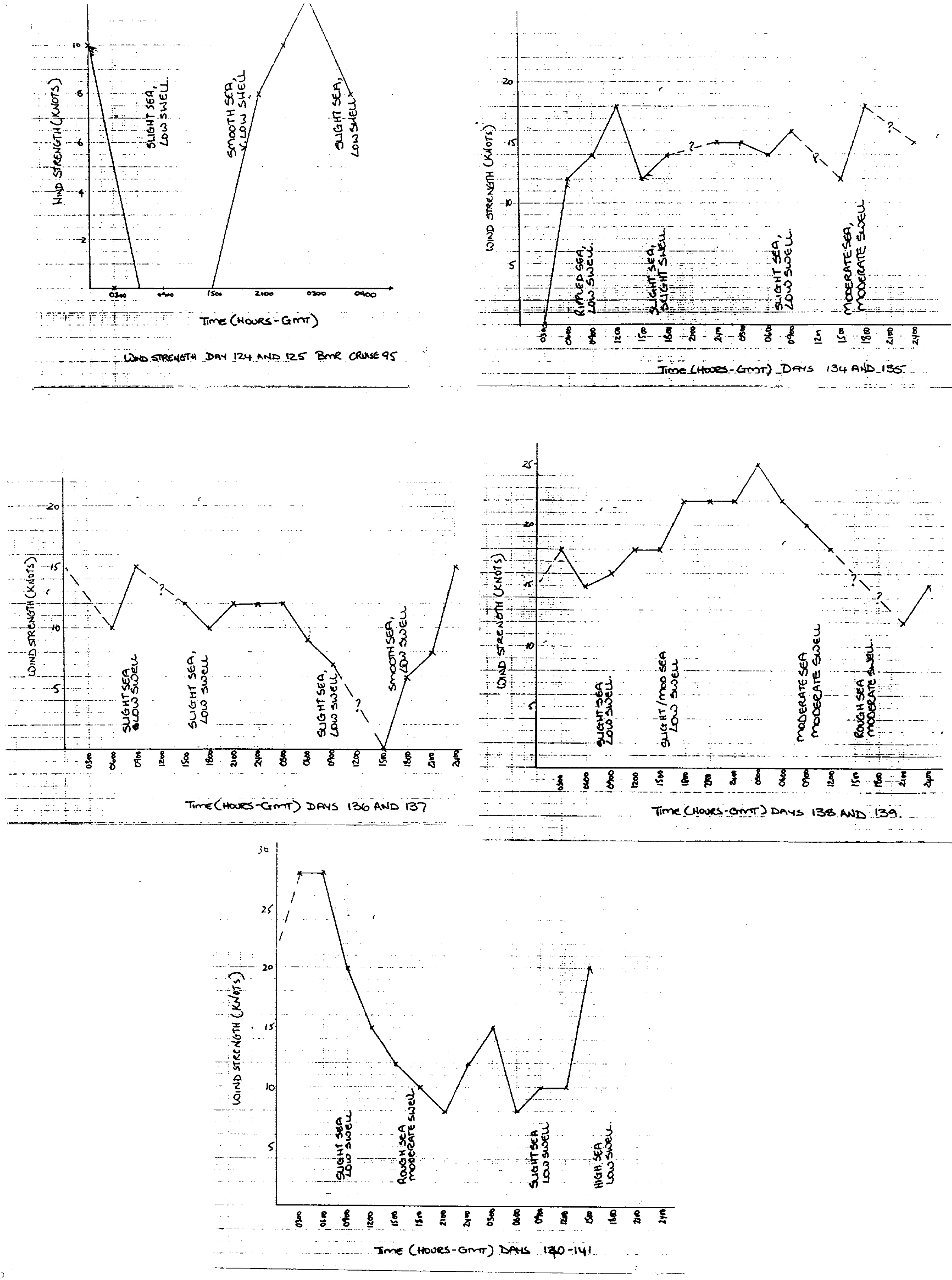


Figure 4. Weather variations during cruise

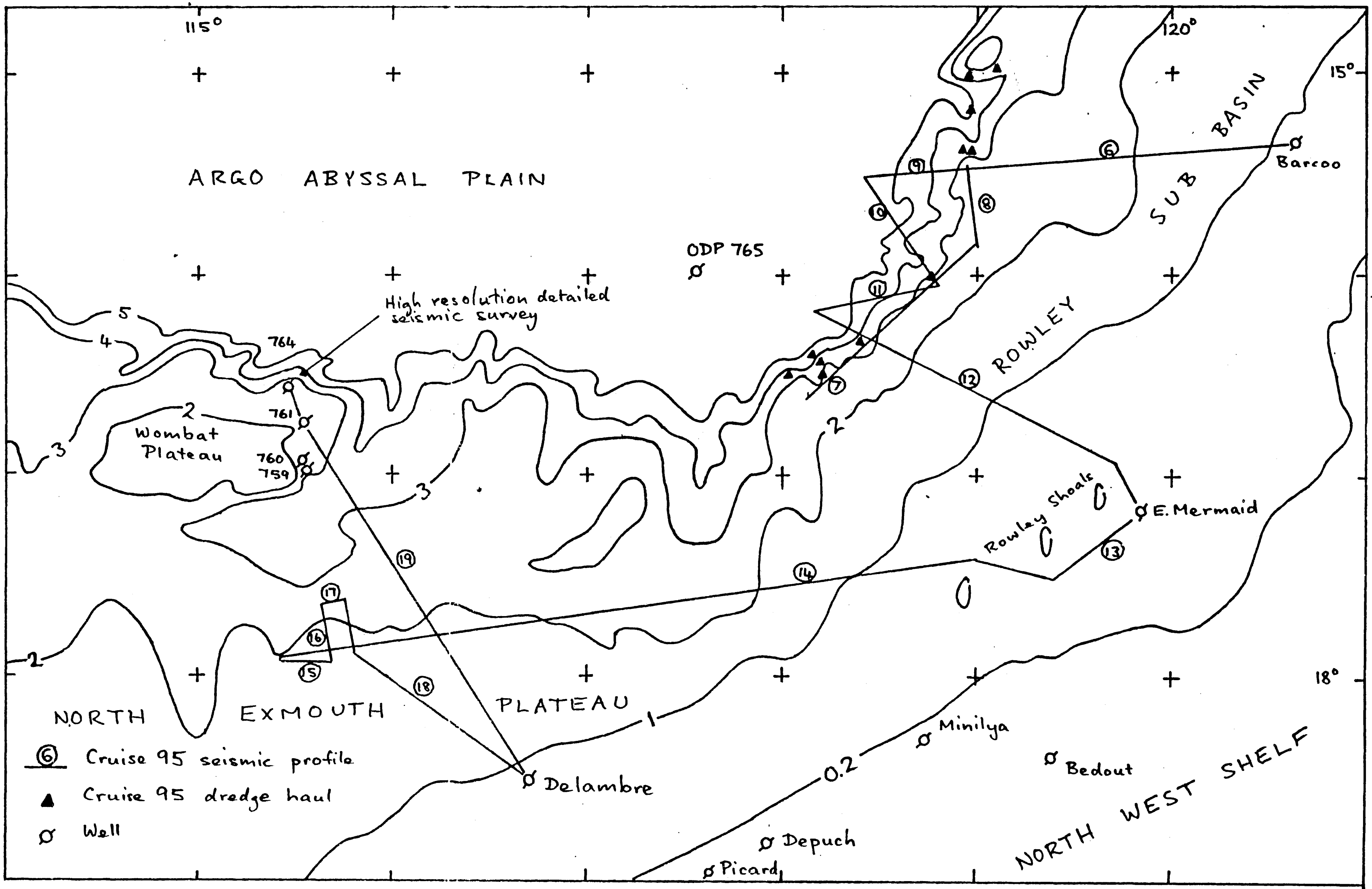


Figure 5. Map showing survey activities carried out

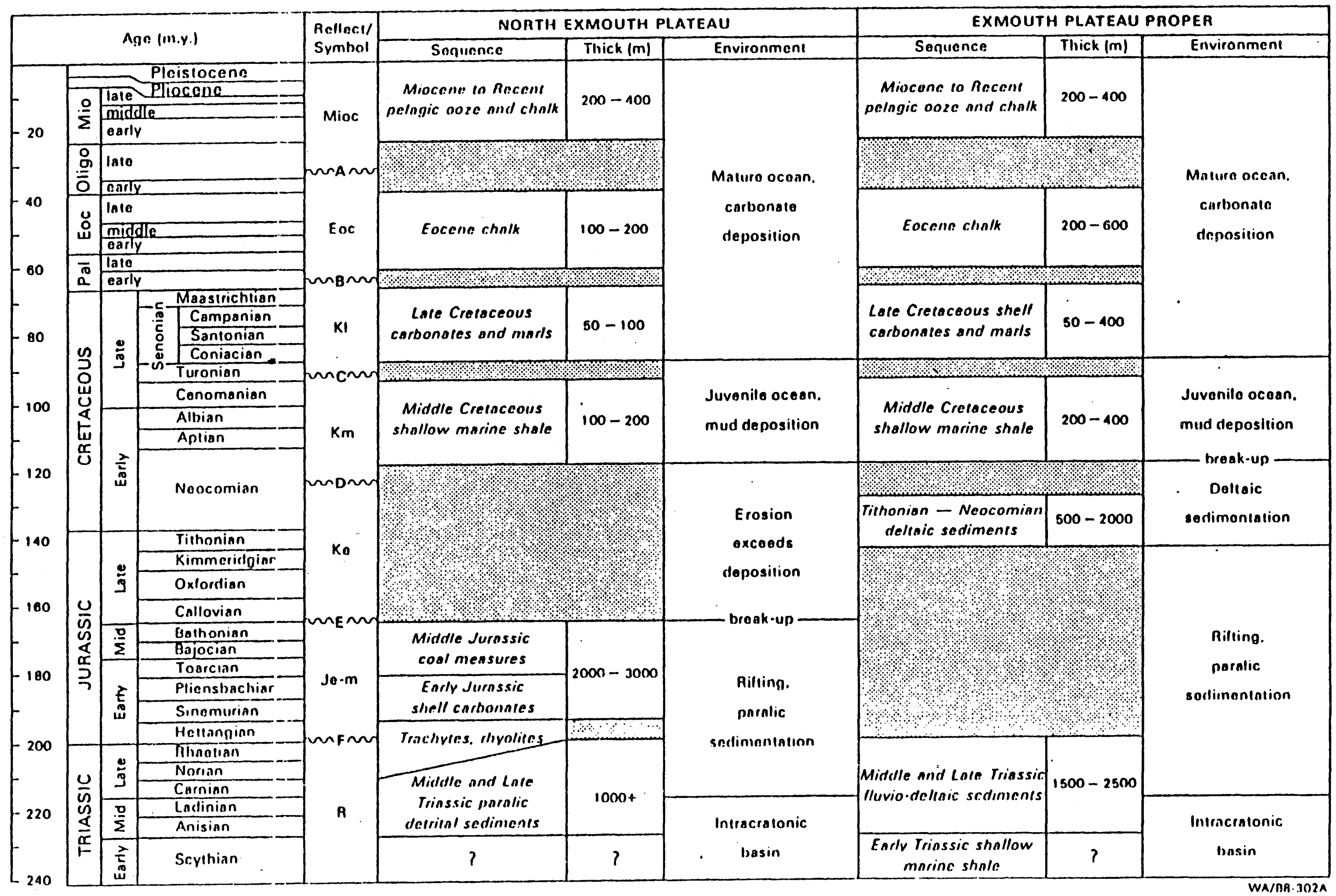


Figure 6. Simplified stratigraphy of the Exmouth Plateau

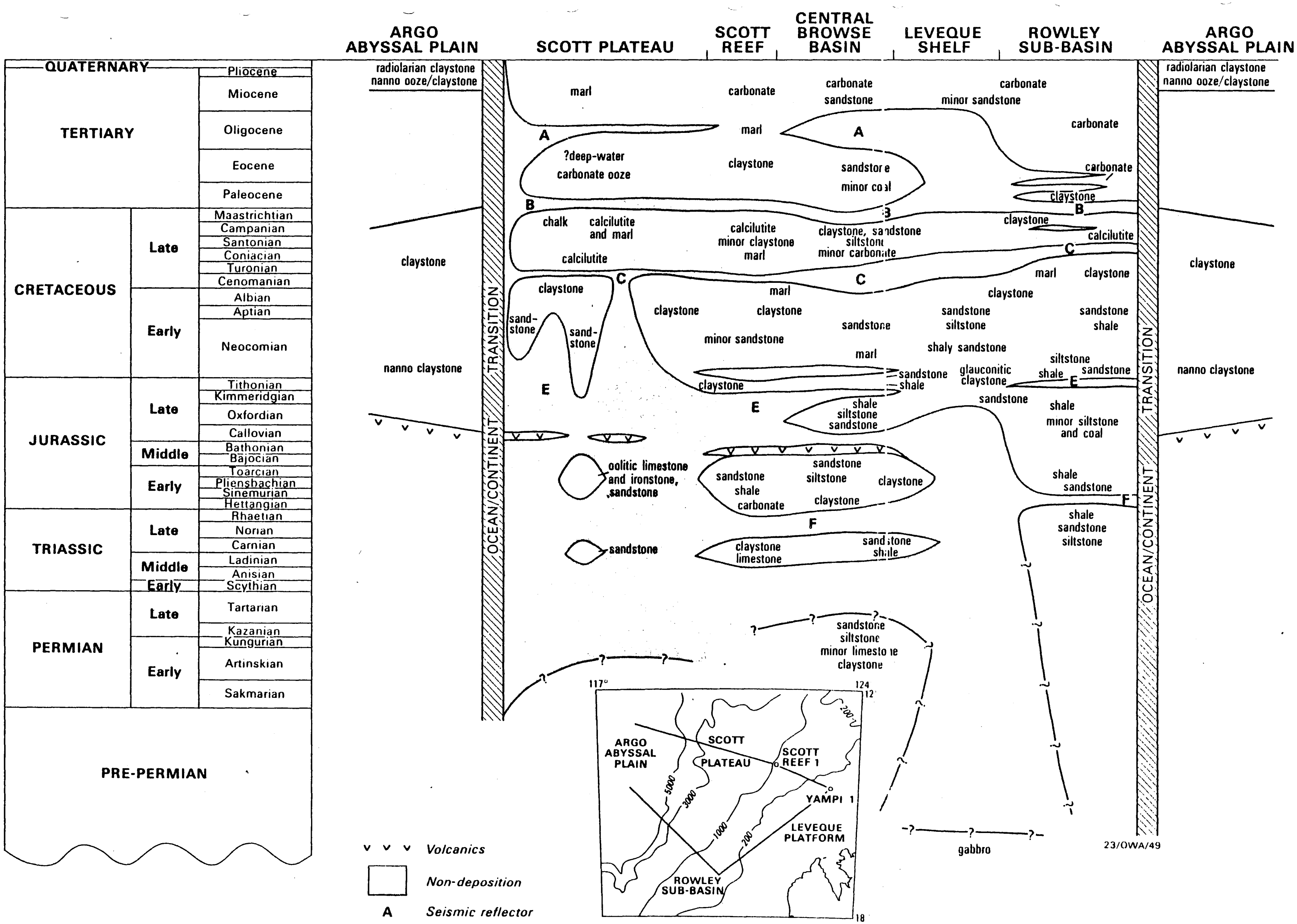


Figure 7. Lithostratigraphic diagram for the offshore Canning Sub-basin and adjacent areas (after Stagg & Exon, 1981)

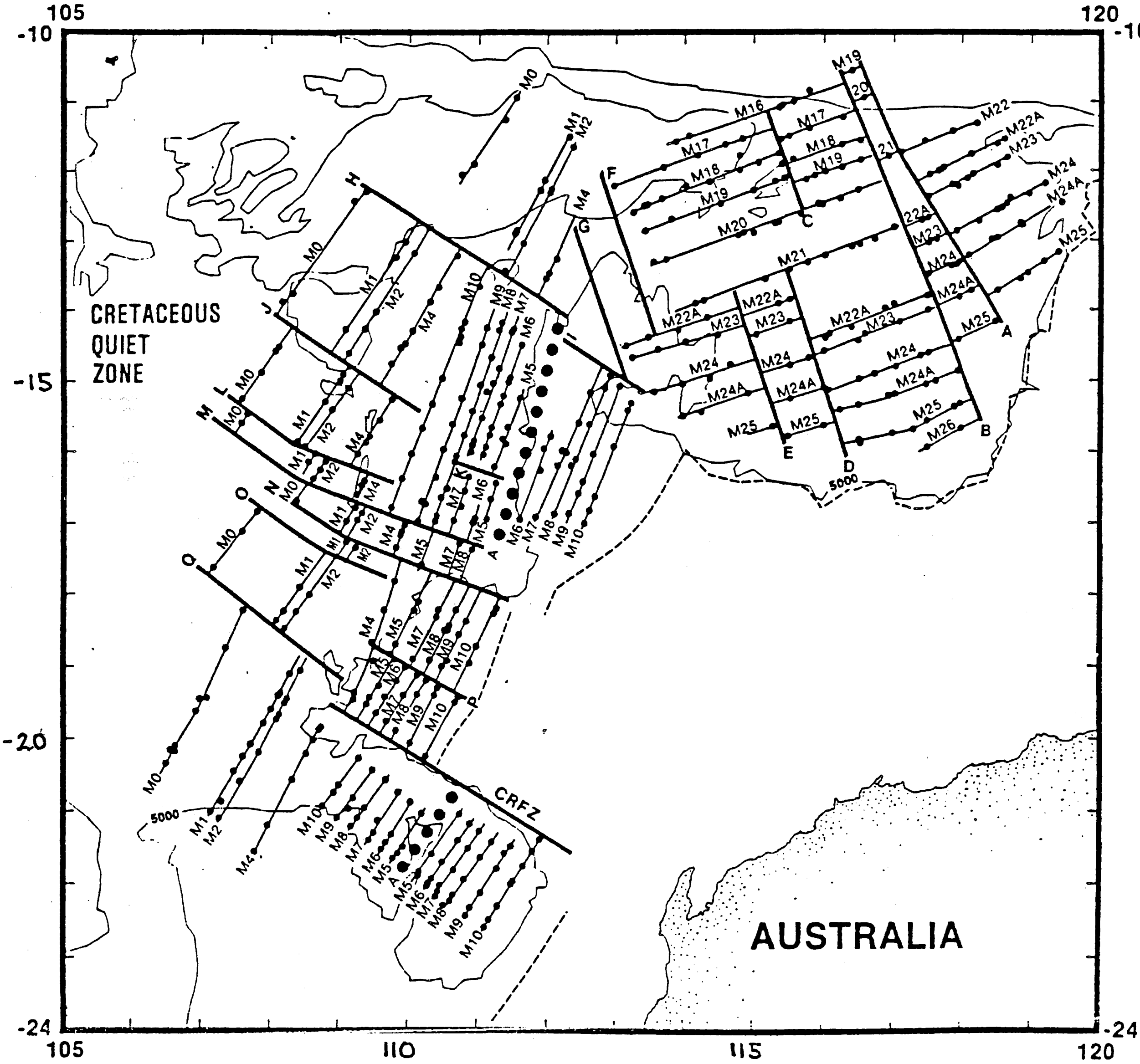


Figure 8. Seafloor spreading anomalies around the Exmouth Plateau (after Fullerton et al., 1989)

