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DEEP STRUCTURE OF THE SOUTHERN NORTH-WEST SHELF: SNOWS-II (SURVEY 110) POST-CRUISE REPORT

by

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Marine Geoscience and Petroleum Geology Program

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EXECUTIVE SUMMARY

In mid-1991, the Bureau of Mineral Resources (BMR) commenced a program of deep-seismic acquisition on the southern North West Shelf with the intention of providing a regional data set for explorers in this highly prospective segment of Australia's continental margin. In particular, the program has the following aims:

- To determine the broad regional structural framework of the southern North West Shelf by examining the relationships between the major structural elements;

- To determine the deep crustal structure of the region;

- To assess the influence of deep structure on the development of the major hydrocarbon fields and plays, and in particular the structural and depositional effects resulting from reactivation of these structures; and

- To acquire a set of high-quality seismic tie lines linking the deeper exploration wells throughout the region to allow regional seismic correlations.

To address these aims, a multi-cruise program was devised. The first cruise, SNOWS-I (for Southern North West Shelf; BMR Survey 101), undertaken in mid-1991, was concentrated in the Barrow and Dampier Sub-basins and inner Exmouth Plateau. 1654 km of high-quality seismic data were recorded and processed; these data frequently show basin structure down to a depth of at least 10 s two-way time (TWT).

During SNOWS-II (BMR Survey 110), undertaken in June-July 1992 and summarised here, a total of 2868 km of apparently high-quality deep-seismic data was recorded along 15 lines in the Beagle, Dampier, and Barrow Sub-basins, and extending across the Exmouth Plateau. These lines were tied to 21 exploration wells.

The seismic data were recorded from a 4800 m streamer, configured with 192 x 25 m active groups. The record length was 16 seconds, and the sample interval 2 msec. The seismic source consisted of dual 'sleeve gun' arrays with a total volume of 49.2 litres (3000 cu in). Shots were fired every 50 m at a ship speed of 4.5-5.0 knots, providing 48-fold coverage. Streamer noise levels were low, with the rms noise on most channels being less than 1.5 microbars.

Navigation for the survey was provided by differential Global Positioning System (DGPS), using shore reference stations at Dampier and Perth. Full differential coverage was achieved for >98% of the survey. During this time, it is estimated that positional accuracy is probably better than +/- 10 metres.

For operational and scientific reasons, the lines recorded during SNOWS-II can be considered in four stages, as follows:

Stage 1 (1239.3 km; 8 wells) was concentrated in the Beagle Sub-basin, and was the highest priority work. The seven lines of this stage extended the coverage of SNOWS-I to the northeast, and also tied with the proposed SNOWS-III program in the offshore Canning Basin. The lines extend into the northwest corner of the Bedout Sub-basin, to the southwestern flank of the Bedout High, and to the inner flank of the Exmouth Plateau. They were designed, where possible, to be orthogonal to the principal trends of the sub-basin.

Stage 2 (462.9 km; 3 wells; 1 well also tied on Stage 3) consists of two co-linear strike lines linking the outer parts of the northern Carnarvon Basin. These lines are parallel to the strike line recorded along the depositional axis of the Dampier Sub-basin and join the SNOWS-I strike line recorded on the inner flank of the Exmouth Plateau. They are designed to image postulated NW-SE oriented cross trends (transfer faults and accommodation zones) at depth.

Stage 3 (591.6 km; 9 wells; 1 well also tied on Stage 2) consists of two dip lines in the central Barrow Sub-basin and one dip line in the Dampier Sub-basin. All three lines extend to the inner half of the Exmouth Plateau and fill some of the gaps left after SNOWS-I. The Dampier Sub-basin line had to be terminated with only the northwestern half of the line recorded, due to a conflict with commercial drilling and seismic activity.

Stage 4 (574.8 km; 2 wells) concentrated on the central and outer Exmouth Plateau, and was principally designed to complete the North West Shelf to Gascoyne Abyssal Plain transect that was commenced on SNOWS-I. Spare time near the end of the survey allowed the Stage 3 dip line in the southwest Dampier Sub-basin to be extended northwest to the Exmouth Plateau Arch.

As with the SNOWS-I data, only gross structural information is visible in the field monitors, particularly in shallow water, due to the extensive primary and interbed multiples generated from Tertiary carbonates and a highly reflective seabed. However, as the SNOWS-I data show crustal reflections down to at least 10 s TWT on several lines, we are confident that the SNOWS-II data will be of at least the same standard at depth. In addition, the 2 ms sample period used on SNOWS-II (vs 4 ms on the earlier survey) should ensure an improved shallow section.

With the acquisition and processing of the SNOWS-I and SNOWS-II data, there will shortly be available to industry a grid of 4523 km of regional deep-crustal seismic lines tied to 38 exploration wells and covering all of the northern Carnarvon Basin and the central Exmouth Plateau.

ACKNOWLEDGEMENTS

The success achieved on SNOWS-II was due in no small part to the skills and professionalism of the Australian Maritime Safety Authority crew, ably led by the master of the *Rig Seismic*, Bob Hardinge.

We would also like to acknowledge the contributions made by companies who responded to the original SNOWS-II survey proposal.

PROJECT BACKGROUND

The North West Shelf is a general term that refers to the suite of geologic provinces comprising the continental margin of northwest Australia, approximately from Northwest Cape to Darwin, a distance of some 2000 km and encompassing an area (including marginal plateaux) of approximately 800000 km^2 (Fig. 1). The principal sedimentary basins include, from south to north, the northern Carnarvon, offshore Canning, Browse, and Bonaparte Basins. While the majority of the sedimentary fill in most of these basins is of Mesozoic age, all of the basins probably began forming in the Palaeozoic.

As production of hydrocarbons from Bass Strait dwindles, the North West Shelf is certain to become the major source of hydrocarbon in Australia. To date, the principal discoveries are oil and gas in the Barrow Sub-basin, gas/condensate and more recently oil in the Dampier Sub-basin, gas/condensate in the Browse Basin, and oil and gas in the Bonaparte Basin. Current estimates suggest that the region contains undiscovered resources of 40-500 million kilolitres (280-3200 million barrels) of crude oil, 240-1300 billion cubic metres (8- 45 tcf) of saleable gas, and 55-440 million kilolitres (350-2800 million barrels) of condensate, primarily in the Carnarvon, Browse, and Bonaparte Basins (BMR, 1989).

While portions of the North West Shelf have been quite intensively explored since the 1960's (particularly the Barrow-Dampier Sub-basins and parts of the Bonaparte Basin), there has been very little recent revision of its regional structural framework using modern extensional tectonic concepts, and large parts of the region, particularly the offshore Canning Basin, remain relatively under-explored. The Marine Geoscience and Petroleum Geology Program at the Bureau of Mineral Resources, as part of its study program on the North West Shelf, is acquiring regional deep-seismic data across and between the major sedimentary basins, with the aim of improving understanding of the linkages between the major structural elements and allowing revision of the gross structure of the region. This information will be critical in developing new exploration strategies, and will aid future basin framework and resource studies in the region.

To address the structural framework problems of the North West Shelf, a series of cruises by the BMR research vessel *Rig Seismic* have been allocated during a 3-year period. The program is as follows:

1) Bonaparte Basin - concentrating in the Vulcan Graben and adjacent areas - 1900 km of deep-seismic data - completed November-December, 1990 (O'Brien & Williamson, 1990).

2) Bonaparte Basin (Petrel Sub-basin) - 2090 km of deep-seismic data - completed April-May, 1991 (Willcox & Ramsay, 1991).