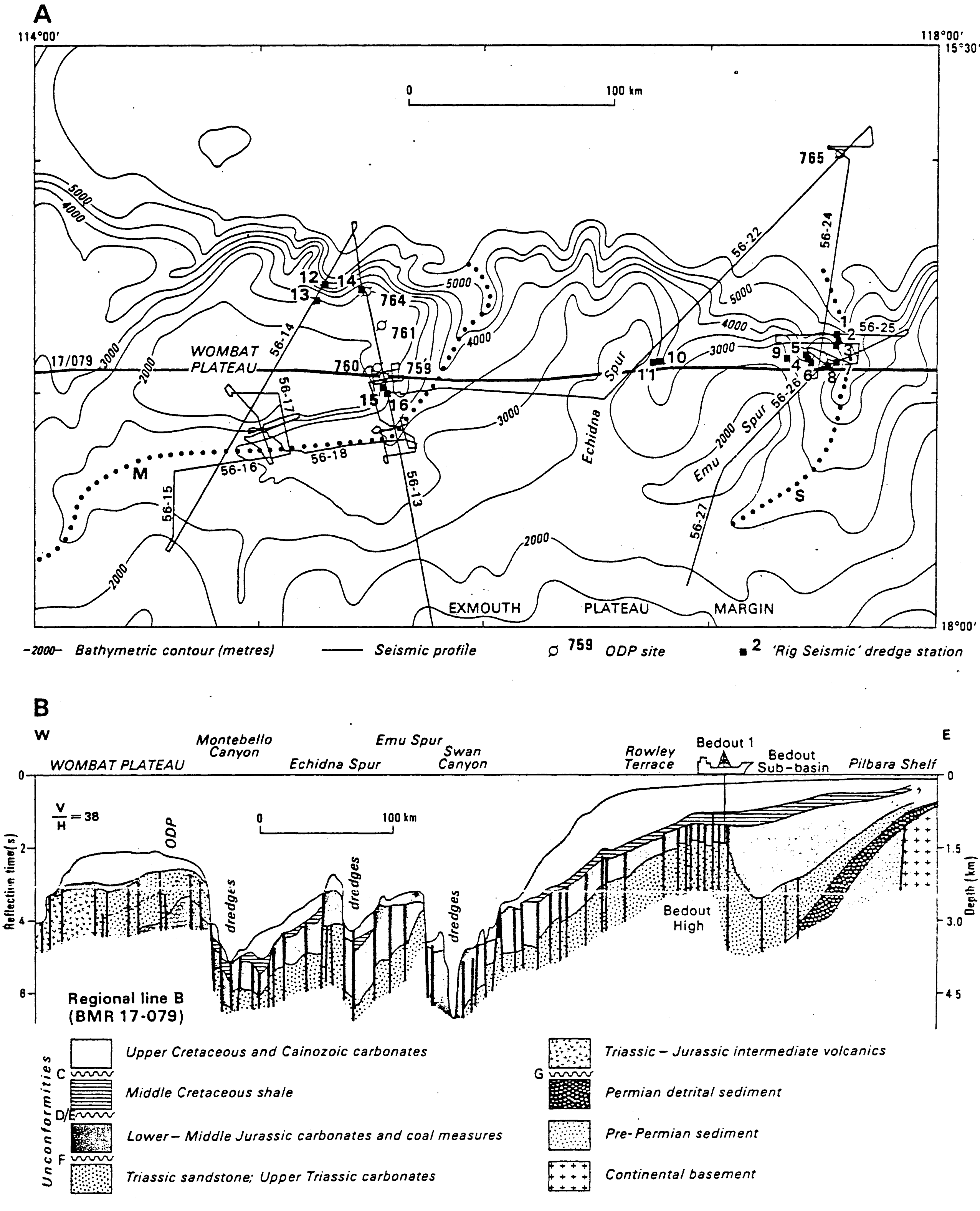
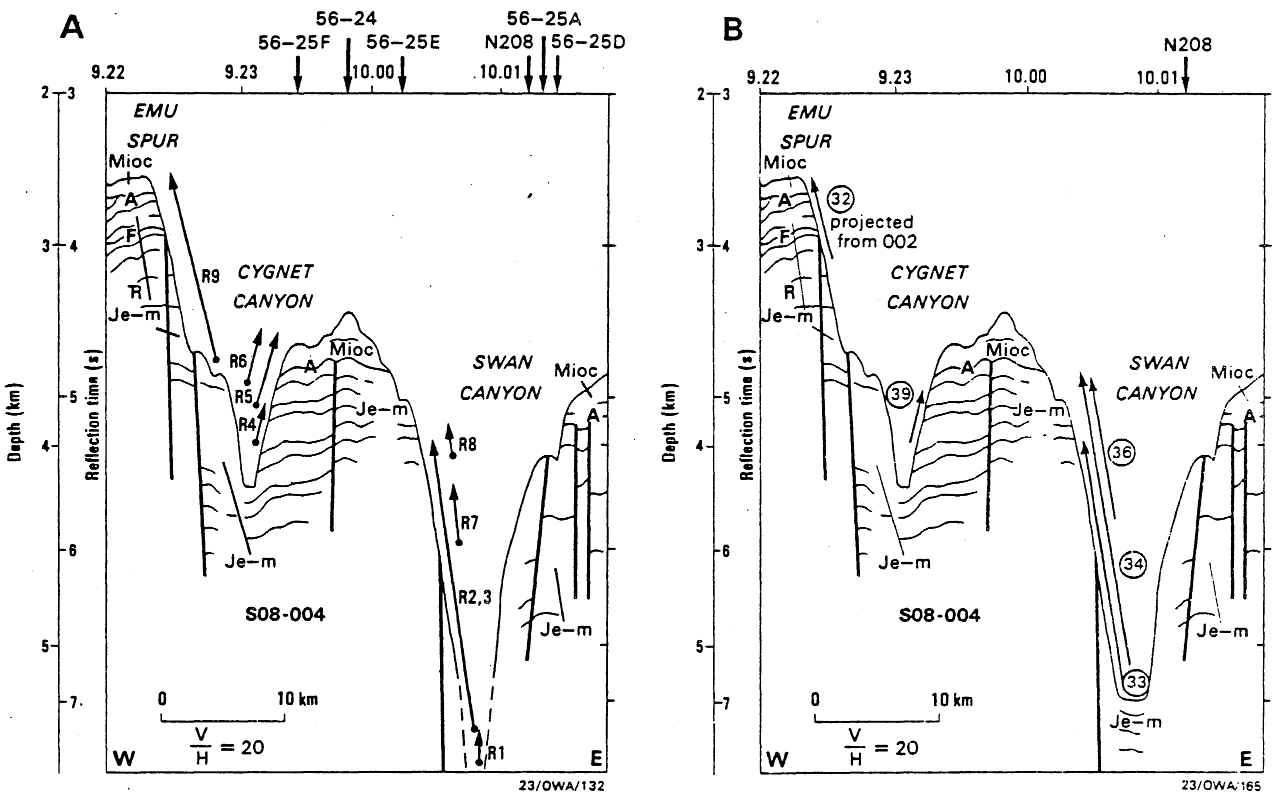


Figure 9. North Exmouth margin. A) Map showing "Rig Seismic" profiles and dredge sites, and ODP sites. B) Schematic east-west profile along northern margin of Exmouth Plateau



Swan Canyon

R1: ? Jurassic coal measures (A2,3,4); ? Cretaceous marine clay (D3)
R2: Callovian coal measures (A2,3,4); ? Cretaceous marly clay (D2)
R3: ? Jurassic coal measures (A2,3,4)
R7: ? Early Cretaceous marine shale, sandstone (D3,4,6)
R8: ? Jurassic ironstone (B1,2,5); ? Cretaceous marine claystone, sandstone (D3,4,6)

Cygnet Canyon

R4: Callovian shelf carbonates (C2,3,4,8); ? Jurassic coal measures (A2) and ironstone (B1,2,3); ? Cretaceous marine claystone (D5)
R5: ? Jurassic coal measures (A2) and ironstone (B3)
R6: ? Jurassic ironstone (B3); Late Aptian and Cenomanian marine mudstone, sandstone, conglomerate (D2,4,6)
R9: ? Oxfordian shelf carbonates (C1,3,4); ? Cretaceous marine sandstone, mudstone (D2,4,6,7)

(32) E1 (Middle Miocene chalk): A2,3 (? Jurassic coal measures); C1,2 (? Jurassic shelf carbonates)

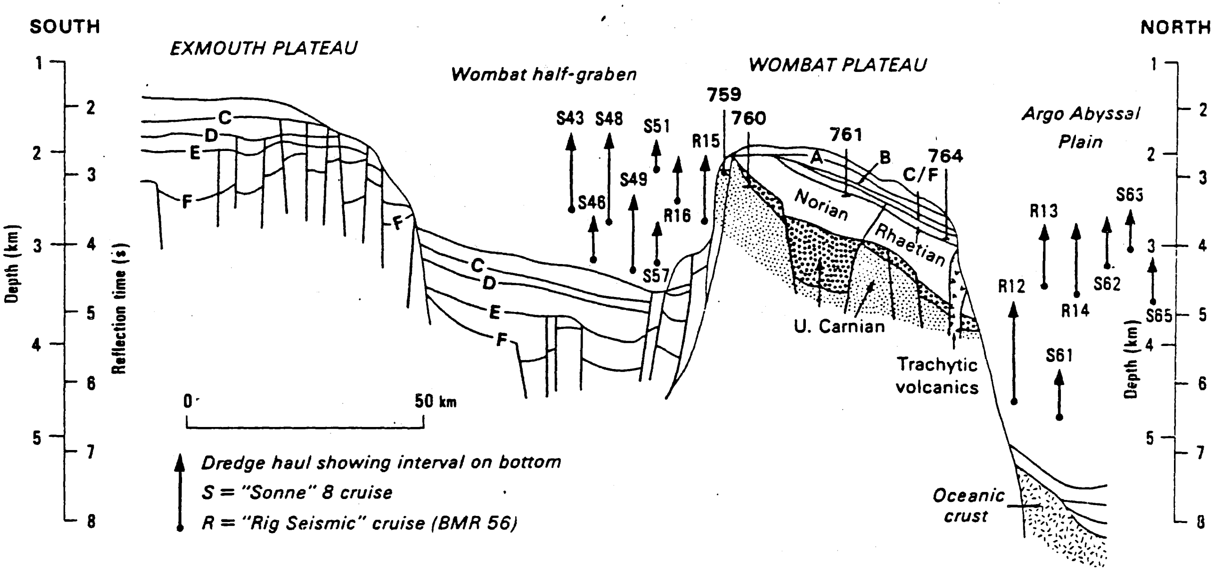
(33) E3,4 (Early Aptian chalk); A2,3 (Middle Jurassic coal measures)

(34) A1–4 (Middle Jurassic coal measures)

(36) E2 (Late Miocene–Early Pliocene chalk); D2 (Late Albian–Early Cenomanian shelf claystone); A1–4 and B1,2 (Middle Jurassic coal measures, some weathered)

(39) D1 (? Cretaceous/Tertiary claystone); D2 (Late Albian–Early Cenomanian shelf claystone); B1–4 (? Jurassic terrest/littoral sediments); A4,5 (? Jurassic coal measures); C1,2,4,5 (? Early Jurassic shelf carbonates)

Figure 10. Dredge locations in the Swan Canyon region of the Exmouth Plateau transposed onto "Sonne" profile 8-004 (locations in Fig. 9)



South of Wombat Plateau

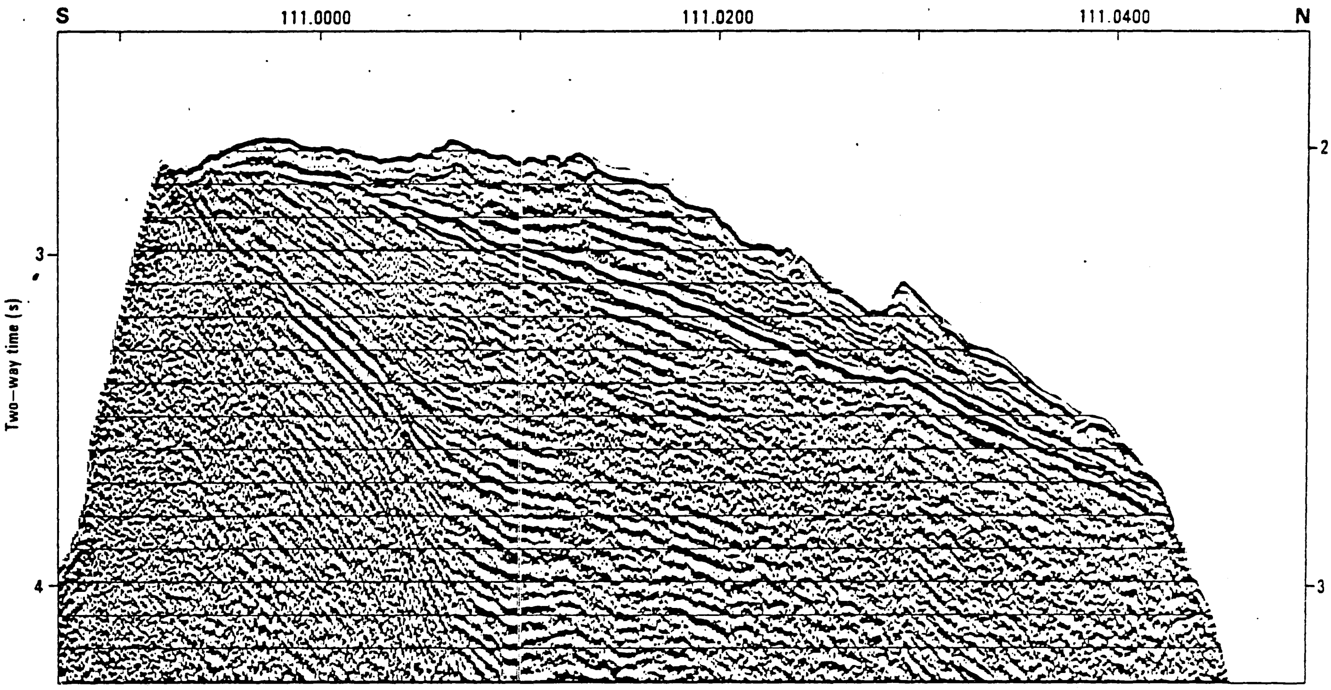
S43: Triassic/Jurassic shelf carbonates (C3,4) and claystone (A4)
S46: Triassic brackish sandstone (A3)
S48: L. Triassic paralic siltstone (A2)
S49: Triassic brackish siltstone (A2,3),
Triassic/Jurassic shelf carbonates (C5,6) and ironstone (B1)
S51: E. Cretaceous shelf mudstone (D2)
S57: Triassic/Jurassic paralic shale, sandstone (A4,6)
R15: Triassic/Jurassic redbeds (D6), coal measures (D4), carbonates (C6)
R16: E. Cretaceous marine sandstone (D4);
L. Triassic shelf carbonates (C2,4); Triassic/Jurassic ironstone (B1,3)

North of Wombat Plateau

S61: L. Triassic/E. Jurassic shelf carbonates and "trachyte" (H4)
S62: E. Jurassic shallow marine carbonates (C2)
S63: Triassic/Jurassic sandstone and mudstone (A2,3,4)
and ironstone (B1,2); L. Triassic/E. Jurassic "trachyte" (H4,7)
S65: L. Triassic "trachyte" (H4); ? Cretaceous bryozoan limestone (C7)
R12: Triassic/Jurassic "trachyte" (H4,8)
R13: Triassic/Jurassic "trachyte" (H1,4,7,8), shelf carbonates (C2),
ironstone (B2,3); ? E. Cretaceous marine mudstone (D2,6)
R14: L. Triassic shelf carbonates (C2,4,6)

23/OWA/131

Figure 11. Wombat Plateau dredge locations transposed onto BMR seismic profile 56-13. Seismic reflectors as in Fig. 6



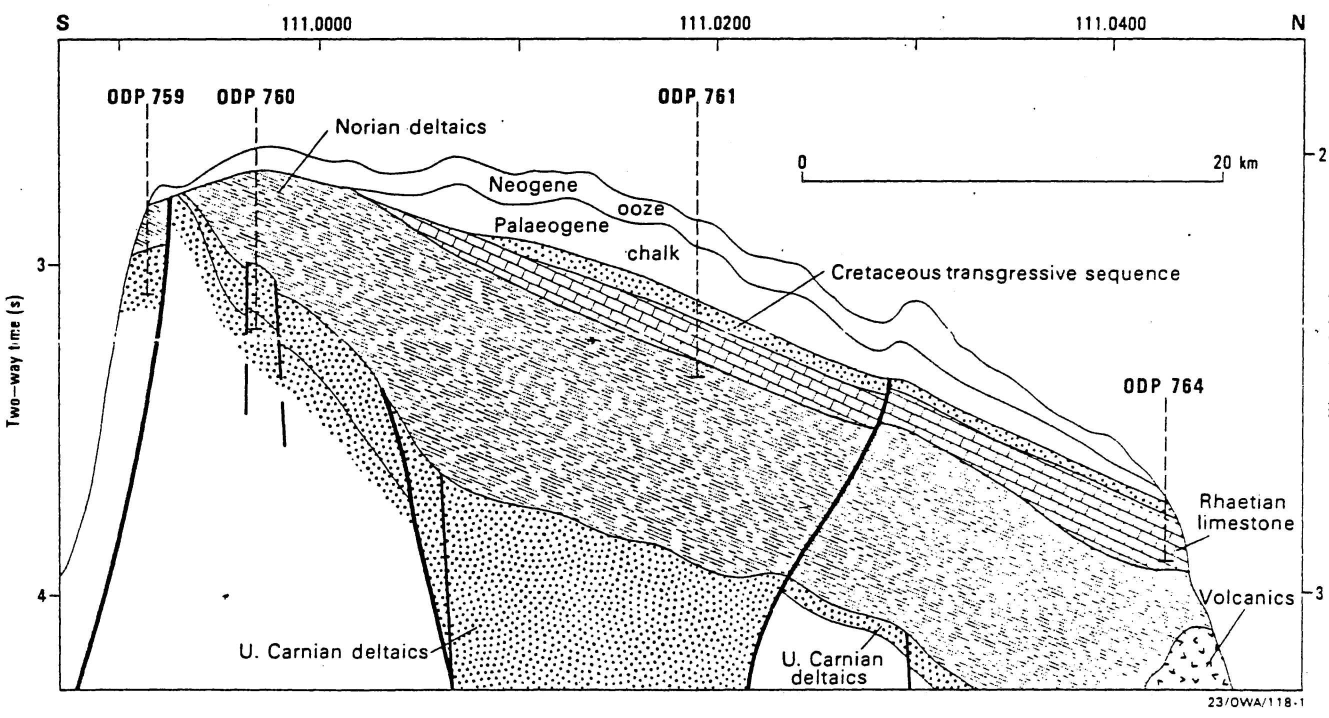


Figure 12. BMR seismic profile 56-13 across Wombat Plateau, showing ODP drill sites (locations in Fig. 1)

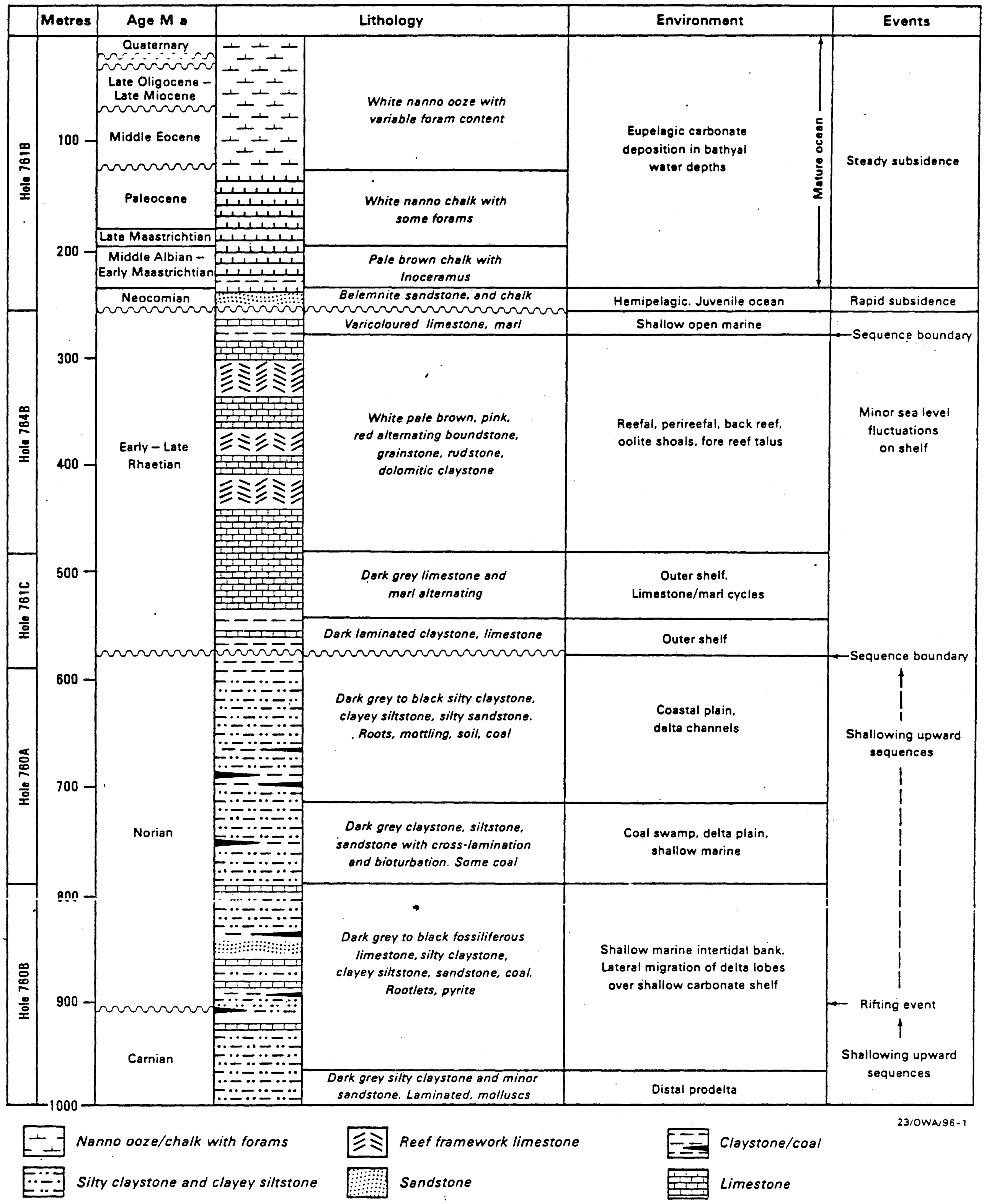


Figure 13. Stratigraphic composite diagram for Wombat Plateau ODP drilling

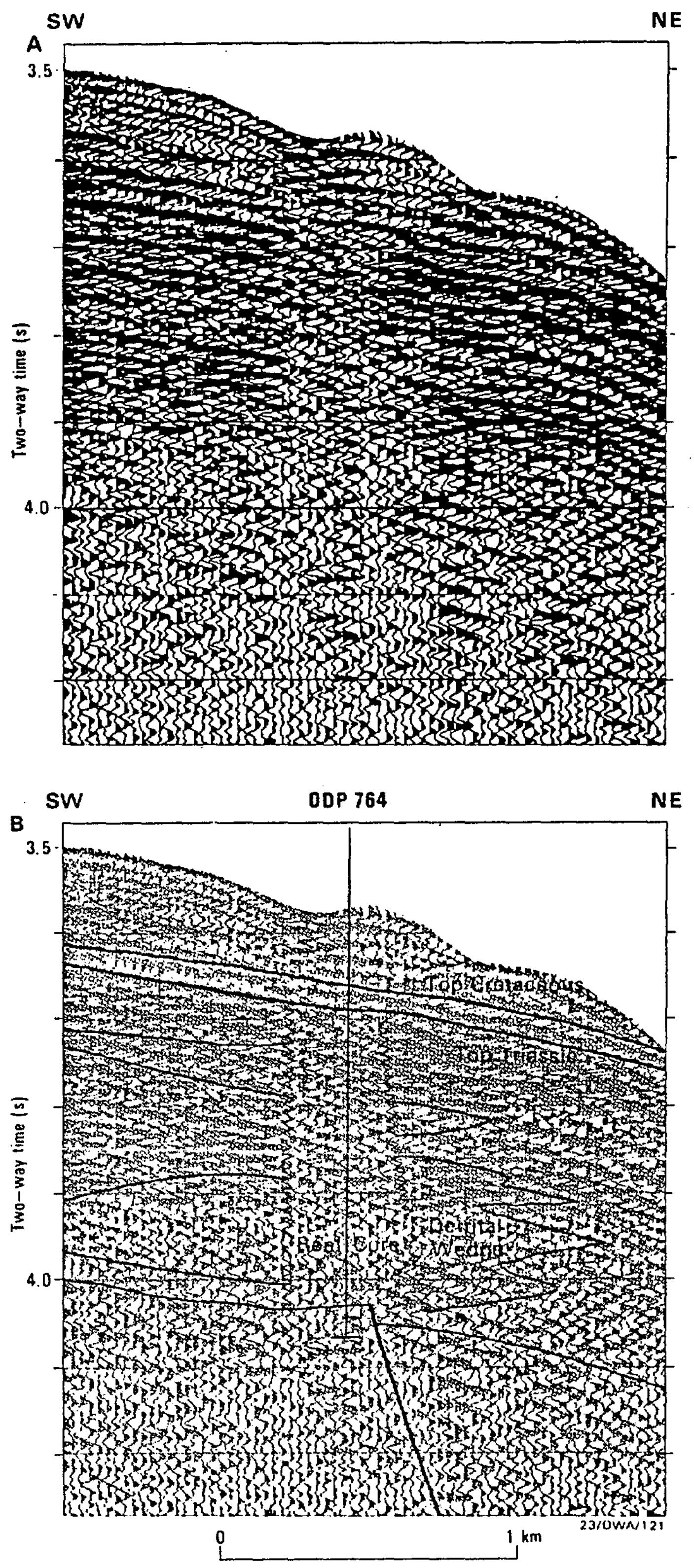


Figure 14. Segment of ODP seismic profile 122-6 showing ODP site 764 which drilled a Rhaetian reef (after Williamson et al, 1989)