3) Northern Carnarvon Basin (Exmouth-Barrow-Dampier-Beagle Sub-basins and Exmouth Plateau; SNOWS-I) - 1654 km of deep-seismic data - completed May-June, 1991 (Stagg & others, 1991; Appendix 1).

4) Northern Carnarvon Basin (Beagle-Dampier-Barrow Sub-basins; Exmouth Plateau; SNOWS-II); 2868 km of deep-seismic data acquired in June-July 1992 (Stagg, 1992a).

5) Timor Sea - 2000+ km of deep-seismic data to be acquired in early 1993 in the Malita Graben area.

6) Browse Basin - approximately 2000-2500 km of deep and conventional seismic data - scheduled for acquisition in mid-late 1993.

7) Offshore Canning Basin (SNOWS-III) - 2000+ km of deep seismic data - scheduled for the second half of 1993.

In addition, there are plans to contract a commercial seismic vessel with shallow-water capabilities to extend the SNOWS-I and SNOWS-II lines in the Barrow Sub-basin southeastwards to the basin-bounding faults (Stagg, 1992b; Appendix 2). This area is generally shallower than 20 m, with many shoals and banks, and is inaccessible to a deep-water seismic vessel, such as *Rig Seismic.*

By the end of the cruise program outlined here, there will be available a network of deep seismic data (recorded at up to 16 seconds TWT) for all of the major basins of the North West Shelf, from Northwest Cape to the Timor Sea.

EXPLORATION HISTORY

The initial oil exploration permits on the North West Shelf were granted to Ampol Petroleum Ltd in 1946. While these leases were primarily onshore, they did cover the offshore Carnarvon Basin out to a water depth of 100 fathoms (~183 m). In 1952, Ampol combined with Caltex to form West Australian Petroleum Pty Ltd (Wapet), and the new company drilled its first well (Cape Range-1) on a surface anticline in 1953. This well flowed oil from a small pool and provided a major impetus to exploration on the southern North West Shelf.

The first offshore seismic work was carried out by Wapet in 1961. In 1964, Wapet drilled a wildcat well on Barrow Island that discovered oil in Upper Jurassic sands. Subsequent appraisal drilling on Barrow Island showed the presence of a major oil field, principally reservoired in Cretaceous sands. In 1965, Wapet was granted acreage west of Barrow Island. At about the same time, Woodside (Lakes Entrance) Oil Co. (subsequently to become Woodside Petroleum) and associated companies were granted leases to the north and offshore from the Wapet leases. This general delineation of operations has persisted since the 1960's, with Wapet being considered the principal explorer in the Barrow Sub-basin, while Woodside is considered to be the prime explorer in the Dampier Sub-basin.

In 1968, Woodside made a non-commercial oil discovery at Legendre-1 on the landward flank of the Dampier Sub-basin. The major Woodside successes came in 1971, with major discoveries of gas/condensate at North Rankin-1, Goodwyn-1, and Angel-1 within or overlying fault blocks of the Rankin Platform (Fig. 3). Wapet continued the run of success on the Rankin Platform with the discovery of a major gas/condensate field in the Gorgon structure at the southwestern extremity of the platform in 1980.

Since the early 1970s, as the full potential of the North West Shelf has become apparent, exploration lease sizes have been steadily reduced and more players have become involved in exploration. During the 1980s, there has been a number of small- to medium-scale commercial and sub-commercial oil discoveries in both the Barrow and Dampier Sub-basins (eg Harriet, Talisman, Saladin, Roller, Wanaea, Cossack, Ramillies, Griffin, Wandoo), and the former distinction between an "inner oil trend" and an "outer gas trend" has become blurred.

During the second half of the 1980s, emphasis has been shifting away from conventional 2-D seismic surveys to 3-D surveys, for exploration as well as field evaluation. One consequence of this shift in seismic techniques, in conjunction with the change to smaller permit sizes, is that there are very few regional seismic lines of post-1970s vintage. As most of the industry data are recorded to 5 or 6 seconds reflection time, it is also very difficult to construct good- quality regional seismic transects that show basin-forming structures, other than at the basin margins.

By 1992, about 150000 km of conventional 2-D reflection seismic data have been recorded, and over 250 wells have been drilled on the southern North West Shelf; the line-km of 3-D seismic data is increasing exponentially. Of these data, less than 2000 km is conventionally recorded deep seismic data (record lengths > 10 seconds). These deep data consist of 2 lines in the central Dampier Sub-basin, recorded by Geophysical Services International (GSI) in 1986, and the 10 lines recorded by BMR during SNOWS-I in mid-1991 (Fig. 5). In addition, a single two-ship wide aperture CDP seismic line was recorded in 1986 by BMR and the Lamont-Doherty Geological Observatory from the Dampier Sub-basin, west- northwestwards across the Exmouth Plateau, to the Gascoyne Abyssal Plain (Williamson & others, 1990). Conventional multichannel seismic lines were recorded by BMR across the western and northern margins of the Exmouth Plateau and reported on by Williamson & Falvey (1988), Exon & Williamson (1988), and Exon & Ramsay (1990). These surveys were related to the drilling of six continuously cored Ocean Drilling Program (ODP) Sites on the Exmouth Plateau (von Rad, Haq, & others, 1992).

GENERAL OBJECTIVES & SPECIFIC PROBLEMS

A summary of the stratigraphy, structure, and hydrocarbon accummulations of the northern Carnarvon Basin is included as Appendix 3.

The broad objectives of the program proposed by Stagg & Willcox (1991) remain definitive and were as follows:

- To determine the regional structural framework of the northern Carnarvon Basin by examining the relationships between major structural elements along key transects of the shelf.
- To determine the deep crustal structure of the sub-basins of the northern Carnarvon Basin and their relationship to the development of the continental margin adjacent to the southeastern Argo Abyssal Plain.
- To assess the effect of deep structure on the development of the major fields and petroleum plays in the region, and in particular the structural and depositional effects resulting from Tertiary reactivation of these deep structures.
- To provide modern regional seismic well-tie data to allow basin-wide seismic correlations.

At a more specific level, it was felt that the following geoscientific problems evident in the northern Carnarvon Basin and offshore Canning Basin could be addressed to varying degrees by the acquisition of deep-seismic data (Stagg & Willcox, 1991):

1) Detachment Models: Recent models of the formation of passive continental margins propose that the formation of sedimentary basins takes place by extension above and below sub-horizontal detachment faults in the crust (Lister & others, 1986). Assuming such detachment models provide a plausible explanation for basin formation, where are the major detachment faults beneath the northern Carnarvon Basin and the Exmouth Plateau and how can detachment models be applied to the area?

2) Original Extension: What is the age, amount, and azimuth of the original extension that formed the nascent northern Carnarvon and Offshore Canning Basins (part of the Westralian Superbasin)? It now appears accepted that the main extensional phase on the North West Shelf took place in the Palaeozoic, no later than the Permo-Carboniferous, and that the major faulting episode in the Late Triassic (often referred to as 'rift onset') was largely a reactivation phase with only minor extension.

3) Strike-Slip Movements: The *en echelon* character of the major fault system and the Rankin Trend fault blocks, and the existence of major anticlines (Barrow Island Anticline) and sedimentary deeps (eg Lewis Trough), has led to the obvious conclusion

that strike-slip movement has been a major factor in the genesis of the northern Carnarvon Basin. What was the age, extent, and azimuth of these ?multiple phases of movement, and what is their relationship to any phases of simple basin-forming extension?

4) Transfer Faults: Major transfer faults in the Barrow-Dampier Sub-basins can be broadly identified or inferred and their reactivation effects may be visible in the bathymetry; however, they have not been delineated seismically. These transfer zones probably have significant effects on the distribution of reservoir and source rocks, on migration paths, and as trapping mechanisms. Is it possible to image these transfer zones in deep seismic data, such that, at a later stage of study, they can be mapped more accurately and related to the known hydrocarbon fields?