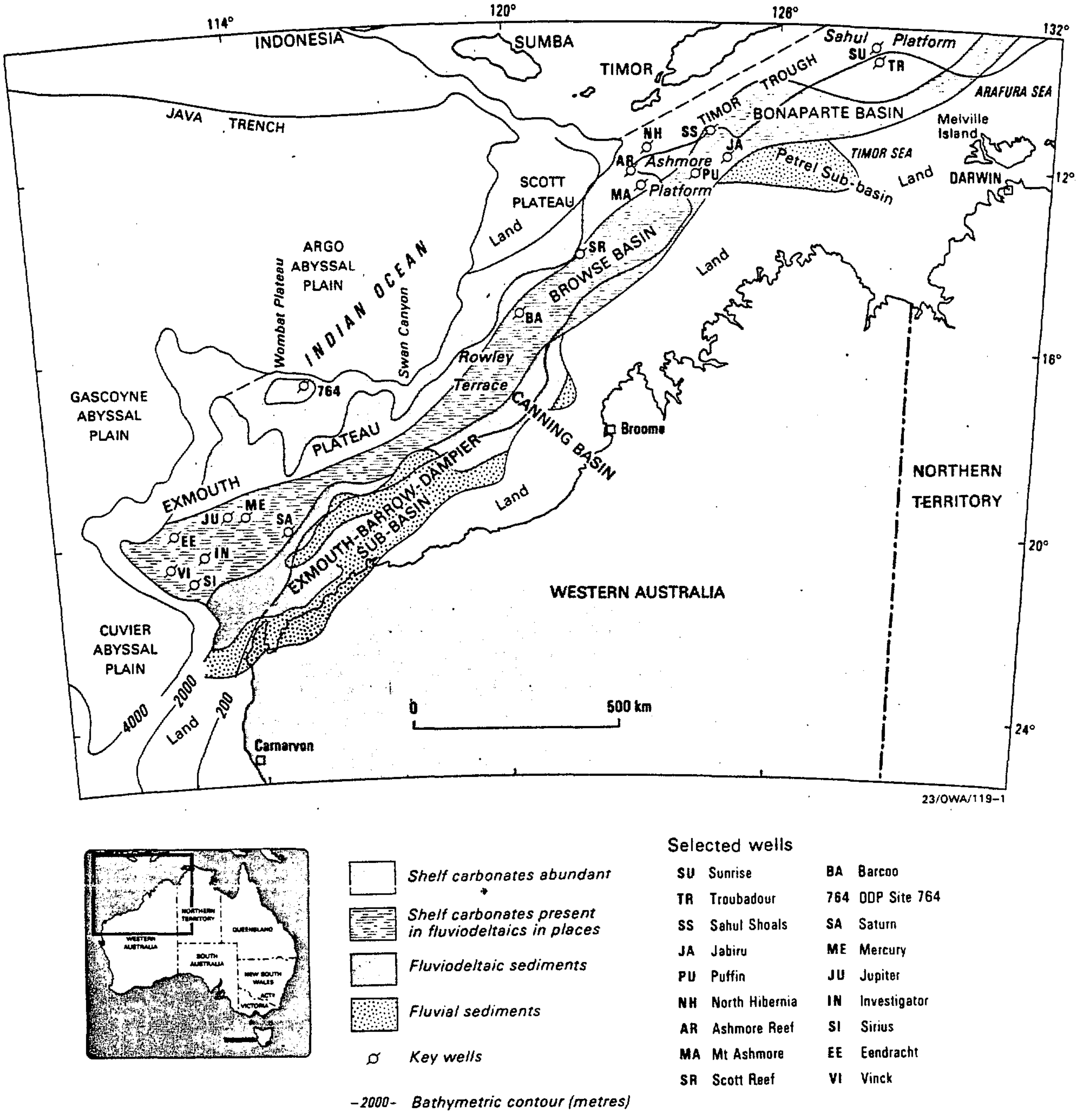


Figure 15. Map of North West Shelf, showing Late Triassic sedimentation patterns derived from well information

Woodside Offshore Petroleum Pty Ltd

DELAMBRE N° 1

STRATIGRAPHIC TABLE

Latitude: 18° 31' 05" S Longitude: 116° 41' 48" E R.T. 10m

AGE				LITHOLOGY	DEPTH (m)	THICKNESS	
				Sea Level	10	10	
				Sea Bed	894	884	
			NOT SAMPLED		1237	343	
CAINOZOIC	NEOGENE		LATE PLIOCENE	FORAMININFERAL ARGILLACEOUS CALCILUTITE	1296	59	
CAINOZOIC	NEOGENE		EARLY PLIOCENE	FORAMININFERAL ARGILLACEOUS CALCILUTITE	1470	174	
CAINOZOIC	NEOGENE		LATE MIOCENE	CLAYSTONE AND CALCISILTITE	1721	251	
CAINOZOIC	NEOGENE		MIDDLE MIOCENE	CALCAREOUS CLAYSTONE, MARL AND CALCILUTITE	1850	139	
CAINOZOIC	NEOGENE		EARLY MIOCENE	CALCILUTITE	1857	7	
CAINOZOIC	PALAEOGENE		LATE OLIGOCENE	CALCILUTITE	1869	12	A 2.15s
CAINOZOIC	PALAEOGENE		MIDDLE EOCENE	CALCILUTITE AND CALCISILTITE	1916	47	
CAINOZOIC	PALAEOGENE		EARLY EOCENE	CALCILUTITE AND CALCISILTITE	1991	75	
CAINOZOIC	PALAEOGENE		LATE PALAEOCENE	CALCILUTITE AND CALCISILTITE	2060	69	
CAINOZOIC	PALAEOGENE		PALAEOCENE UNDIFF.	CALCILUTITE AND CALCISILTITE	2066	6	
CAINOZOIC	PALAEOGENE		EARLY PALAEOCENE	CLAYSTONE	2069	3	B 2.35s
MESOZOIC	CRETACEOUS	LATE	LATE MAASTRICHTIAN	MARL	2101	32	
MESOZOIC	CRETACEOUS	LATE	EARLY MAASTRICHTIAN	MARL	? 2120	19	
MESOZOIC	CRETACEOUS	LATE	LATE CAMPANIAN	MARL	2156	36	
MESOZOIC	CRETACEOUS	LATE	INDETERMINABLE	MARL AND CALCILUTITE	2169	13	
MESOZOIC	CRETACEOUS	LATE	LATE SANTONIAN	MARL AND CALCILUTITE	? 2193	24	
MESOZOIC	CRETACEOUS	LATE	EARLY SANTONIAN	MARL AND CALCILUTITE	2200	7	
MESOZOIC	CRETACEOUS	LATE	CONIACIAN	MARL AND CALCILUTITE	2222	22	
MESOZOIC	CRETACEOUS	LATE	? TURONIAN	CALCILUTITE	2240	18	C 2.50s
MESOZOIC	CRETACEOUS	LATE	LATE CENOMANIAN	MARL AND CALCILUTITE	? 2245	5	
MESOZOIC	CRETACEOUS	EARLY	EARLIEST CENOMANIAN TO LATE ALBIAN	MARL	2253	8	
MESOZOIC	CRETACEOUS	EARLY	MIDDLE TO EARLY ALBIAN	MARL AND CALCILUTITE	2286	33	
MESOZOIC	CRETACEOUS	EARLY	INDETERMINABLE	CLAYSTONE	2288	2	
MESOZOIC	CRETACEOUS	EARLY	BARREMIAN	CLAYSTONE	2318	30	D 2.57s
MESOZOIC	CRETACEOUS	EARLY	BERRIASIAN	CLAYSTONE AND SANDSTONE	2346	28	E 2.60s
MESOZOIC	JURASSIC	MID	BATHONIAN TO BAJOCIAN	SANDSTONE, SILTSTONE AND CLAYSTONE	3353	1007	
MESOZOIC	JURASSIC	EARLY	AALENIAN TO TOARCIAN	CLAYSTONE	3964	611	
MESOZOIC	JURASSIC	EARLY	PLIENSBACHIAN TO HETTANGIAN	CLAYSTONE, LIMESTONE AND SANDSTONE	4287	323	F 3.75s
MESOZOIC	TRIASSIC	LATE	RHAETIAN	CLAYSTONE AND SANDSTONE	4604	317	
MESOZOIC	TRIASSIC	LATE	NORIAN	CLAYSTONE AND SANDSTONE	4665	61	
MESOZOIC	TRIASSIC	LATE	NORIAN TO CARNIAN	CLAYSTONE, SANDSTONE AND SILTSTONE	5264	599	
MESOZOIC	TRIASSIC	LATE	CARNIAN	CLAYSTONE, SANDSTONE AND SILTSTONE	T.D. 5495	231	

Compiled: R. Malcolm Drawn: J. Boshart Date: April, 1981 400 - 7323s

Figure 16. Lithological log of Woodside Delambre No.1 well

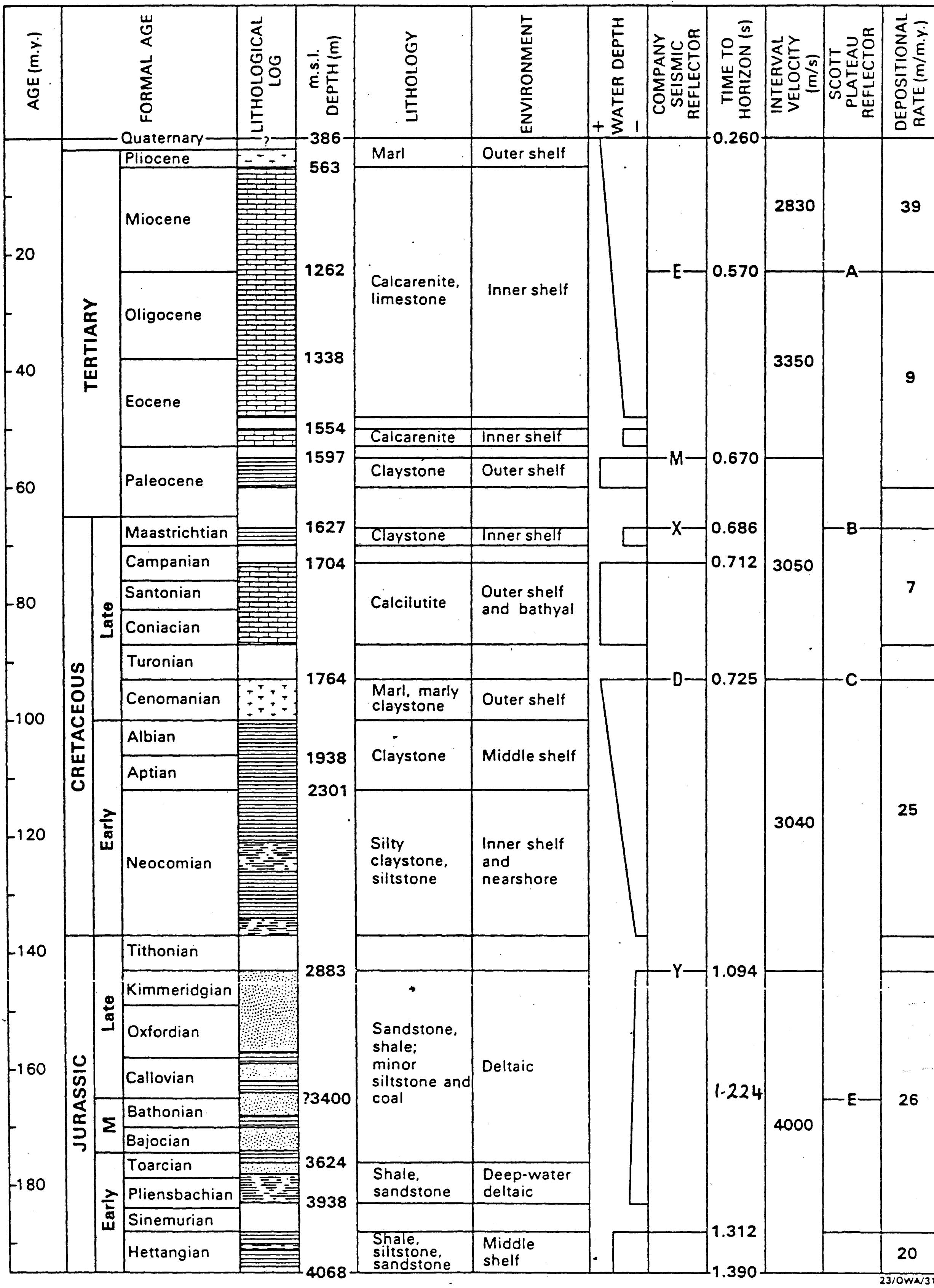


Figure 17. Lithological log of Shell East Mermaid No.1 well

Woodside Petroleum Development Pty Ltd

BARCOO N°1

STRATIGRAPHIC TABLE

Latitude 15° 20' 37.0" S Longitude 120° 38' 12.2" E RT 11m

Era	Period	AGE	LITHOLOGY	DEPTH (m)	THICKNESS (m)	
			Sea Level	11	11	
			Sea Bed	731	720	
		NOT SAMPLED		1125	394	
CAINOZOIC	NEOGENE	MIDDLE MIOCENE	CALCARENITE, SKELETAL, MINOR CALCISILTITE	1705	580	
CAINOZOIC	NEOGENE	UPPERMOST EARLY MIOCENE	CALCARENITE, CALCISILTITE AND CALCILUTITE	2222	517	
CAINOZOIC	NEOGENE	EARLY MIOCENE	MARL AND CALCILUTITE	?2285	63	
CAINOZOIC	PALAEOGENE	LATE OLIGOCENE		2343	58	A
CAINOZOIC	PALAEOGENE	LATE EOCENE	CALCILUTITE AND MARL	2355	12	
CAINOZOIC	PALAEOGENE	INDETERMINABLE	CALCILUTITE	2400	45	
CAINOZOIC	PALAEOGENE	MIDDLE EOCENE	CALCILUTITE, PARTLY RECRYSTALLISED	2430	30	
CAINOZOIC	PALAEOGENE	INDETERMINABLE	CALCILUTITE, PARTLY RECRYSTALLISED, AND MINOR SILTSTONE	2457	27	
CAINOZOIC	PALAEOGENE	EARLY EOCENE	CALCILUTITE AND CLAYSTONE	2530	73	
CAINOZOIC	PALAEOGENE	LATE PALAEOCENE		2538	12	
CAINOZOIC	PALAEOGENE	LATE PALAEOCENE	ARGILLACEOUS CALCILUTITE, CLAYSTONE AND MARL	?2638	100	
CAINOZOIC	PALAEOGENE	MIDDLE PALAEOCENE	ARGILLACEOUS CALCILUTITE	2675	37	
CAINOZOIC	PALAEOGENE	EARLY PALAEOCENE	MARL, MINOR CALCILUTITE	2702	27	B 2.28s
MESOZOIC	CRETACEOUS	LATE MAASTRICHTIAN	MARL, CALCILUTITE, MINOR CLAYSTONE	2749	47	
MESOZOIC	CRETACEOUS	LATE CAMPANIAN	MARL, MINOR CALCILUTITE	2966	217	
MESOZOIC	CRETACEOUS	EARLY CAMPANIAN		2967	1	
MESOZOIC	CRETACEOUS	SANTONIAN	CALCILUTITE, MARL AND CLAYSTONE	3001	34	
MESOZOIC	CRETACEOUS	CONIACIAN	CLAYSTONE AND MINOR CALCILUTITE	3006	5	
MESOZOIC	CRETACEOUS	TURONIAN	CALCILUTITE	3007	1	C 2.47s
MESOZOIC	CRETACEOUS	PROBABLE MIDDLE CENOMANIAN	CLAYSTONE	3054	47	
MESOZOIC	CRETACEOUS	EARLIEST CENOMANIAN TO LATEST ALBIAN	CLAYSTONE, MINOR CALCILUTITE	3137	83	
MESOZOIC	CRETACEOUS	LATE TO MIDDLE ALBIAN	CLAYSTONE	3174	37	
MESOZOIC	CRETACEOUS	ALBIAN UNDIFF.		3330	156	
MESOZOIC	CRETACEOUS	EARLY ALBIAN TO LATE APTIAN	CLAYSTONE, SILTSTONE AND LIMESTONE	3653	323	
MESOZOIC	CRETACEOUS	EARLY APTIAN TO LATE BARREMIAN	CLAYSTONE	?3712	59	
MESOZOIC	CRETACEOUS	BARREMIAN TO BERRIASIAN	CLAYSTONE AND MARL	3796	84	
MESOZOIC	JURASSIC	OXFORDIAN TO LATE CALLOVIAN	CLAYSTONE, MINOR SANDSTONE	3816	20	
MESOZOIC	JURASSIC	CALLOVIAN	CLAYSTONE, MINOR CALCILUTITE	3829	13	E 3.02s
MESOZOIC	JURASSIC	BAJOCIAN TO AALENIAN	SANDSTONE, CLAYSTONE, MINOR SILTSTONE	4105	276	
MESOZOIC	JURASSIC	TOARCIAN	CLAYSTONE, SANDSTONE, MINOR SILTSTONE	4283	178	
MESOZOIC	JURASSIC	PLIENSBACHIAN TO HETTANGIAN	CLAYSTONE, SANDSTONE, SILTSTONE, RECRYSTALLISED LIMESTONE	?4748	465	
MESOZOIC	TRIASSIC	RHAETIAN	CLAYSTONE, MINOR SANDSTONE AND SILTSTONE	~4845	97	F 3.57s
MESOZOIC	TRIASSIC	RHAETIAN TO NORIAN	CLAYSTONE, RECRYSTALLISED LIMESTONE, SANDSTONE, SILTSTONE, MINOR ACID INTRUSIVES	TD 5109m	264	

Compiled S J. Robinson Drawn T Wood Date. September, 1980 400-7188 s

Figure 18. Lithological log of Woodside Barcoo No.1 well

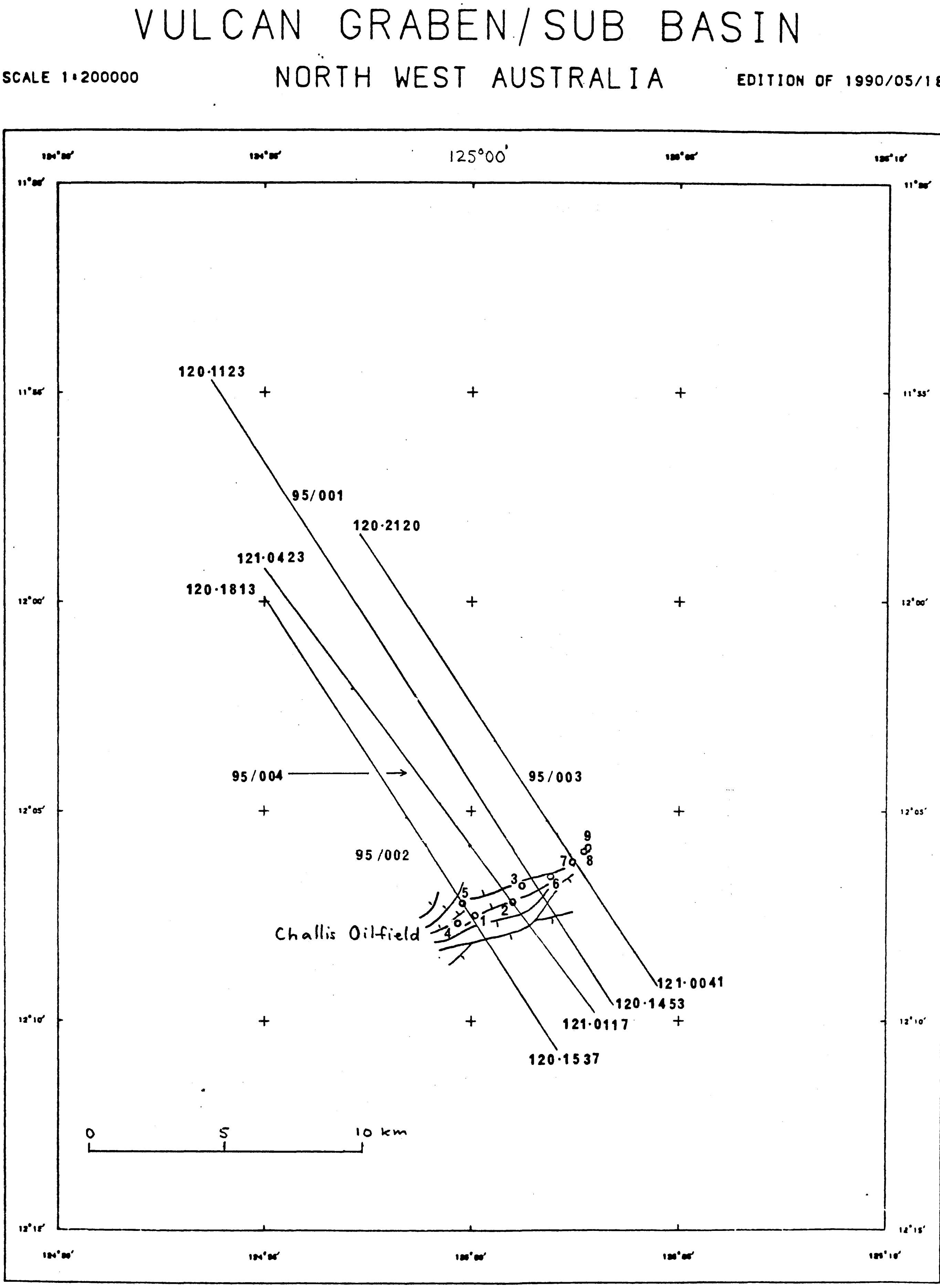
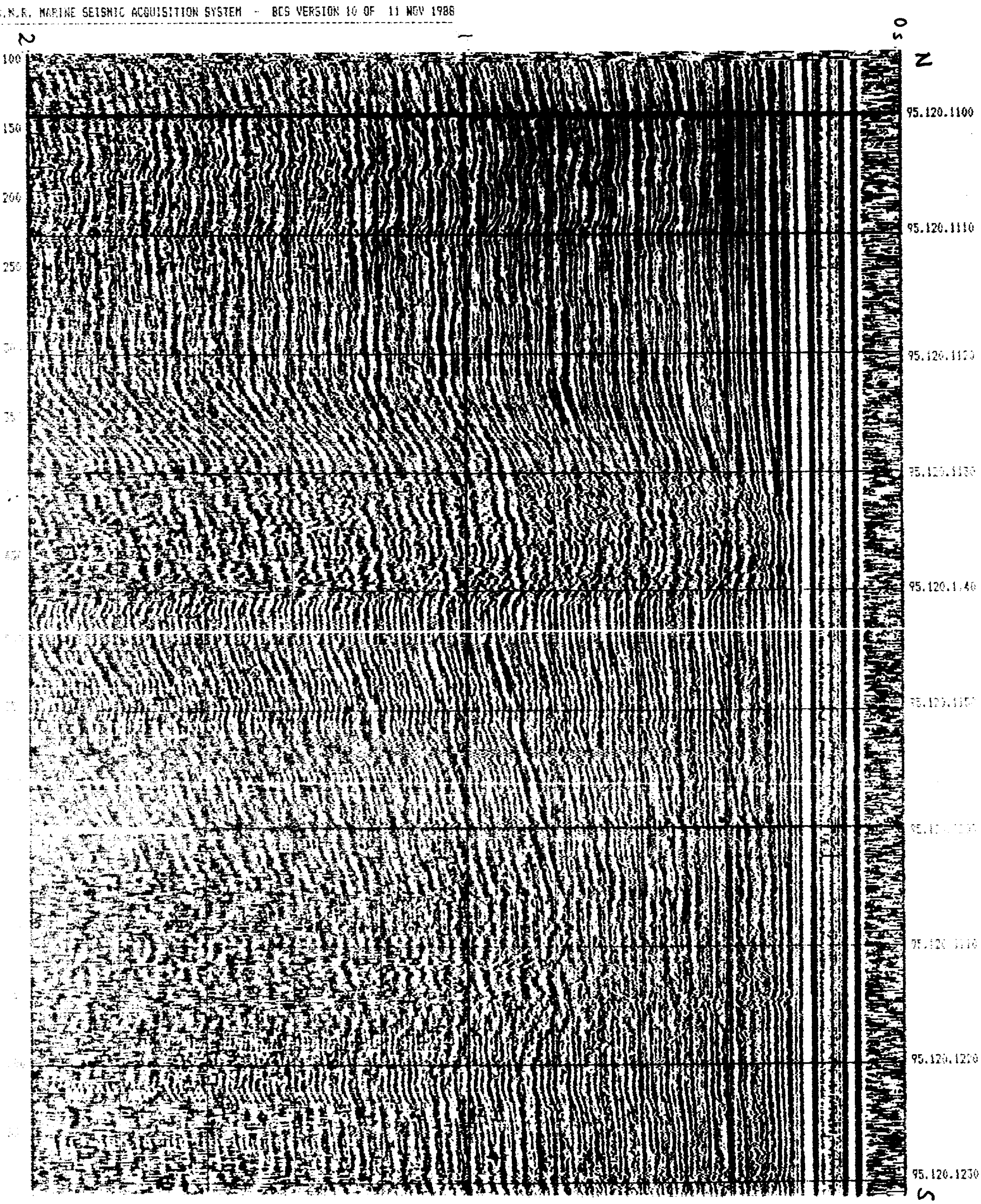