5) Late Reactivation: A number of hydrocarbon discoveries in the 1980s on the North West Shelf have been in traps that have been subjected to Cretaceous-Tertiary reactivation. How are these reactivation traps related to deep structures and can an understanding of such deep structures lead to a prediction of likely locations for late hydrocarbon trapping?

6) Inter-relationship of Sub-basins: There is a lack of a regional understanding of the relationships between the Exmouth, Barrow, Dampier, and Beagle Sub-basins. Can good- quality, deep strike lines allow the pre-Callovian histories of these four sub-basins to be better related?

7) Rankin Platform Gravity: The most prominent gravity feature of the southern North West Shelf is the positive southwest trending anomaly associated with the Rankin Platform (Fig. 4), and it is obvious that the Rankin Platform is a structure that is fundamental to the genesis of the area. Why is the peak of the anomaly offset from the shallowest part of the Rankin Platform and what bearing does this have on extensional basin models?

8) Alpha Arch: At the southwest end of the Rankin Platform, the trend of the gravity high changes to south-southwest (overlying the Gorgon structure and the Alpha Arch). In addition to hosting the Gorgon gas field, the southern Rankin Platform/Alpha Arch is proving to be a fruitful exploration area for oil (Griffin, Chinook, Ramillies).What is the deep structure of this part of the Barrow Sub-basin and how does it control the distribution of hydrocarbon fields?

9) Beagle Sub-basin: While the Barrow and Dampier Sub-basins are both well-explored and hydrocarbon-rich, the same cannot be said for the next basin to the northeast, the Beagle Sub-basin. This complexly-structured basin has been little explored in the 1980s and has been penetrated by a limited number of wells. What is the deep structure of this basin and what influence has this had on the lack of exploration success to date?

The first cruise in the region, SNOWS-I (mid-1991; Stagg & others, 1991), was designed to acquire a basic data set in the most actively explored areas in the Barrow and Dampier Sub-basins. Also, since only two lines of deep seismic data had previously been recorded in the region, SNOWS-I was considered to be a pilot study that would determine whether the deep seismic technique would be successful in the northern Carnarvon Basin. In the event, the processed SNOWS-I data have proved to be of high quality, with crustal reflections clearly visible on a number of lines in the depth range 8-11 s TWT (~12-20+ km). A brief description of the processed SNOWS-I data is included as Appendix 5.

CRUISE NARRATIVE - SNOWS-II

The SNOWS-II survey (BMR Survey 110) commenced in Darwin on June 5 and finished in Fremantle on July 8, 1992. The following is a brief summary of the principal events; chronology is given as Julian day and GMT hours and minutes.

157.0830	Sail from Darwin
160.1000	Rendezvous with fishing vessel off Broome, to pick up ARGOS transmitters and streamer spares.
160.2200-2400	Deploy and test GPS-equipped tailbuoy; tests successful.
161.0030-2400	Deploy 1200 m streamer with 6.25 m groups to test engine noise at a range of pitch and revolution settings.
161.0340-1500	Engine noise tests.
161.1530	Commence building and testing 4800 m streamer.
164.2115	Streamer building and testing completed; peak noise level is 3-4 microbars; most of the streamer has noise levels of <1.5 microbars.
165.0148	First good shot-point (FGSP) at SOL 110/1A.
165.0740	Last good shot-point (LGSP) at EOL 110/1A. Cartridge tape jammed in tape drive; acquisition suspended and commence loop.
165.1209	FGSP at SOL 110/1B.
166.0602	LGSP at EOL 110/1B.
166.0613	Source interference from seismic vessel *Geotide* is first detected.
166.1947	FGSP at SOL 110/2A (line 110/3 of cruise proposal).
167.0425	LGSP at EOL 110/2A; starting a loop to avoid source interference from *Geotide*.
167.0829	FGSP at SOL 110/2B.
167.1918	LGSP at EOL 110/2B.
168.0241	FGSP at SOL 110/3 (line 2 of cruise proposal).
169.0004	LGSP at EOL 110/3.
169.0233	FGSP at SOL 110/4.
169.1300-1449	Noise interference on streamer from large ore carrier.
170.0026	LGSP at EOL 110/4.
170.0650	FGSP at SOL 110/5A.
170.1445	LGSP at EOL 110/5A. Start loop as streamer depth got out of control in choppy seas, and a large segment of streamer came to the surface.
170.2032	FGSP at SOL 110/5B.

171.0621	LGSP at EOL 110/5B.
171.1139	FGSP at SOL 110/6.
172.0327	LGSP at EOL 110/6.
172.1511	Start shooting before SOL 110/7A.
172.1542	Compressor blow-off timer failure; guns turned off.
172.1632	Compressor problems circumvented; FGSP at SOL 110/7A.
172.2018	Compressor shut-down due to wiring problems in compressor room; LGSP at EOL 110/7A. Commence loop.
173.0058	FGSP at SOL 110/7B.
173.1720	LGSP at EOL 110/7B.
174.0021	FGSP at SOL 110/8A.
174.2122	LGSP at EOL 110/8A. Apparent salt-water ingress at active section 45 (~4700 m along streamer). Retrieve streamer and swap out active section 45 (fish bight). The tension cell at the end of the tow leader was also removed, as it was producing extremely erratic results. Lead added to the first 1200 m of the streamer to improve balance.
175.1656	FGSP at SOL 110/8B.
176.1121	LGSP at EOL 110/8B.
176.2037	FGSP at SOL 110/9.
177.1001	LGSP at EOL 110/9. This line was terminated prematurely due to a 3-D seismic survey underway on the Campbell oil field near the middle of line 9. Line 110/10 was deleted from the program as it was not considered worth an additional 12 hours transit time to record only 30 km of data.
178.0012	FGSP at SOL 10. This line was the last segment of line 8 in the cruise proposal (way points 4 to 5). It was decided to number this line separately to the remainder of line 8 because line 9 interrupted the shooting of line 8. Shooting of this line was delayed because of excessive cable noise. This noise was found to be entirely dependent on the direction of shooting, and is ascribed to the long swell running at the time. Since this line was considered to be of relatively low priority, it was decided to go ahead with shooting, even though recording was marginally outiside specifications, to allow *Rig Seismic* to be re-positioned to the higher priority lines in the Barrow Sub-basin.
178.1342	LGSP at EOL 110/10.
179.0110	FGSP at SOL 11.
179.0900-1000	Noise on streamer from passing ship.
179.1647	LGSP at EOL 110/11.
179.2152	FGSP at SOL 110/12A. Because of extremely shallow water at the start of the line, shooting commenced when half of the streamer was straight.
179.2205	Streamer straight on line 110/12A.
180.2345	LGSP at EOL 110/12A. Sailing a loop for gun repairs.
181.0515	FGSP at SOL 110/12B.
181.1536	LGSP at EOL 110/12B.

182.0147	FGSP at SOL 110/13
182.2202	LGSP at EOL 110/13
183.0000	Retrieve first 400 m of streamer to replace bird 2.
183.0447	FGSP at SOL 110/14
183.1308	LGSP at EOL 110/14
183.2316	FGSP at SOL 110/15
185.1002	LGSP at EOL 110/15
185.1100-2000	Retrieve streamer. The following problems were found: bird 4 was missing 1 wing; tail stretch section was holed and contained water; one of the two tailbuoy ropes had broken, and the tailbuoy had shipped a large quantity of water.
185.2000	Start transit to Fremantle.
190.0300	Arrive in Fremantle.

SEISMIC DATA RECORDED

Seismic data were recorded in four stages, due to scientific and operational considerations.