Figure 19. Map showing high-resolution seismic lines recorded in the Vulcan Sub-basin across the Challis oilfield

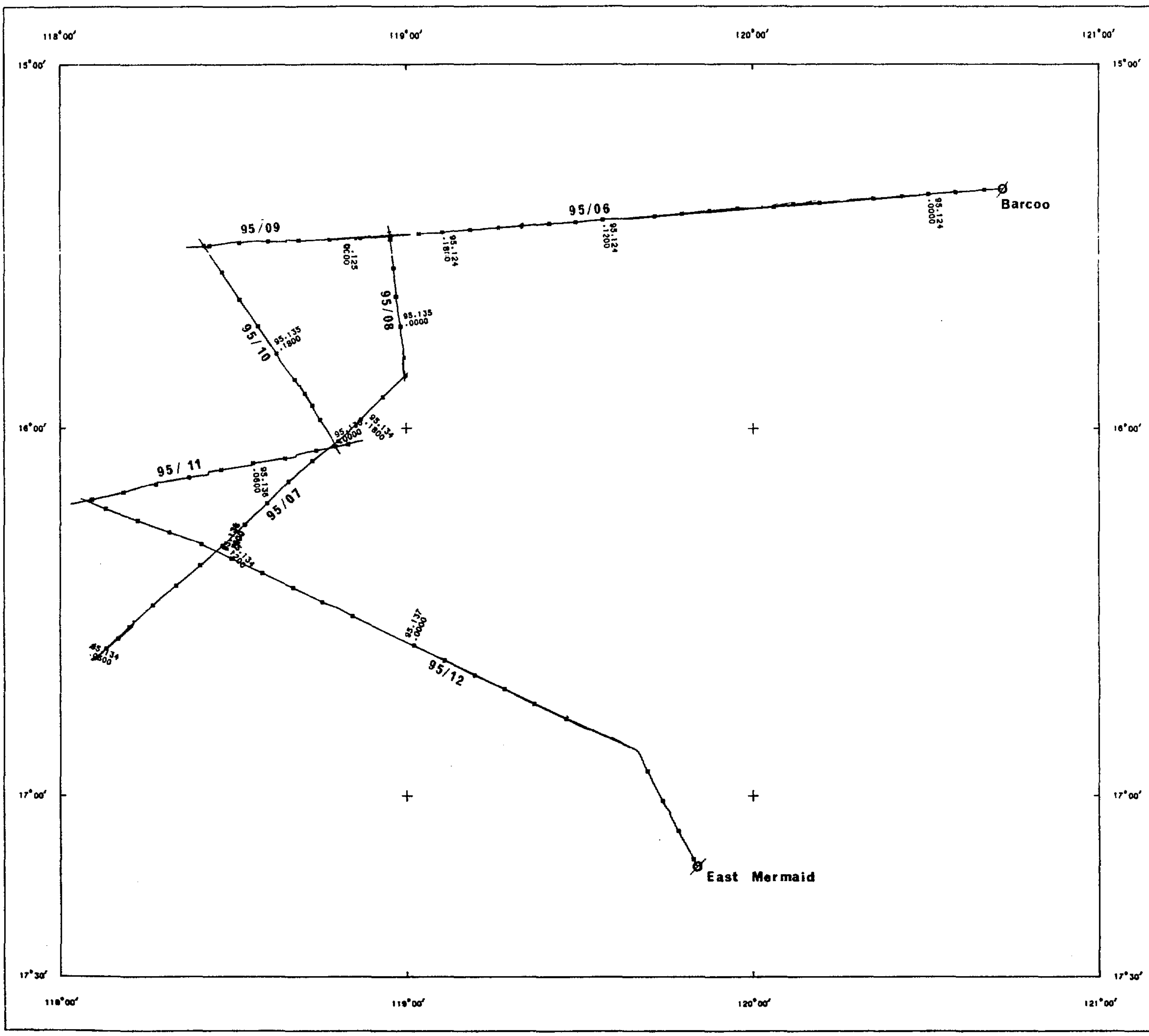
Figure 20. Part of seismic monitor record 95/001 across the Challis oilfield



B.M.R. CRUISE 95

SCALE 1:1500000

EDITION OF 1990/05/24



WORLD GEODETIC SYSTEM 1972
UNIVERSAL MERCATOR (SPHERE)
WITH NATURAL SCALE CORRECT
AT LATITUDE 12 00

CANNING BASIN REGIONAL SEISMIC SURVEY

B.M.R. CRUISE 95

Figure 21. Map of seismic survey in the offshore Canning Basin

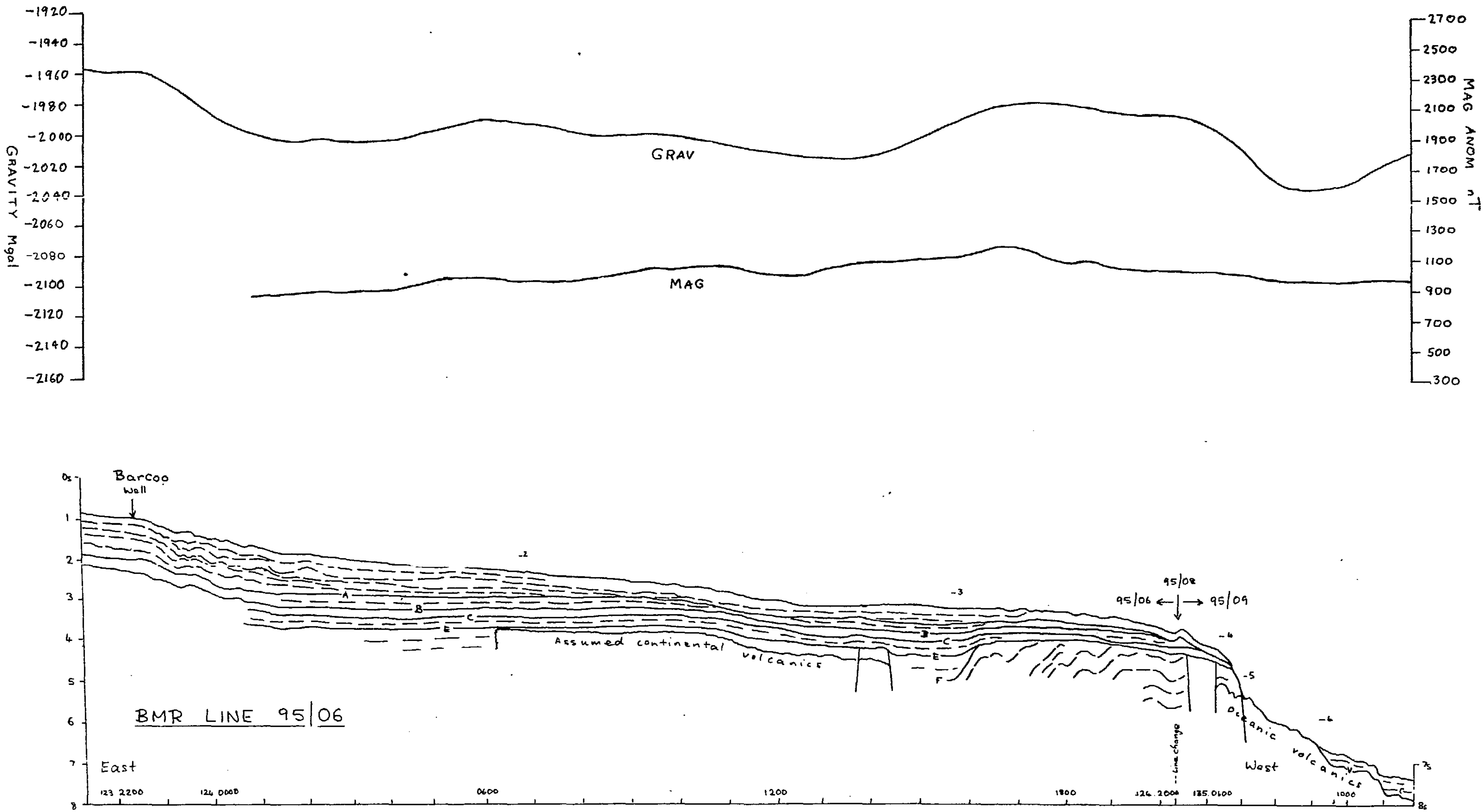


Figure 22. Line drawing of monitor records of BMR 95/06 & 09

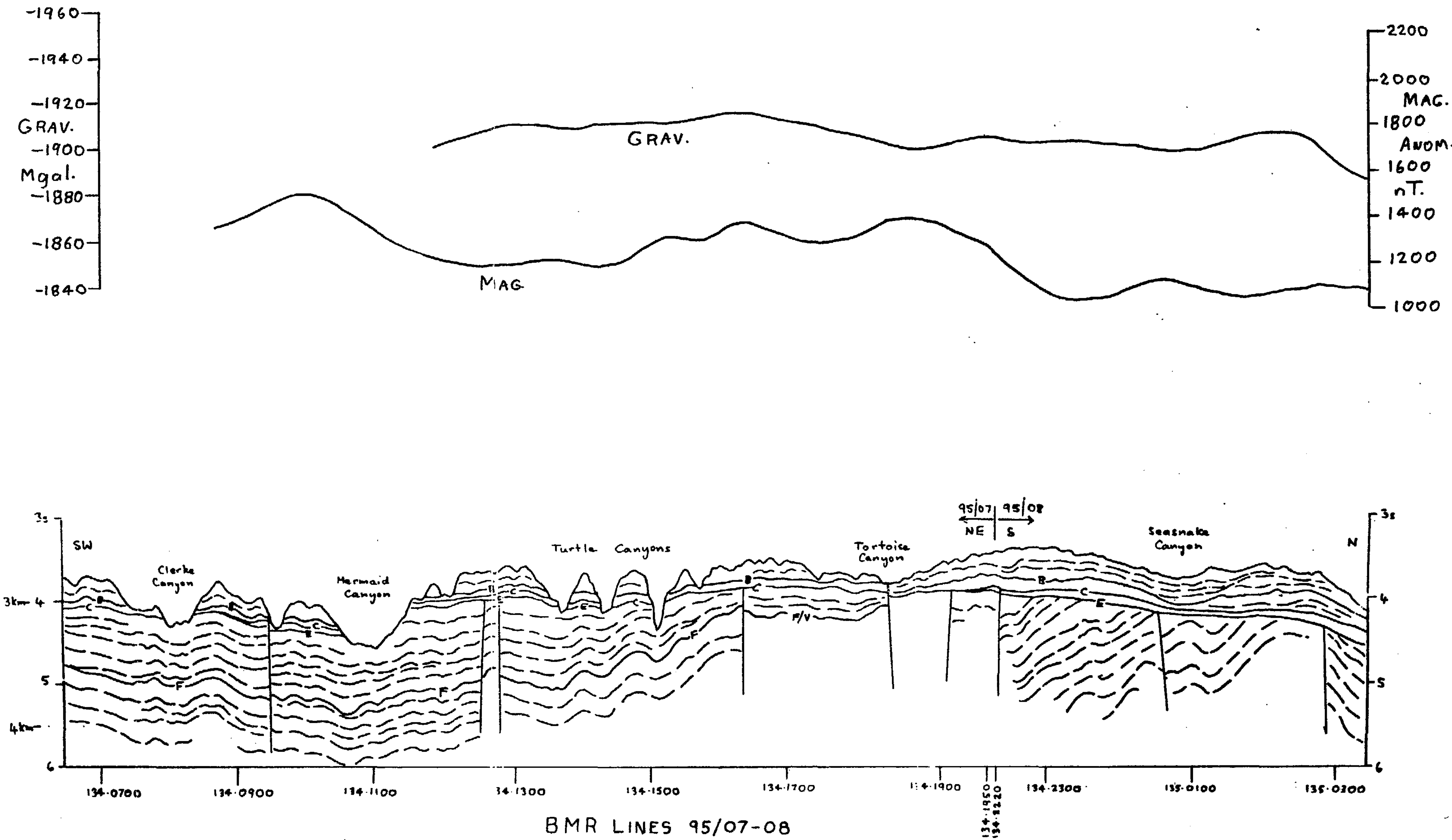


Figure 23. Line drawing of monitor records of BMR 95/07 & 08

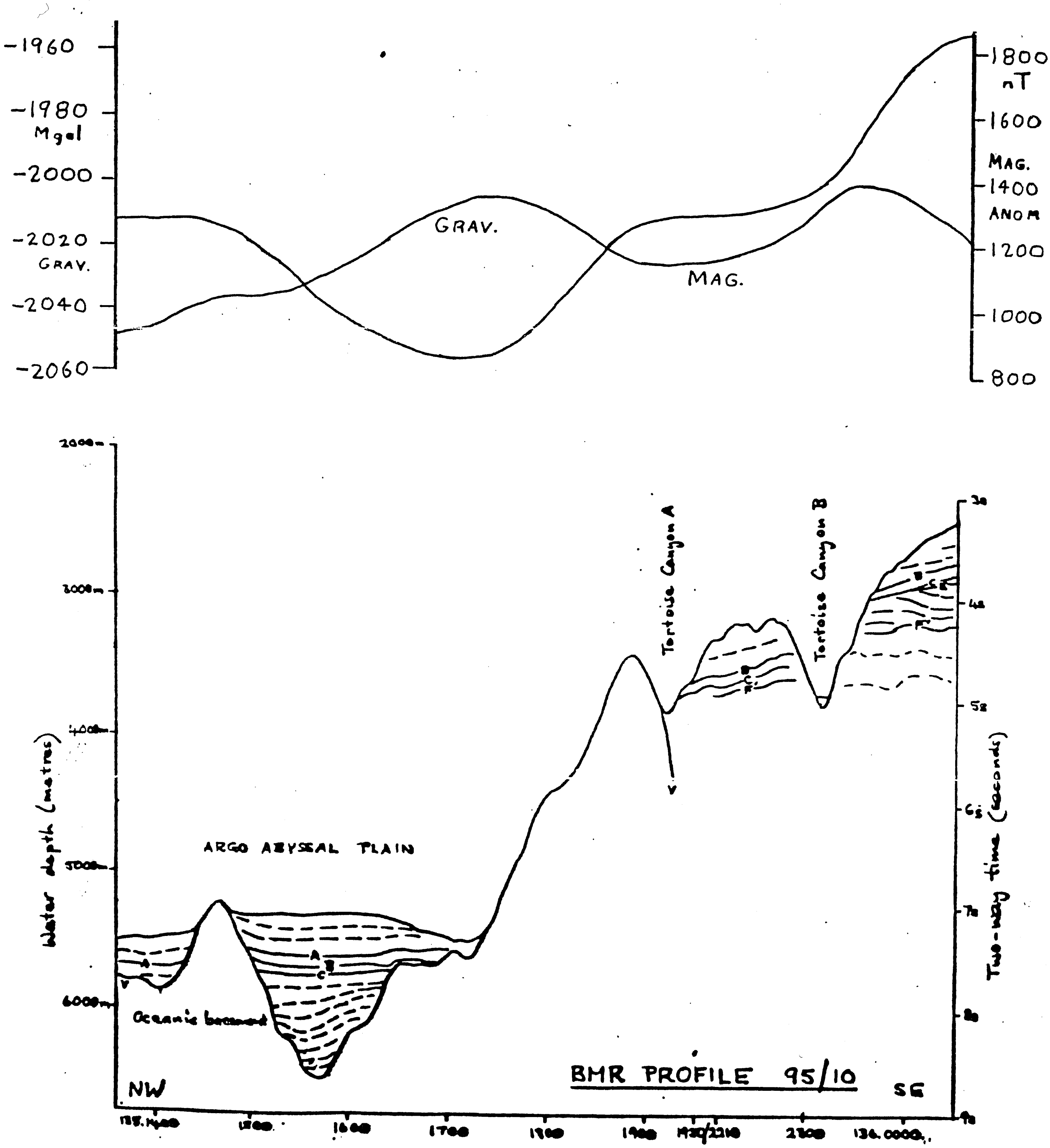


Figure 24. Line drawing of monitor record of BMR 95/10

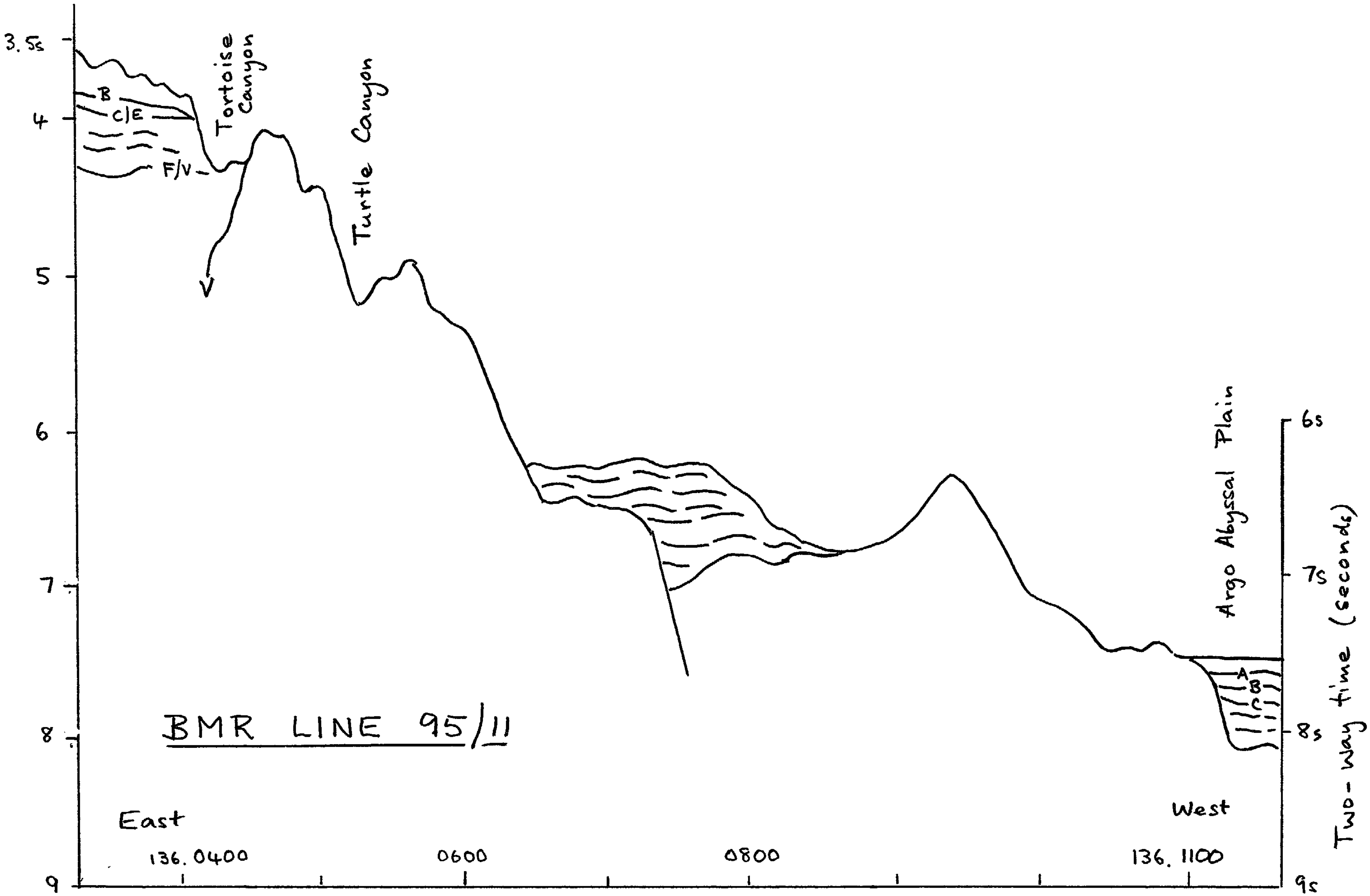


Figure 25. Line drawing of monitor record of BMR 95/11

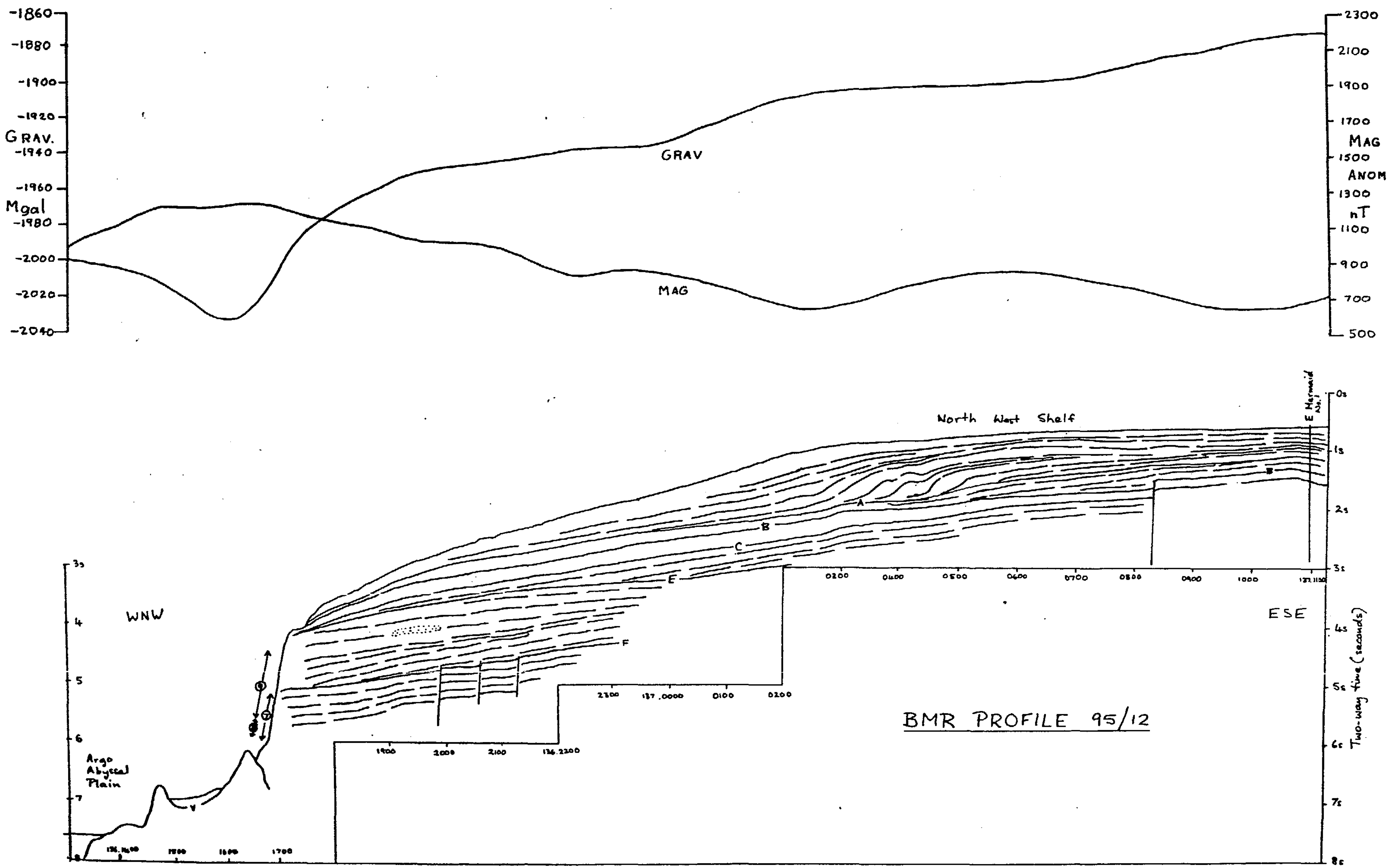
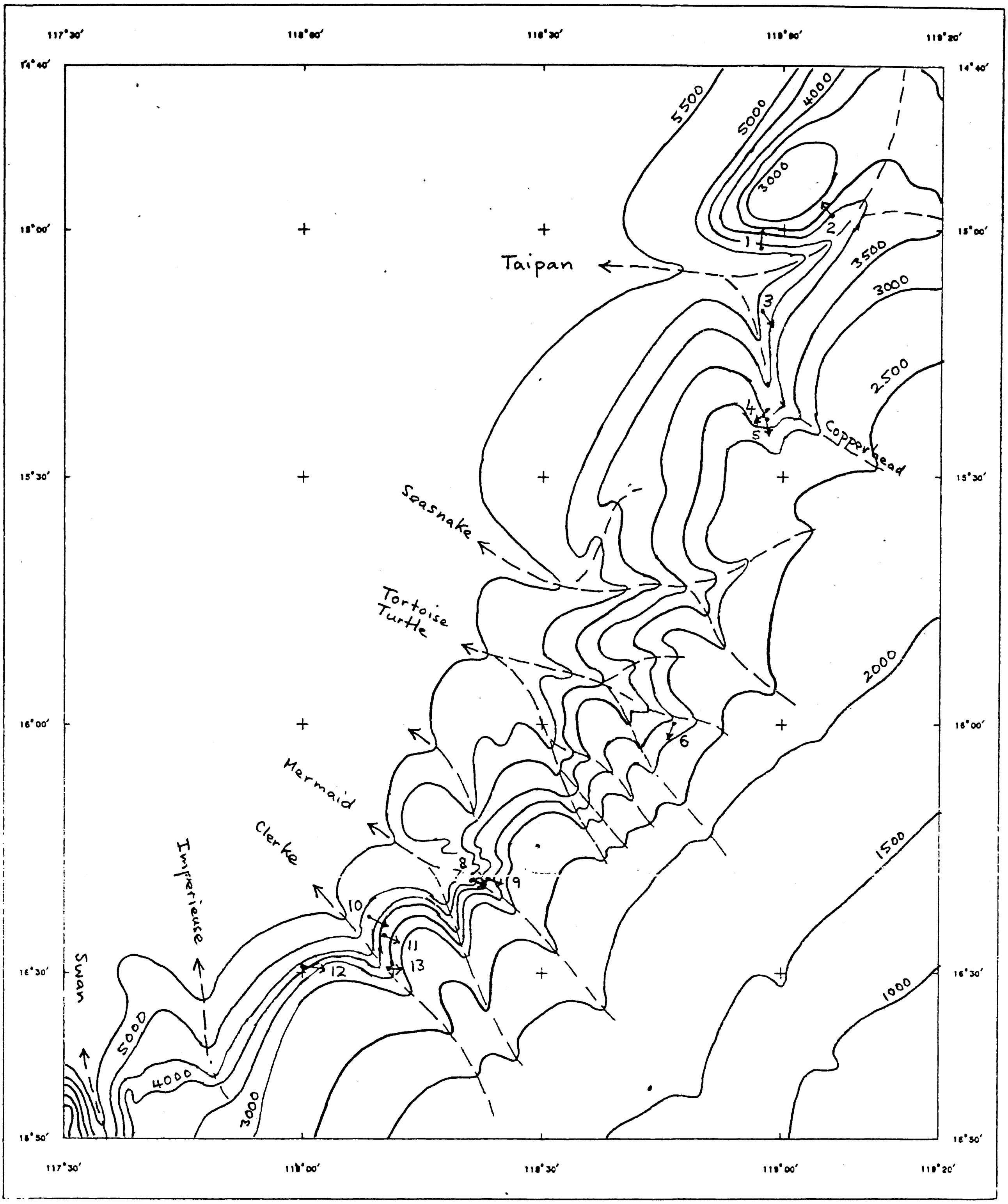


Figure 26. Line drawing of monitor record of BMR 95/12

SCALE 1:999999 EDITION OF 1990/05/20



WORLD GEODETIC SYSTEM 1972
UNIVERSAL MERCATOR (SPHERE)
WITH NATURAL SCALE CORRECT
AT LATITUDE 33 00

Figure 27. Map of dredge sampling survey in the offshore Canning Basin related to bathymetry

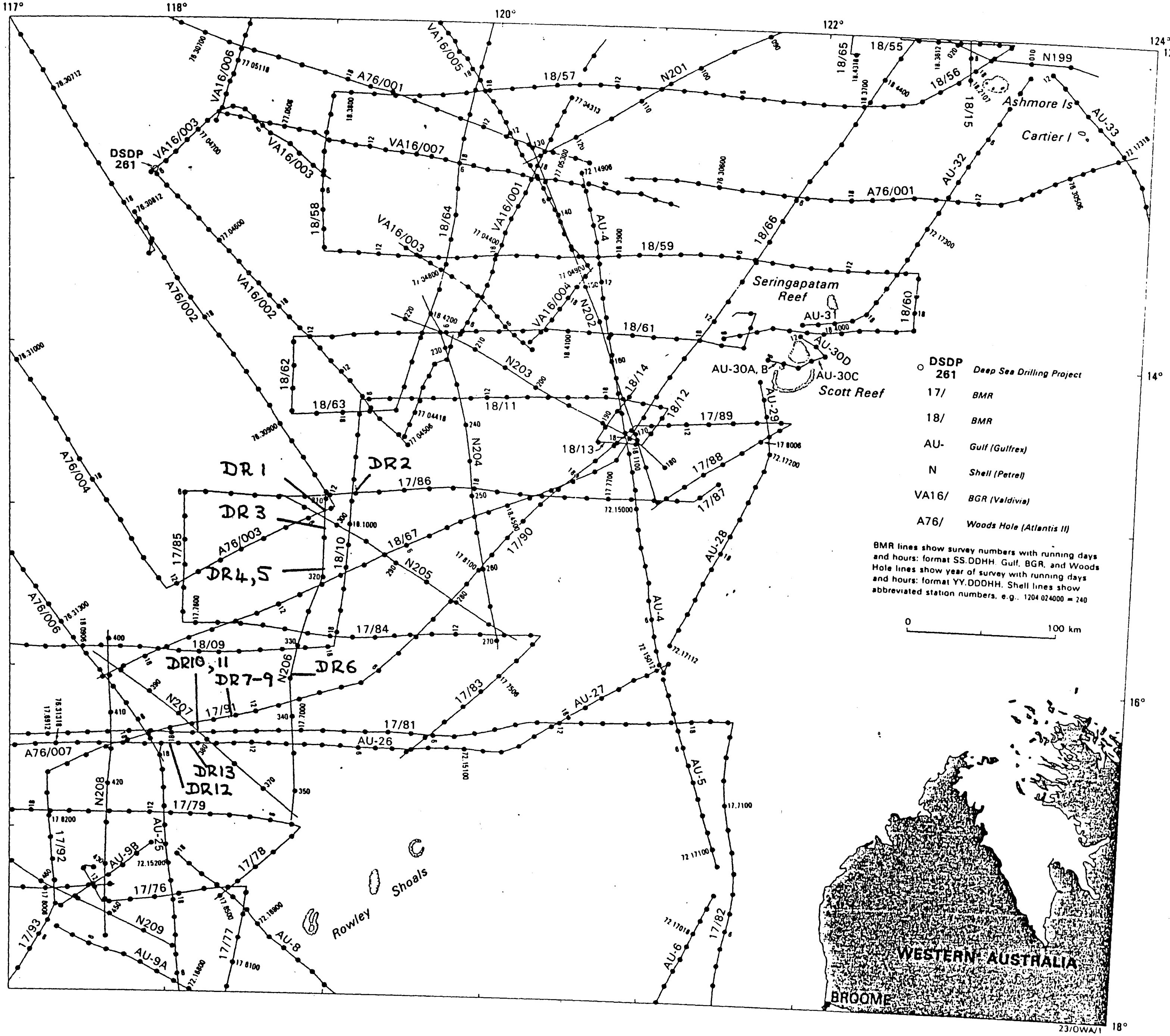
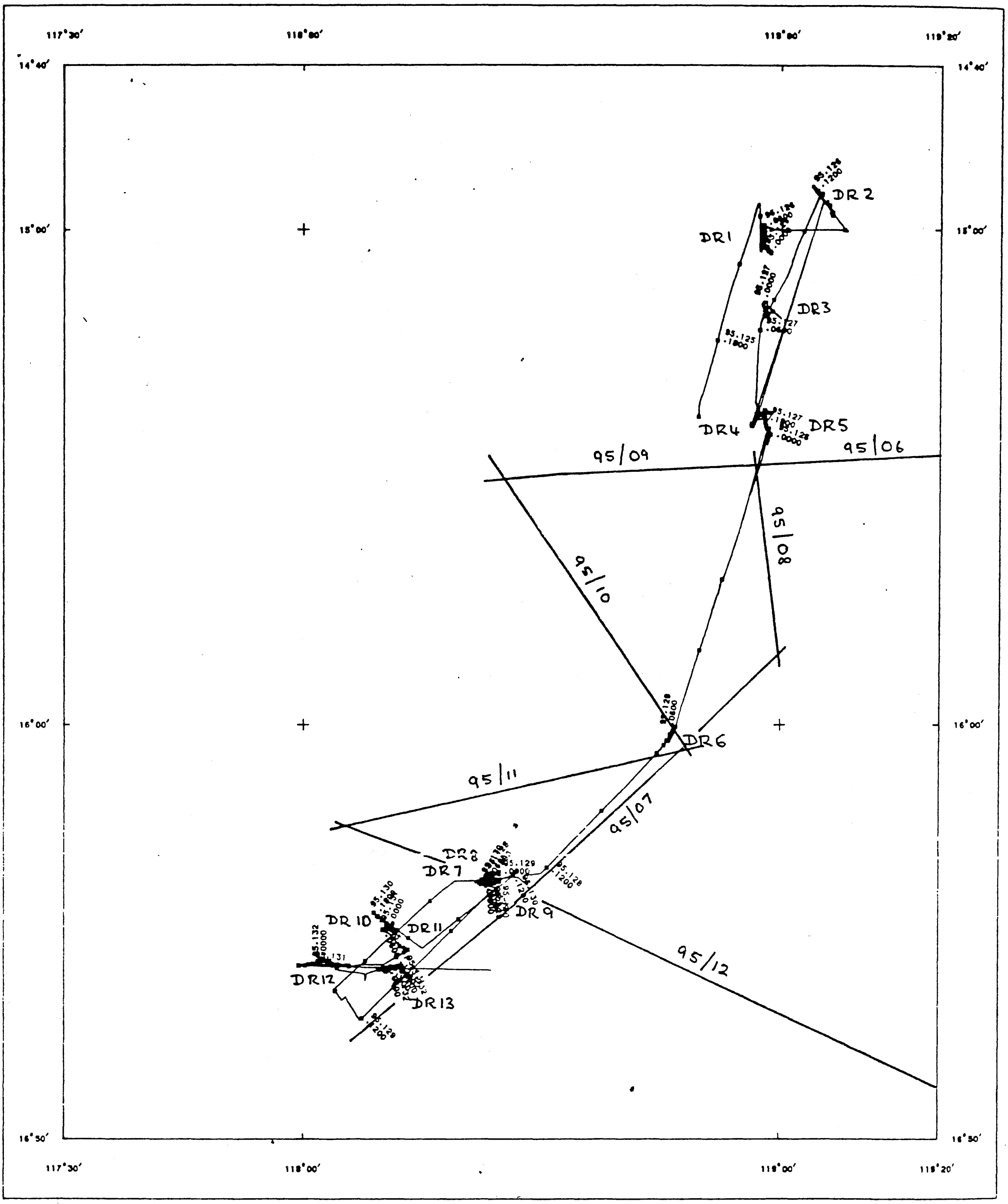