STAGE 1: BEAGLE SUB-BASIN (1239.3 km; 8 wells tied; Figs 5-6)

LINE 110/1 (209.0 km)
Southern flank of the Bedout High, through the northwest corner of the Bedout Sub-basin, across the North Turtle Hinge, and along the axis of the Cossigny Trough, tying to line 101/2 of SNOWS-I. Ties to lines 110/2, 3, 4, 6, and 7, and to Phoenix-1 and North Turtle-1.

LINE 110/2 (172.2 km)
Dip line across the southwest Beagle Sub-basin, from the Lambert Shelf, across the central Cossigny Trough and northeast Picard Trend, to the inner flank of the Exmouth Plateau. Ties to lines 110/1, 4, and 8, and to Bruce-1 and Picard-1.

LINE 110/3 (193.5 km)
Dip line across the southwest Beagle Sub-basin, from the Lambert Shelf, across the southwest end of the Cossigny Trough and the Picard Trend, to the inner flank of the Exmouth Plateau. Ties to lines 1110/ and 8, and to Cossigny-1, Ronsard-1, and Delambre-1.

LINE 110/4 (200.8 km)
?Dip line from the Lambert Shelf, across the northeast end of the Cossigny Trough, and along the axis of the Thouin Graben to the inner flank of the Exmouth Plateau. Ties to lines 110/1, 3, 4, and 7. No well ties.

LINE 110/5 (144.7 km)
Extends from the Bedout High, across the North Turtle Hinge and the northern end of the Thouin Graben, to the inner flank of the Exmouth Plateau. Ties to lines 110/4 and 6, and to Minilya-1.

LINE 110/6 (142.6 km)
Dip line from the Bedout High, across the western end of the Bedout Sub-basin, to the Lambert Shelf. Ties to lines 110/1, 5, and 7, and to Phoenix-1.

LINE 110/7 (176.5 km)
Northwest end of the Bedout Sub-basin, across the North Turtle Hinge and southern Thouin Graben to the inner flank of the Exmouth Plateau. Ties to lines 110/1, 4, 6, and 8. No well ties.

STAGE 2: OUTER BASIN STRIKE LINE (462.9 km; 3 wells tied; Figs 5, 7)

One well from this stage (Saturn-1) is also tied on Stage 3.

LINES 110/8 & 110/10 (345.3 km & 117.6 km)
Strike lines along the inner flank of the Exmouth Plateau from offshore of the Beagle Sub-basin, outside the Dampier Sub-basin, to the Kangaroo Syncline. Ties to lines 110/2, 3, 7, 9, 101/8, 9, 10, 7, 6, and 16, and to Brigadier-1, Gandara-1, and Saturn-1.

STAGE 3: BARROW-DAMPIER-EXMOUTH IN-FILL (591.6 km; 9 wells; Figs 5,7-8)

One well from this stage (Saturn-1) is also tied on Stage 2.

LINE 110/9 (121.6 km)
Dip line from the southwest end of the Lewis Trough, across the northern end of the Barrow Island Anticline and the Rankin Platform, to the Kangaroo Syncline. Ties to lines 110/8 and 10 and to Venture-1, Sultan-1 and Saturn-1.

LINE 110/11 (142.0 km)
Dip line from the southern Barrow Sub-basin to the southwest Exmouth Plateau. Ties to lines 101/4 and 16, and to Outtrim-1, Novara-1, and Zeewulf-1.

LINE 110/12 (328 km)
Dip line from the Barrow Depocentre, across the Kangaroo Syncline, to the northwest flank of the Exmouth Plateau. Ties to lines 110/13, 101/4 and 16, and to Ramillies-1, Investigator-1, and Eendracht-1.

STAGE 4: OUTER EXMOUTH PLATEAU (574.8 km; 2 wells tied; Figs 5, 8)

LINE 110/13 (180.3 km)
Strike line along the Exmouth Plateau Arch through the Scarborough gas field. Ties to lines 110/12, 14, and 15, 101/7, and to Scarborough-1 and Jupiter-1.