Figure 2ᴗ. Map of dre̲ge sampling ̲urvey relate(to pre-exist'ng

SCALE 1:999999

EDITION OF 1990/05/15



WORLD GEODETIC SYSTEM 1972
UNIVERSAL MERCATOR (SPHERE)
WITH NATURAL SCALE CORRECT
AT LATITUDE 33 00

Figure 29. Map of dredge sampling survey related to new BMR seismic lines

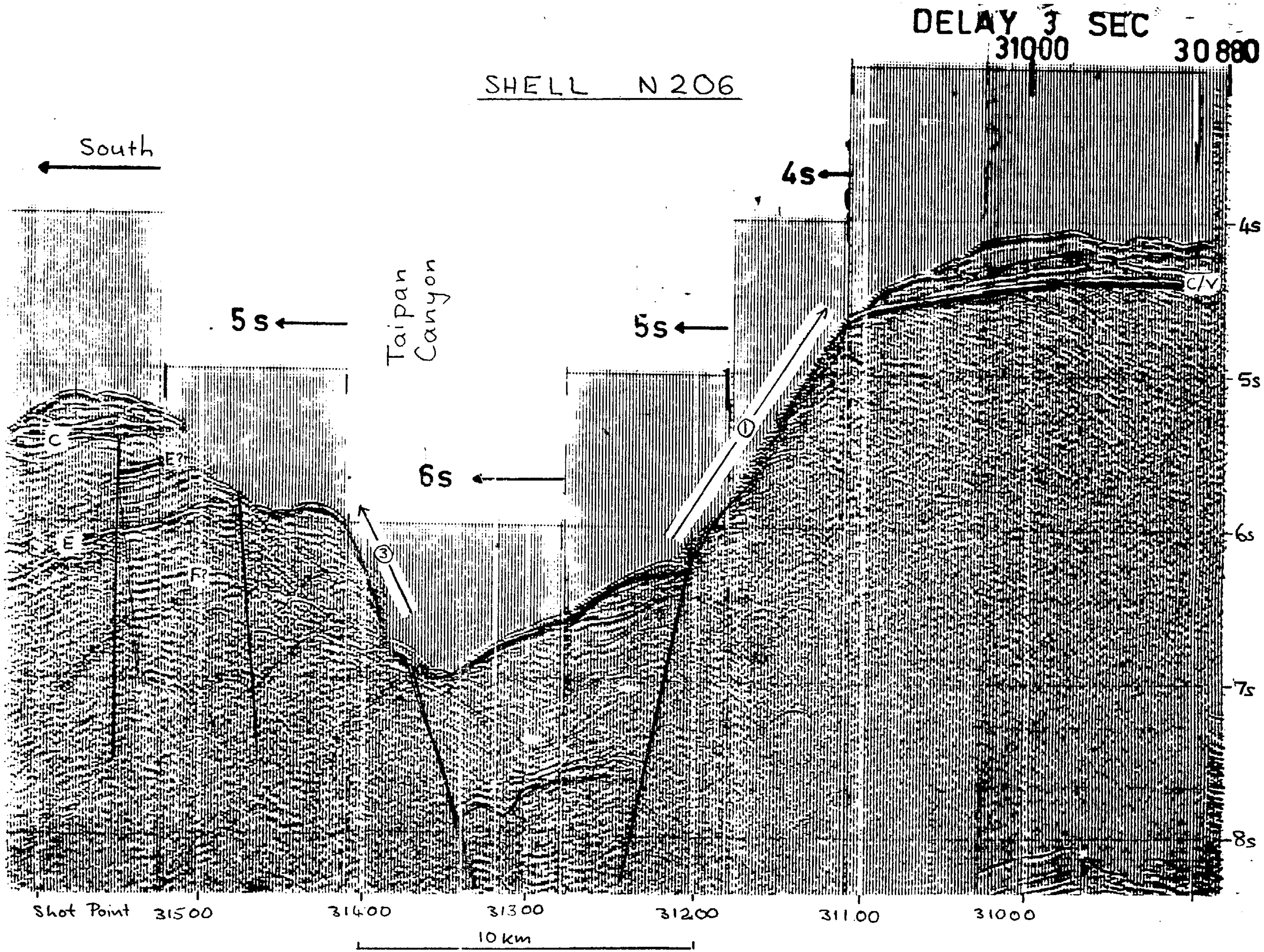


Figure 30. Dredges 95/01 & 03 related to Shell seismic profile N206

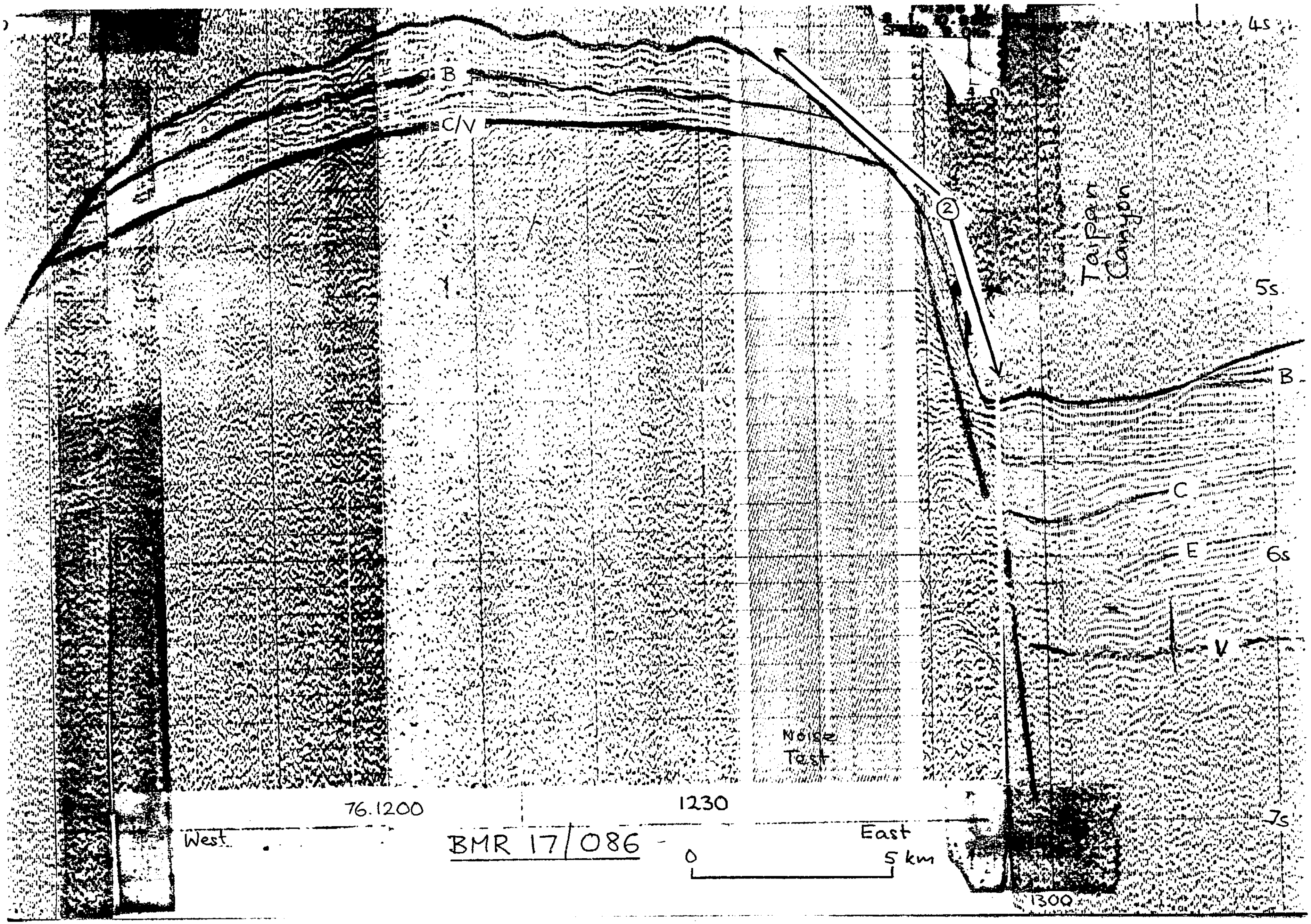


Figure 31. Dredge 95/02 related to BMR seismic profile 17/86

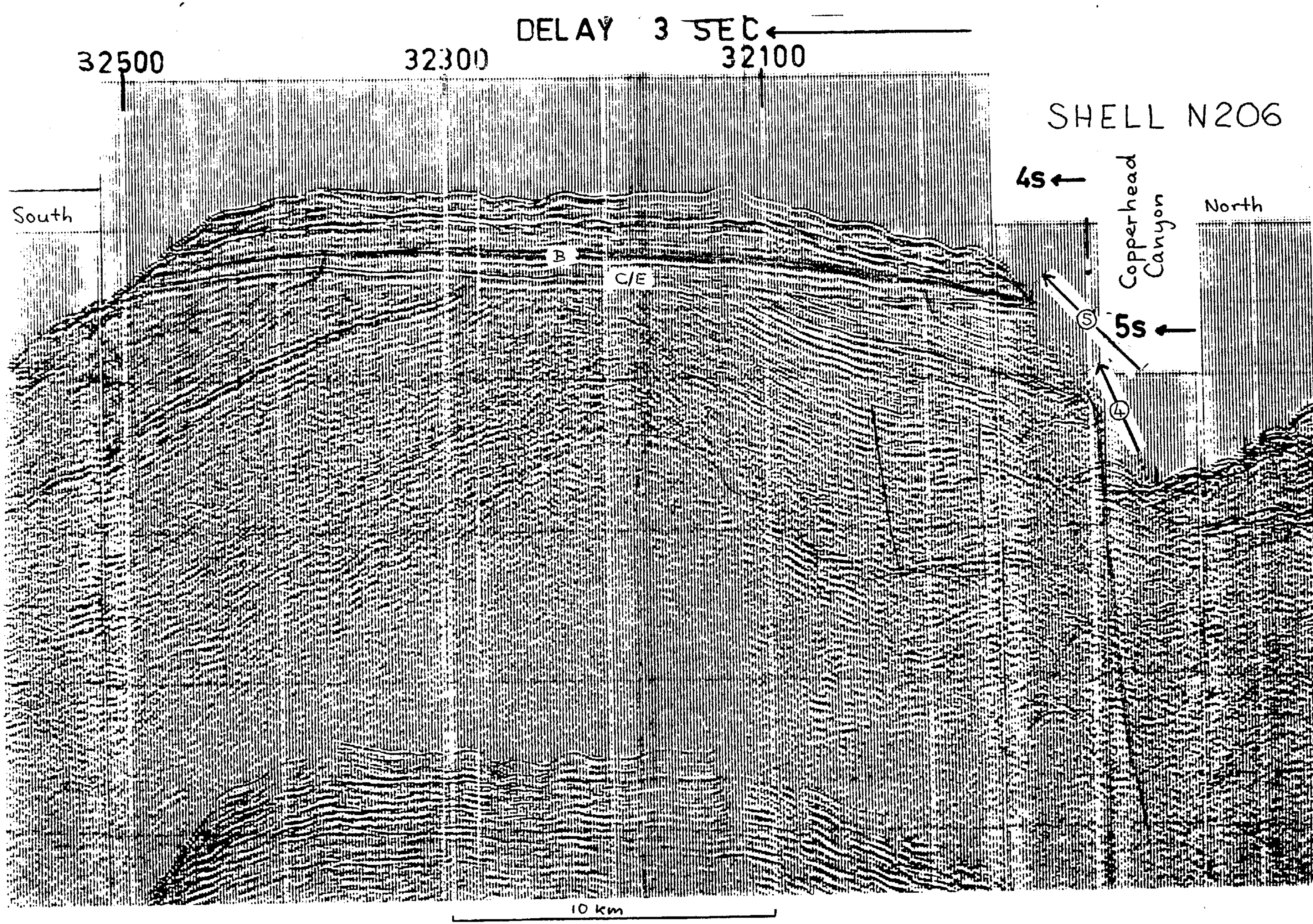


Figure 32. Dredges 95/04 & 05 related to Shell seismic profile N206

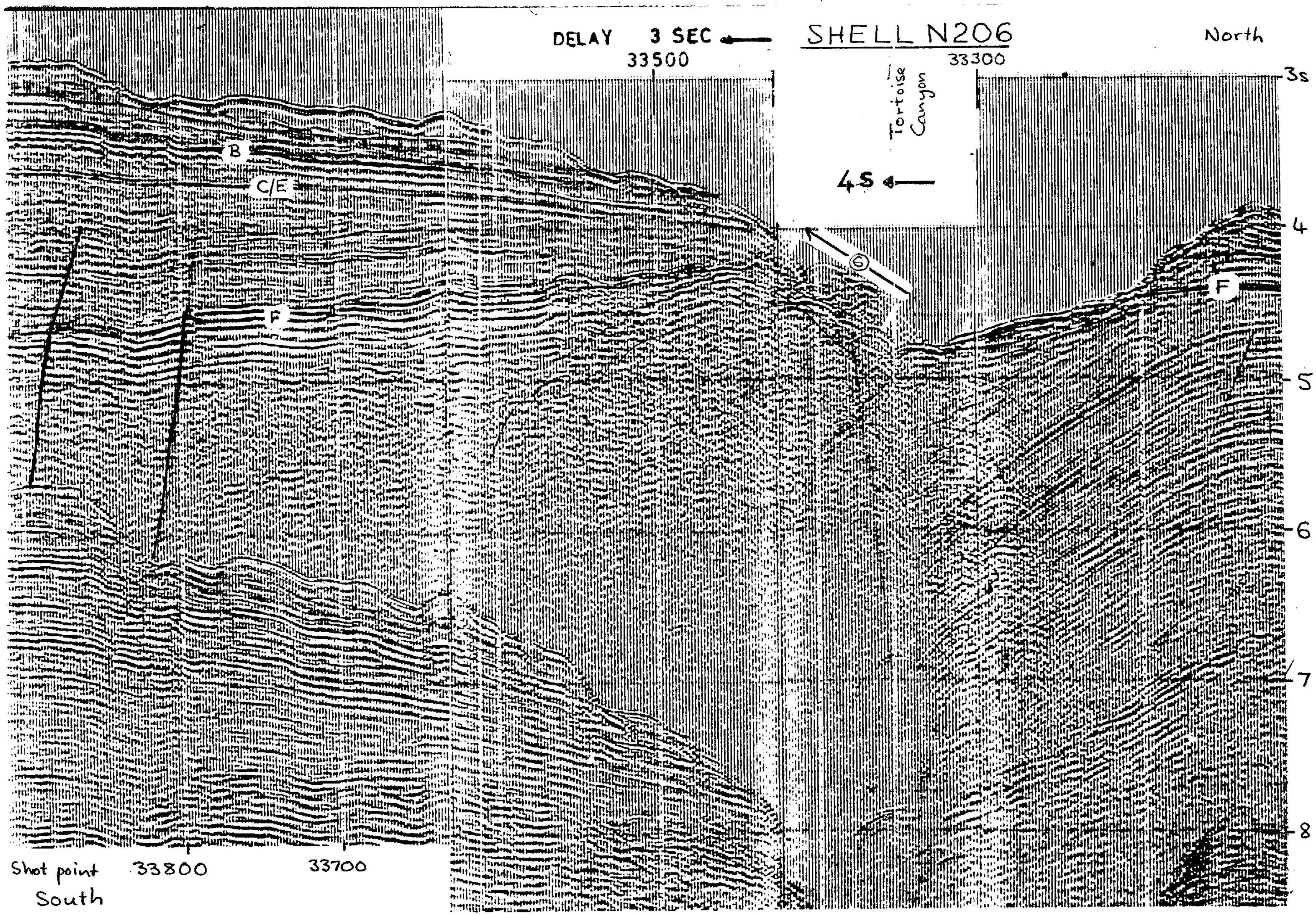


Figure 33. Dredge 95/06 related to Shell seismic profile N206

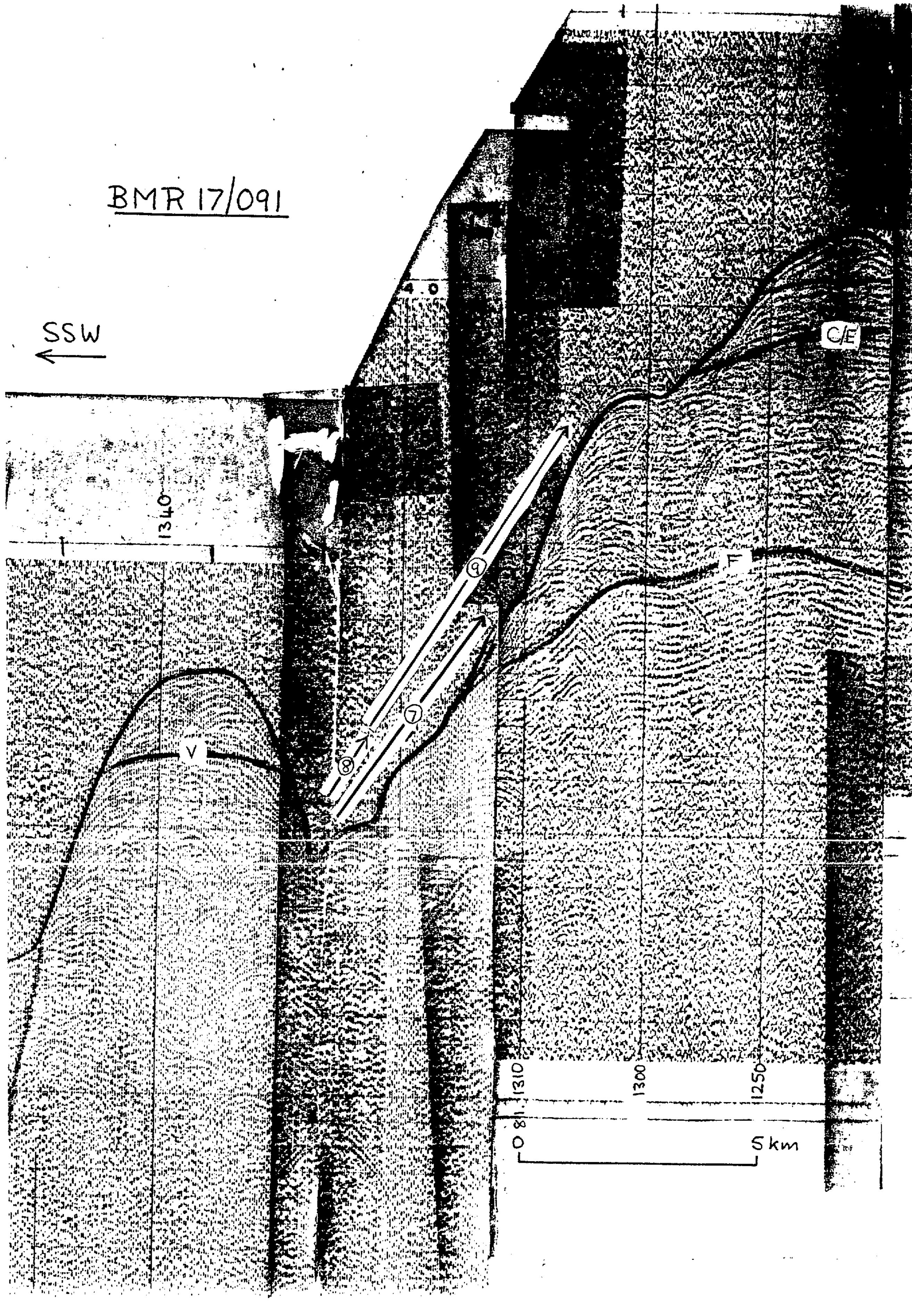


Figure 34. Dredges 95/07, 08 & 09 related to BMR seismic profile 17/91

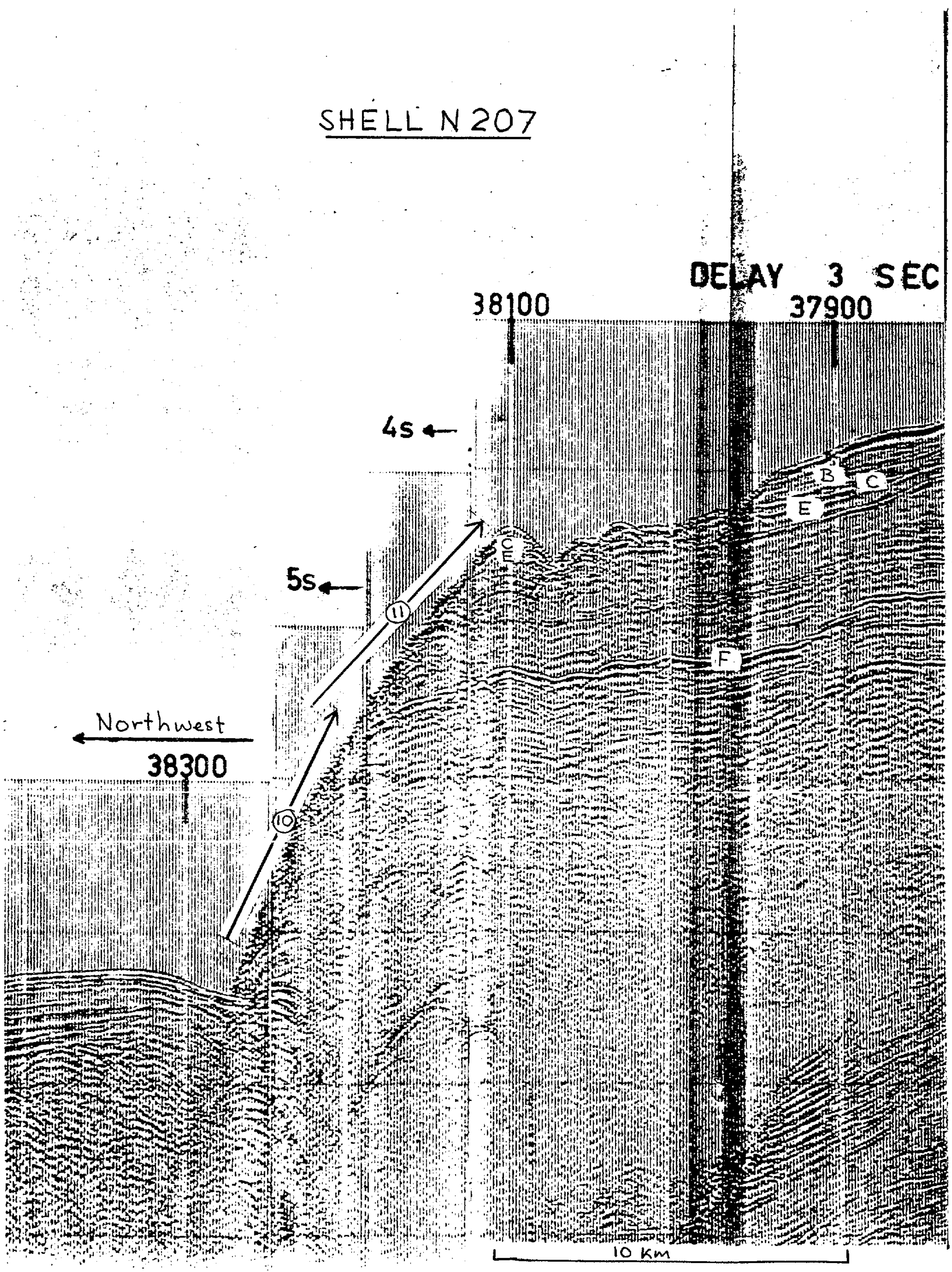


Figure 35. Dredges 95/10 & 11 related to Shell seismic profile N207

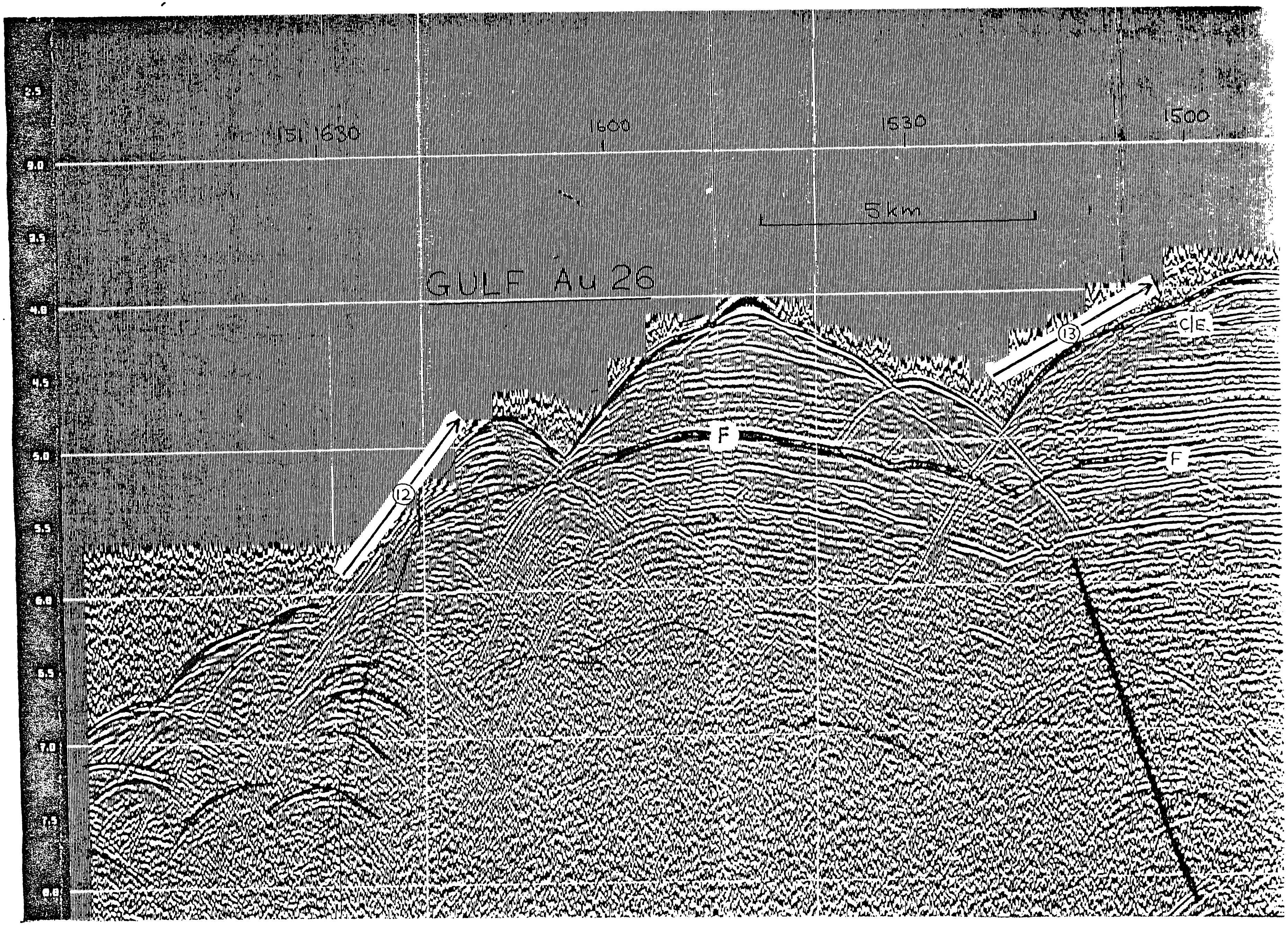
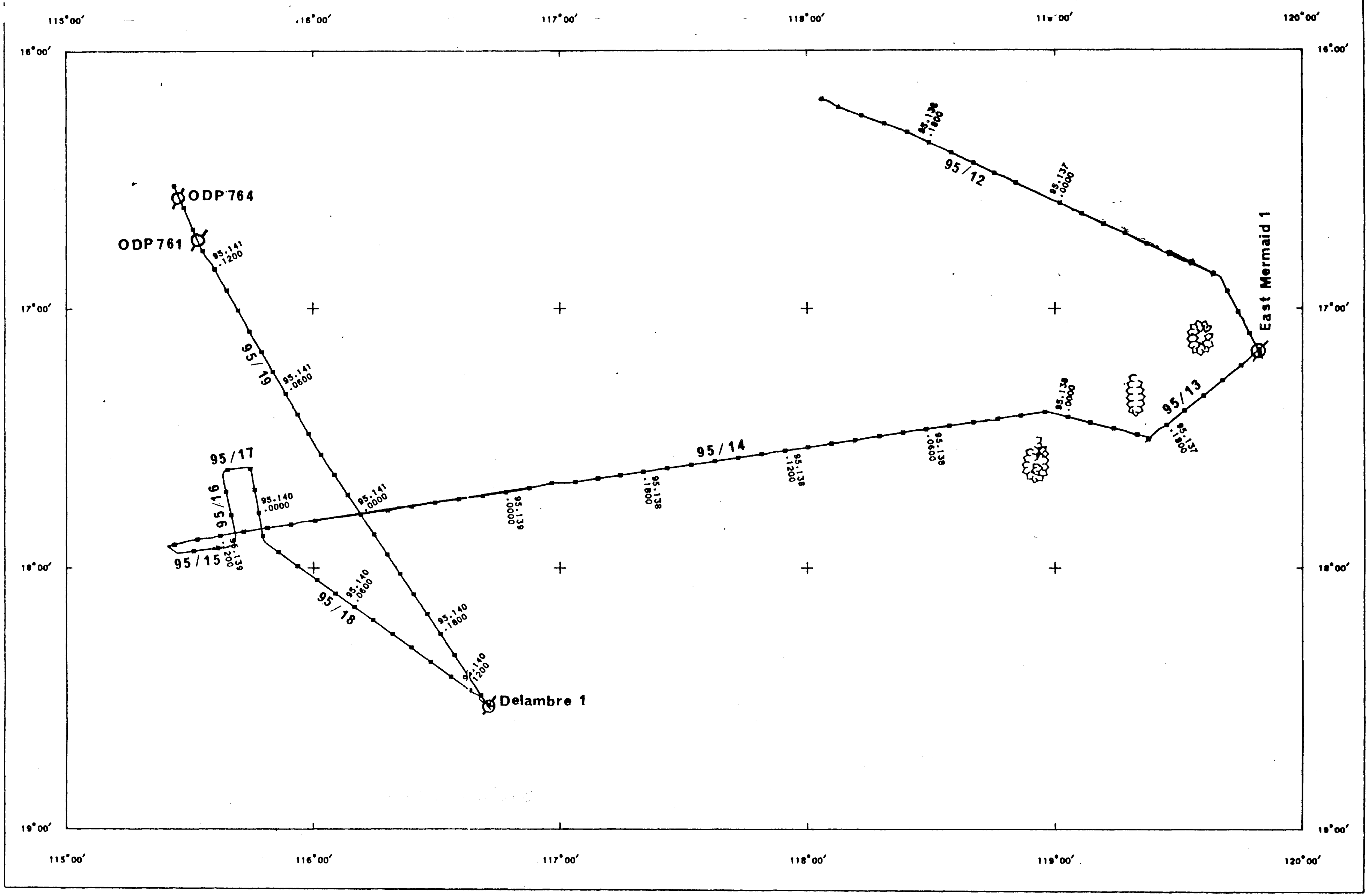


Figure 36. Dredges 95/12 & 13 related to Gulf seismic profile AU26



WORLD GEODETIC SYSTEM 1972
UNIVERSAL MERCATOR (SPHERE)
WITH NATURAL SCALE CORRECT
AT LATITUDE 33 00

Figure 37. Map of regional seismic survey on the northern Exmouth Plateau

B.M.R. CRUISE 95

NORTH EXMOUTH REGIONAL SEISMIC SURVEY

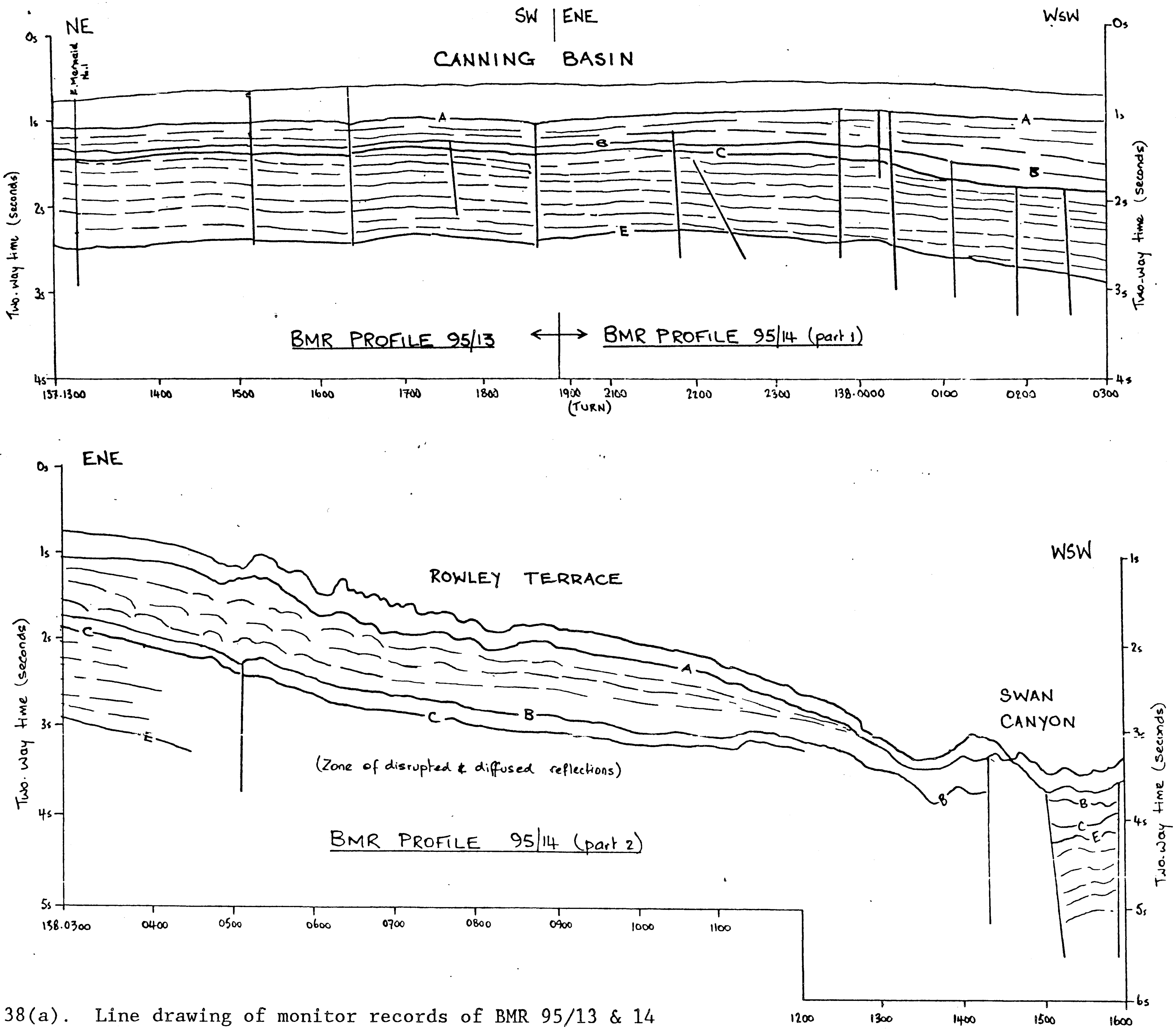
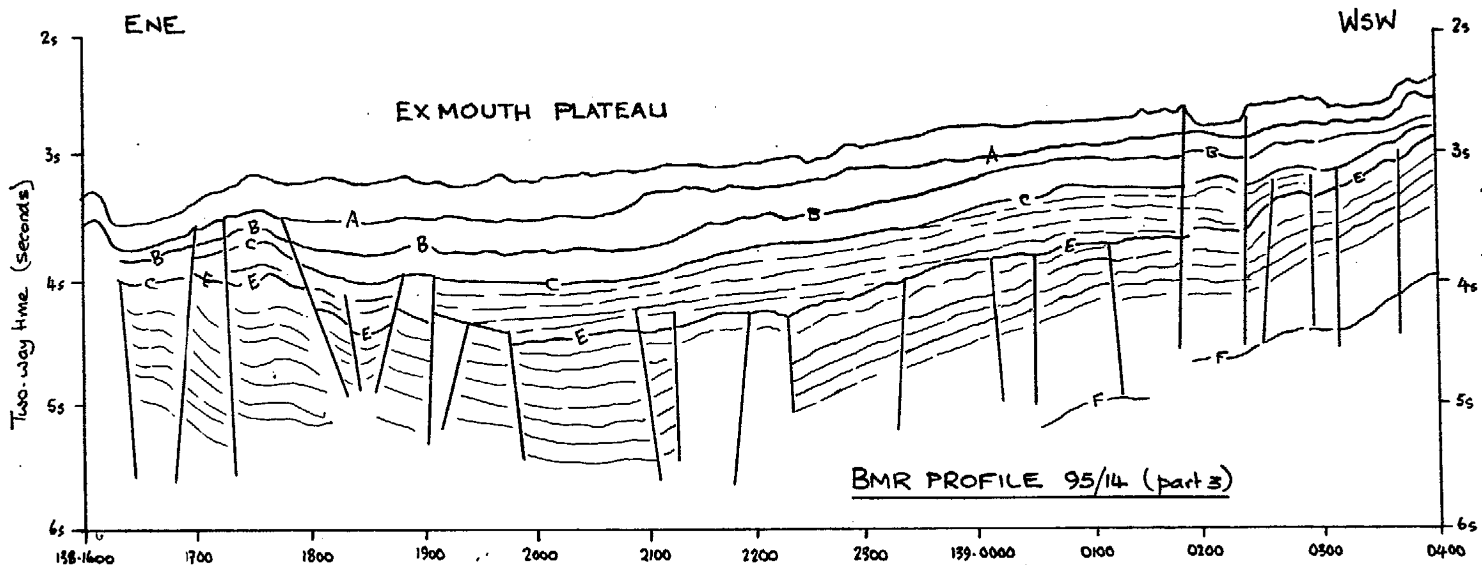


Figure 38(a). Line drawing of monitor records of BMR 95/13 & 14



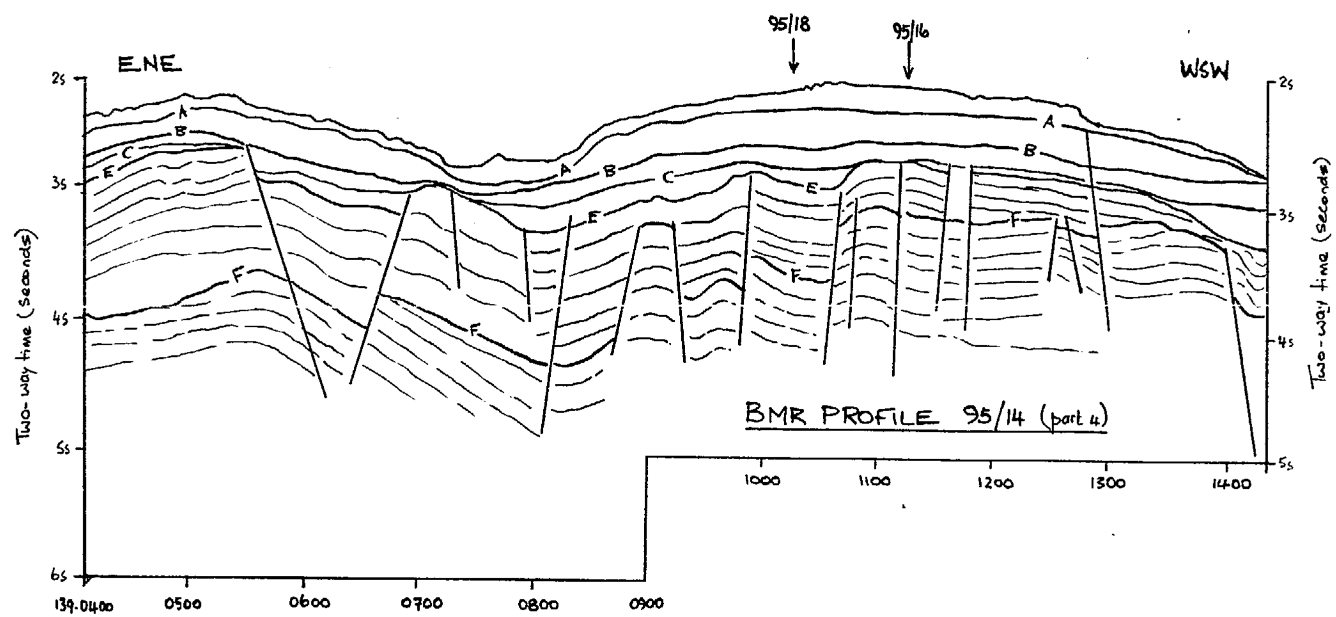


Figure 38(b). Line drawing of monitor records of BMR 95/13 & 14

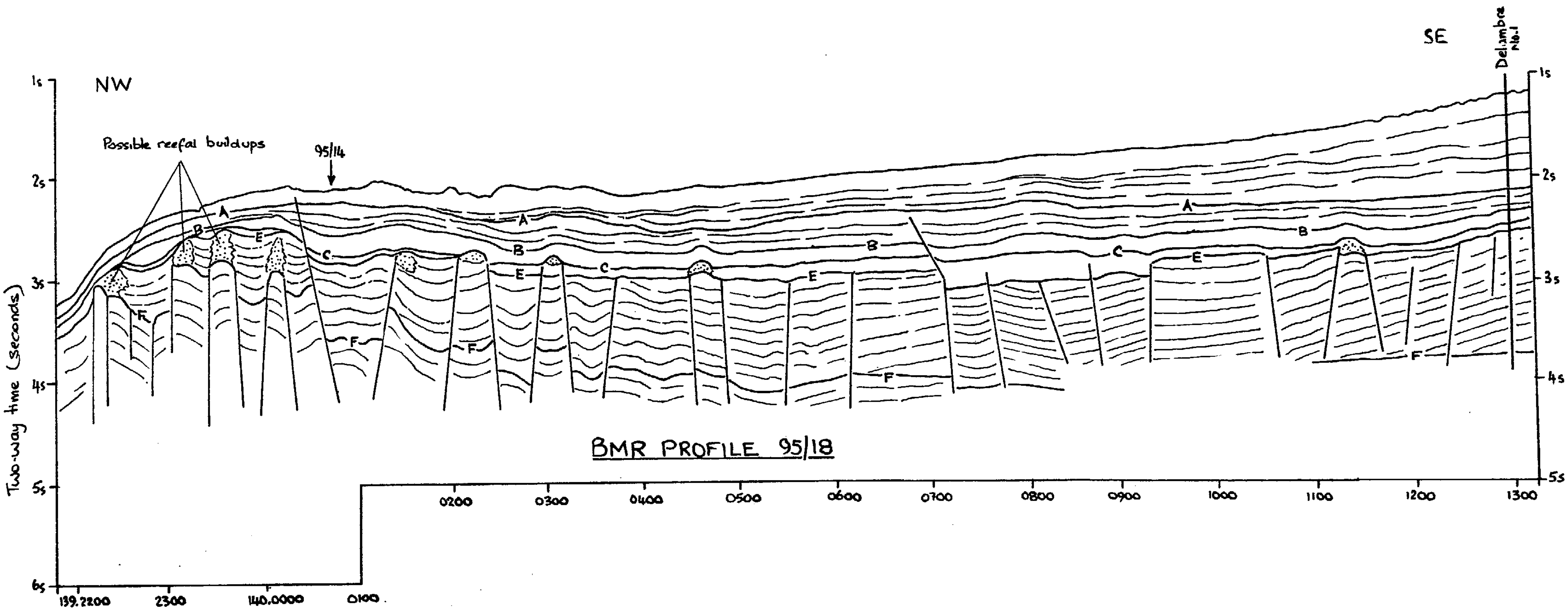


Figure 39. Line drawing of monitor record of BMR 95/18

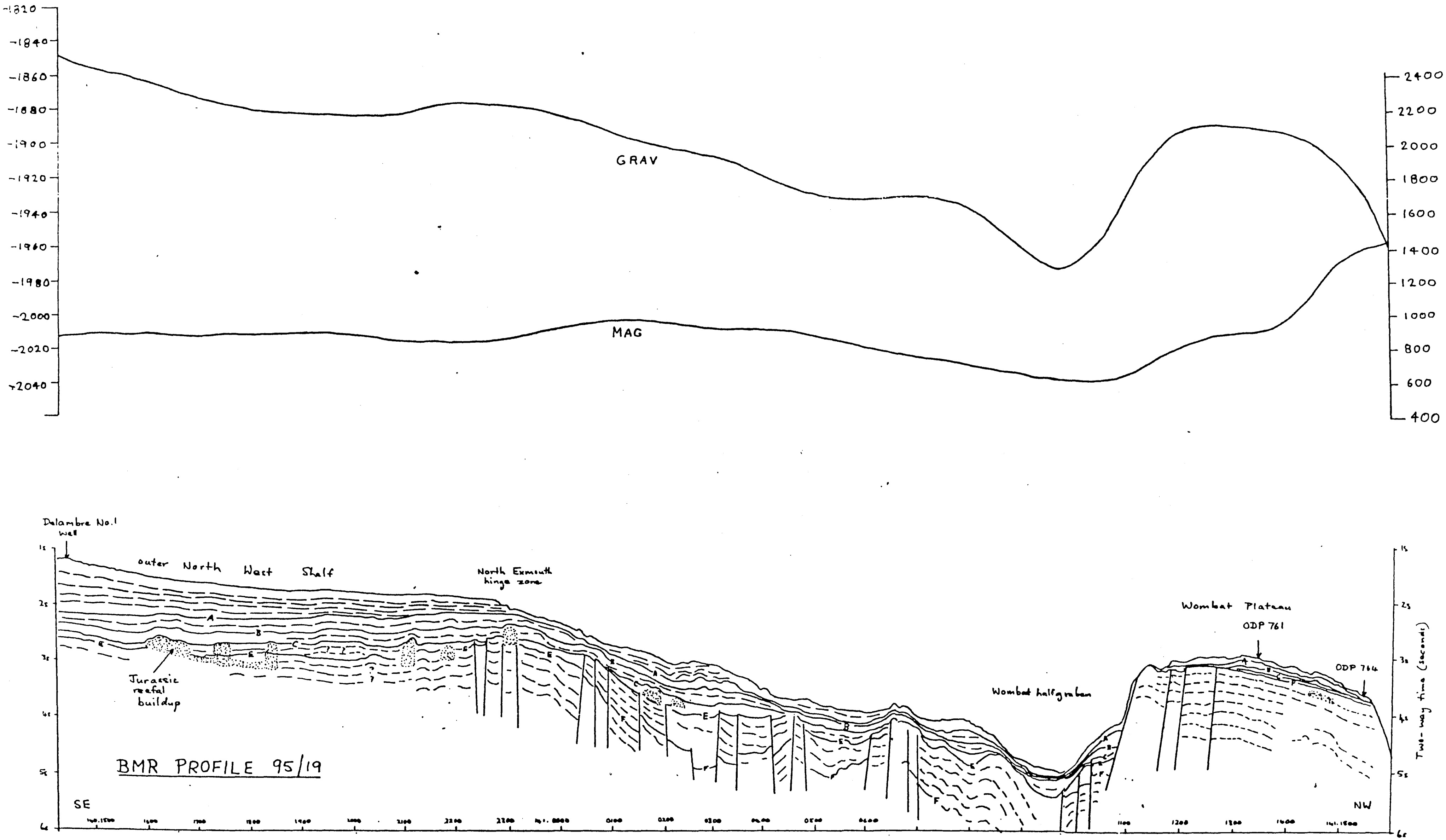


Figure 40. Line drawing of monitor record of BMR 95/19 showing presumed reefal buildups (stippled)

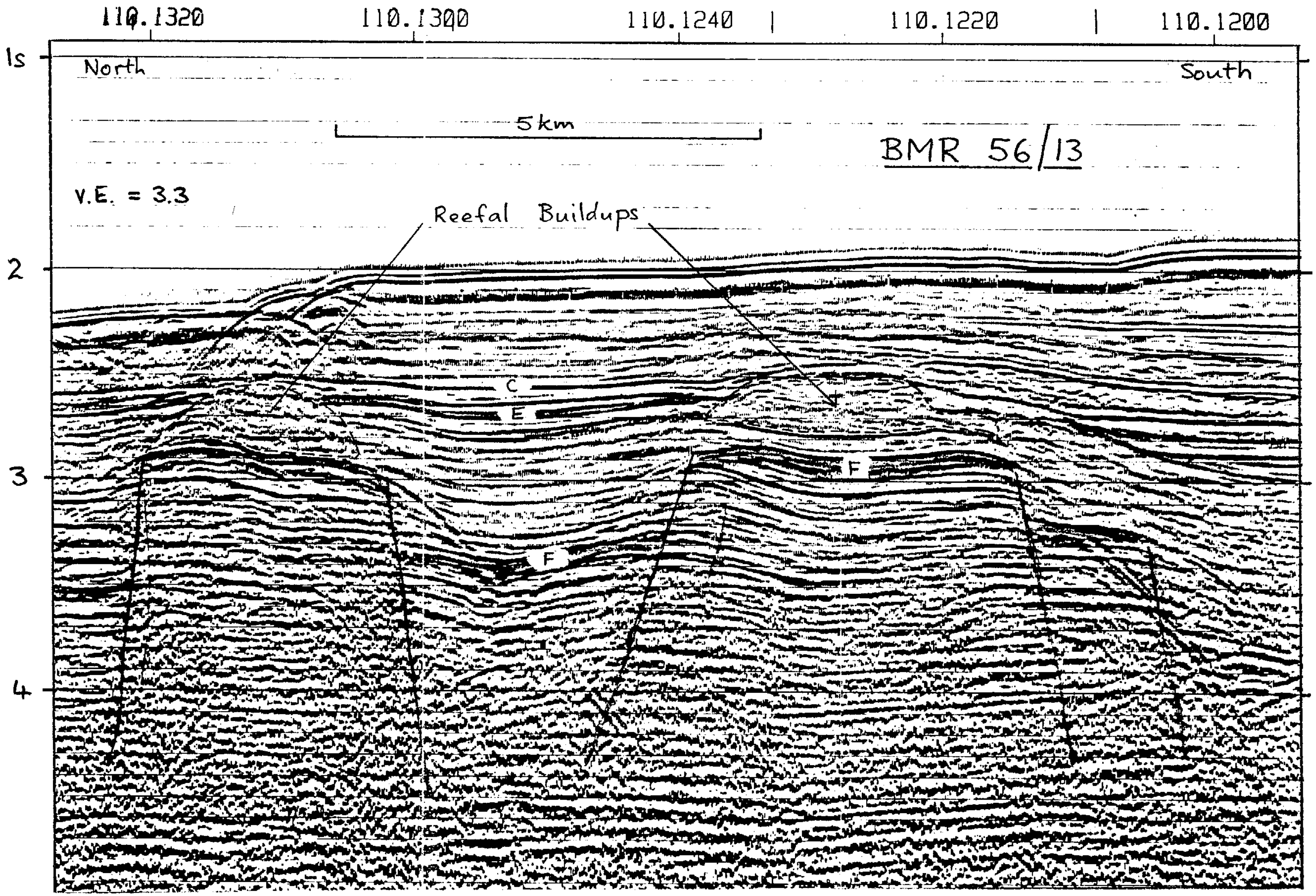


Figure 41. BMR seismic profile 56/13 showing two presumed reefal buildups (stippled). Location in Fig. 45

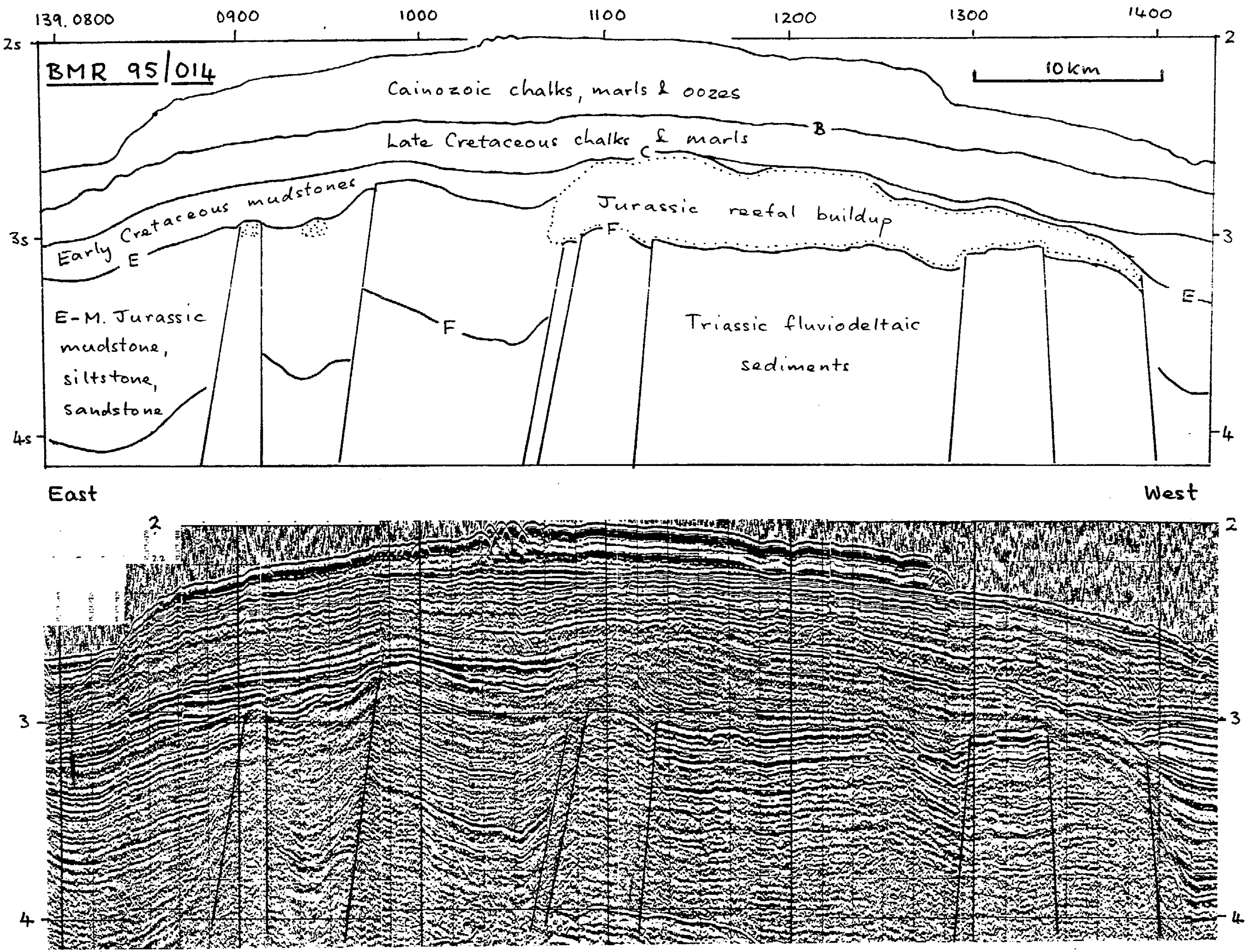


Figure 42. Line drawing of part of monitor record of BMR 95/14 showing presumed reefal buildup (stippled). Location in Fig. 45

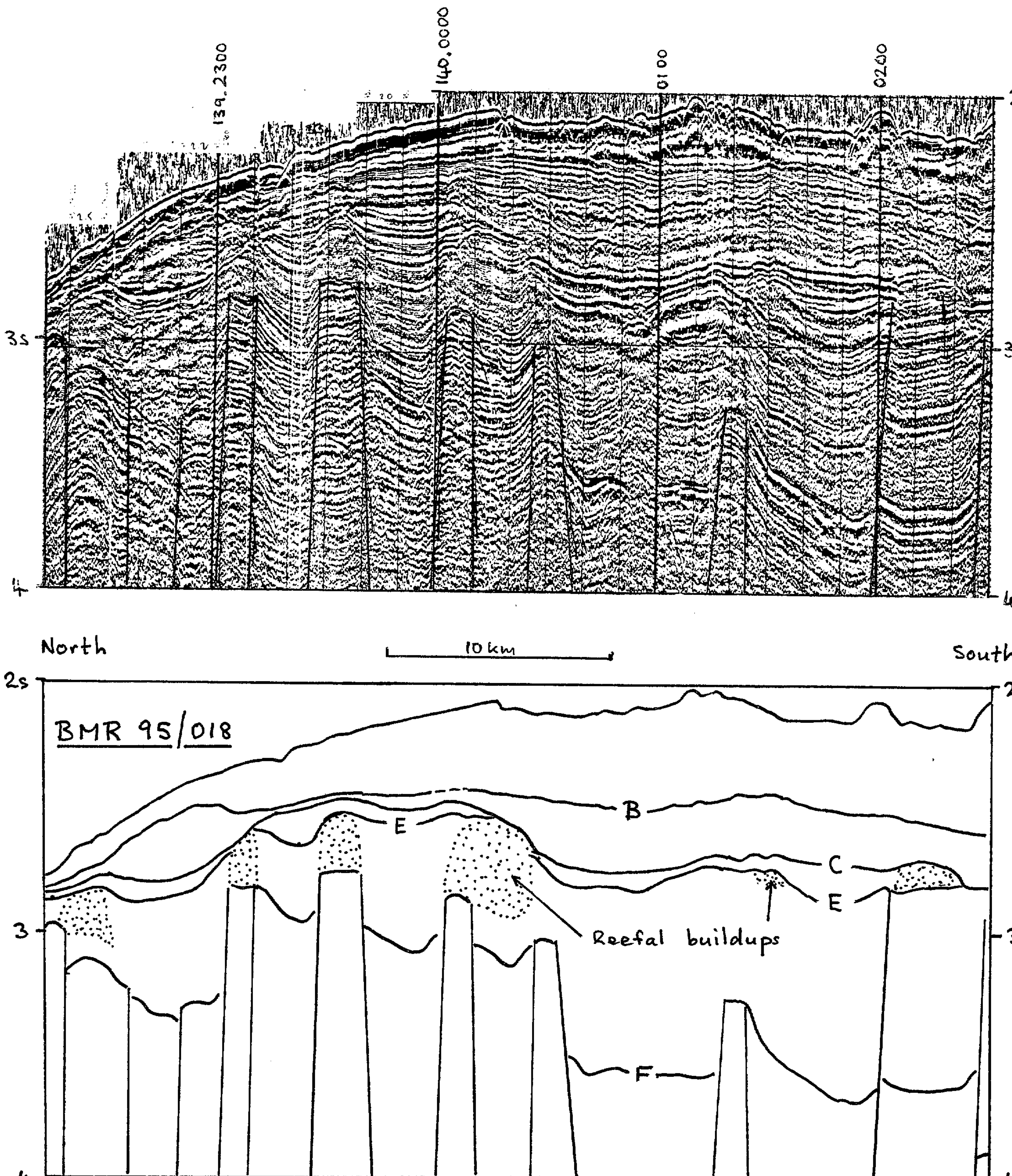


Figure 43. Line drawing of monitor record of BMR 95/18 showing presumed reefal buildups (stippled)

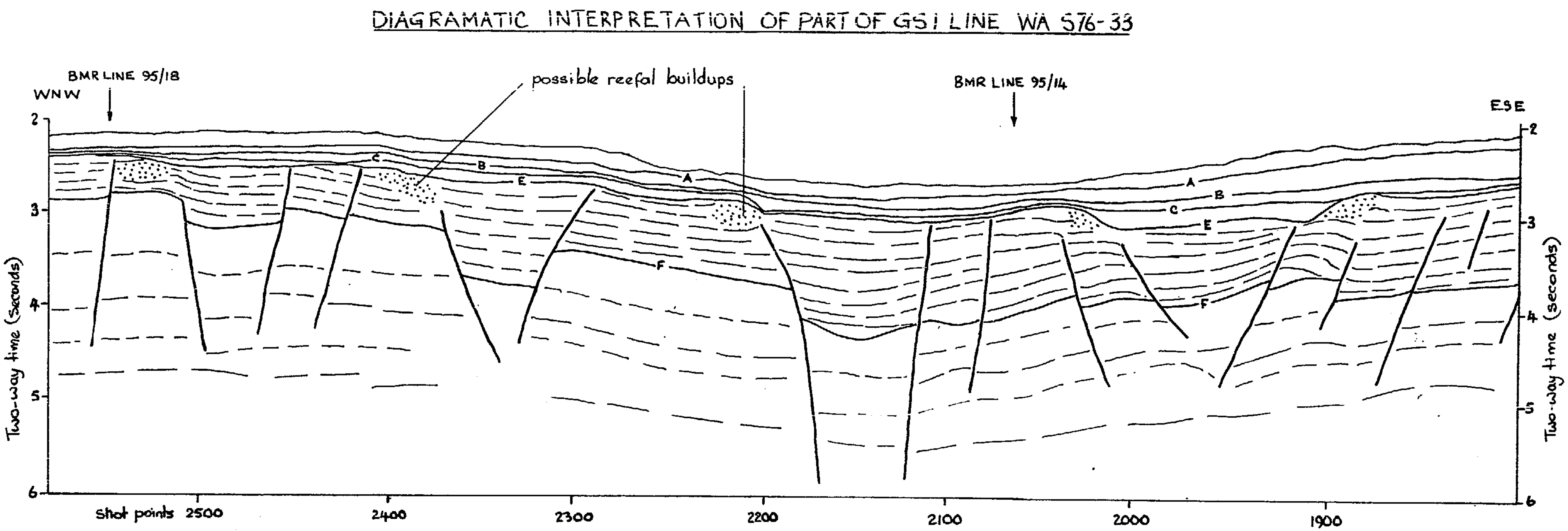


Figure 44. Piece of GSI profile WA S76-33 showing presumed reefal buildups

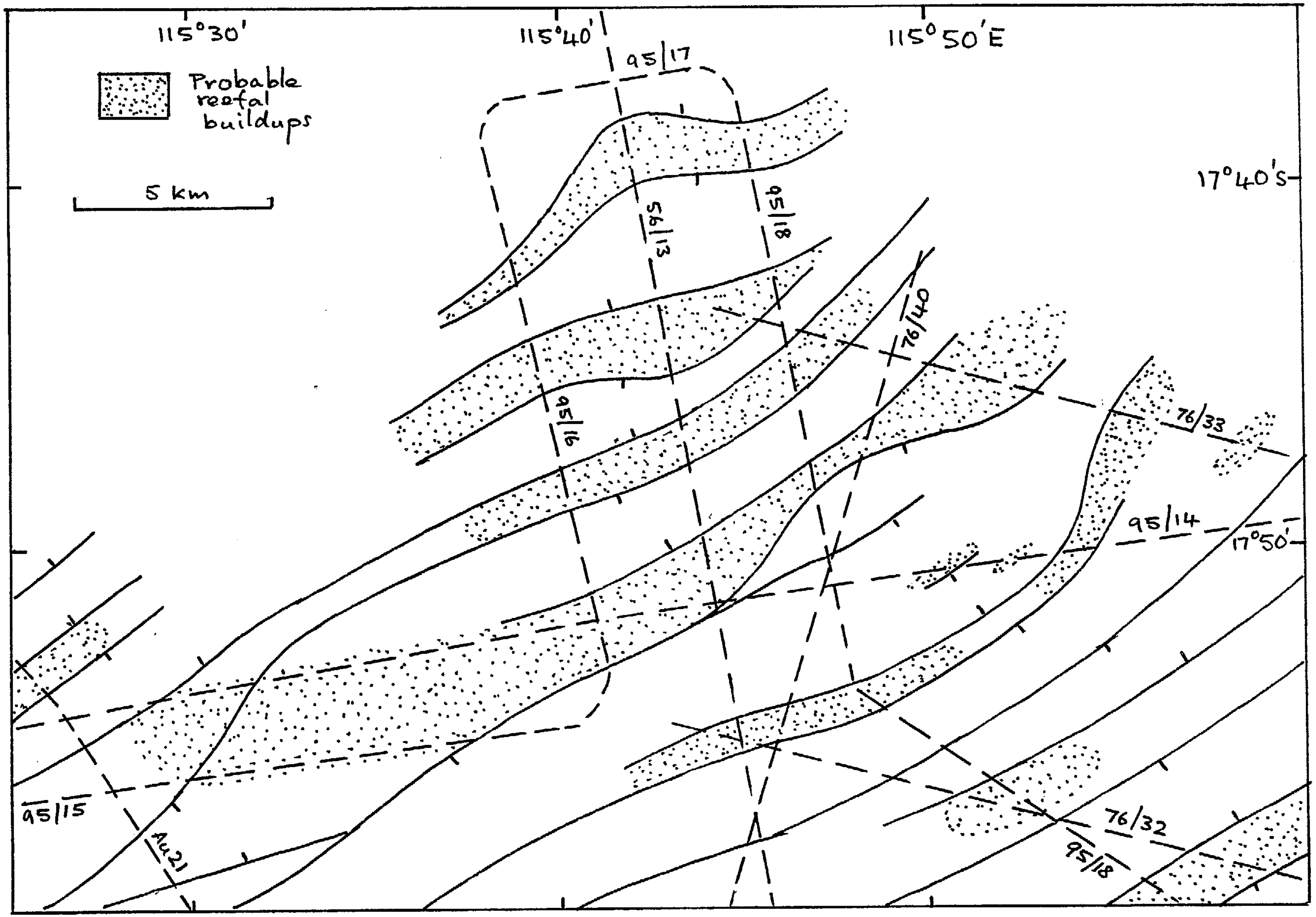


Figure 45. Map showing trends of fault blocks in part of the northern Exmouth Plateau, and the distribution of presumed Jurassic reefal buildups

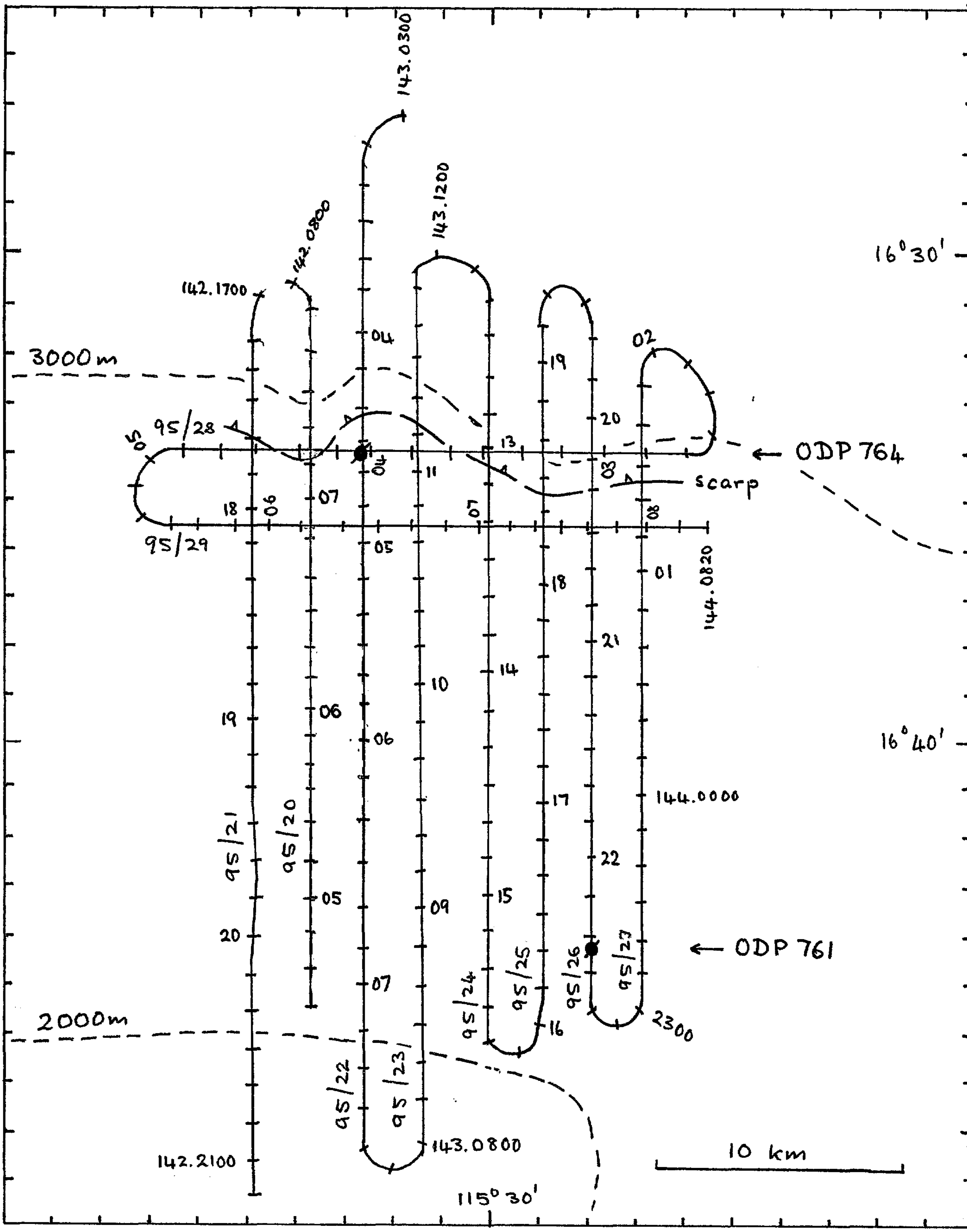


Figure 46. Map of high-resolution seismic survey on northeast Wombat Plateau

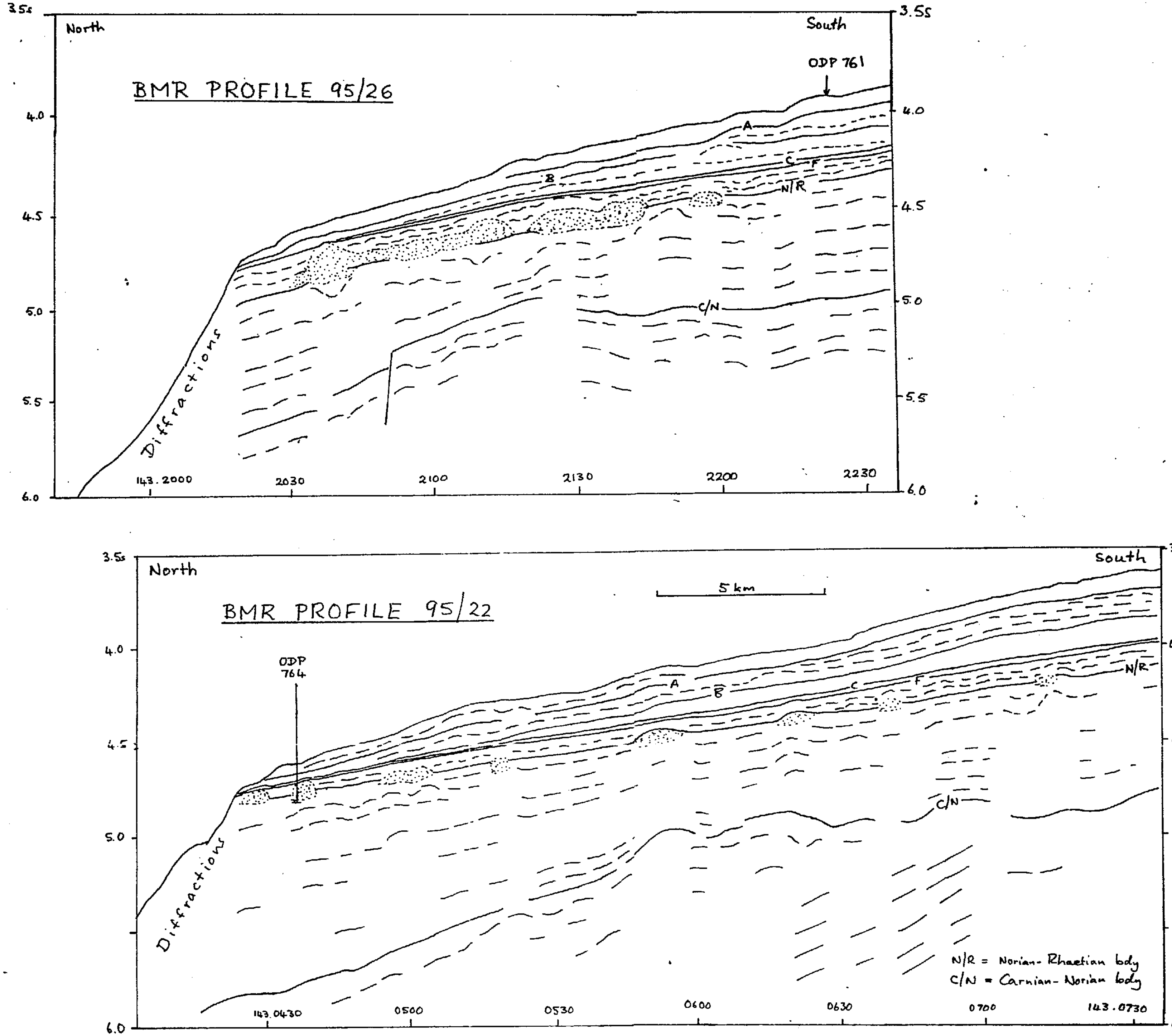


Figure 47. Line drawings of monitor records of BMR 95/22 & 26 showing presumed reefal buildups (stippled) and proven buildup at ODP site 764