LINE 14 (76.6 km)
Dip line from the Exmouth Plateau Arch (northeast end of line 110/13) joining with the

northwest end of line 110/9.

LINE 110/15 (317.9 km)
Strike line from the Exmouth Plateau Arch across the northwest flank of the Exmouth Plateau, to the oceanic crust of the Gascoyne Abyssal Plain, thus completing the North West Shelf - Gascoyne crustal transect. Ties to lines 110/13 and 101/7, and to Jupiter-1.

EQUIPMENT AND SYSTEMS REPORTS

NAVIGATION/GEOPHYSICAL DATA ACQUISITION (DAS)

The DAS ran for the duration of the cruise with only two breaks in data acquisition. The first break occurred on seismic line 110/04 when 9 minutes of data were lost (169.0319-169.0328). During this break, the ship speed and heading were not changed; as there was little divergence from the line at the end of the break, and as differential GPS data are recorded independently on optical disc, seismic acquisition was not suspended. The second break occurred after the streamer was retrieved, and had no relevance to the recording of seismic data.

GPS/dGPS:
The prime navigation systems for survey 110 consisted of two effectively identical differential Global Positioning Systems (dGPS) supplied by Racal Survey Ltd ('Skyfix'). Each system comprised a Trimble 4000 GPS receiver, Racal demodulator, and Compaq 386 Personal Computer running real-time differential software. Base stations at Dampier and Perth were utilised and data were recorded by the DAS and also on optical disc.

While there was a number of problems with one or other of the dGPS systems at various times during the survey, at no time was dGPS coverage lost from both systems, beyond the short periods each day when stand-alone GPS or dead-reckoning (DR) were used.

Fifteen seismic lines were shot comprising some 15 days 6 hours 22 minutes of seismic acquisition time (including loop time but not cable repair time). During that period, 94.6% of navigation was provided by the primary differential GPS system, 4.6% was provided by the backup dGPS system, 0.5% was provided by stand-alone GPS, and 0.3% came from dead-reckoning (Fig. 9). The total of 66 minutes of DR is considered acceptable given that most of that time occurred in blocks of less than one minute. All seismic lines used 99% or greater dGPS, except for line 7 (1.1%), line 8 (3.2 % non-differential), line 10 (1.4% DR), and line 14 (2.8% non- differential). In general, noise levels during the survey were of the order of 5-10 meters, depending on the geometry and which satellites were available. Satellite 11 was used by one system but flagged as bad by the other on occasion.

The Magnavox T-set GPS receiver ran in the background with little interference. However, the reliability of the Skyfix system meant that it was never needed as the primary navigation system.

Sonar Dopplers and Gyro-compasses:
The sonar doppler and various gyro-compasses provide backup dead-reckoned navigation for the brief periods when GPS or dGPS coverage was not available. The Magnavox MX610D was calibrated and used in water-track mode to provide speed through the water.

Heading data were recorded from the Instrument Room and bridge Sperry gyro-compasses throughout the survey, with no significant problems.

Magnetics:
The magnetometer was deployed during the shooting of all seismic lines except for the first few hours of line 1 and for part of line 8, when the magnetometer head became contaminated with salt water. With no white spirit on board, the head was re-filled with isopar-M as an emergency measure, which produced a very clean signal although it decayed faster than when the head was filled with white spirit. Noise was typically of the order of 3-4 nT and there was no noticeable difference in noise level due to the change in fluid used.

Gravity:
From 176.0200 the gravity meter began to get noisy and started exhibiting an oscillation of around 10 mGal /minute at its worst. Previously noise had been generally of the order of 2-3 mGal and eventually it did quieten down somewhat to around 5 mGal or so. Gravity ties were carried out before and after the survey, in Darwin and Fremantle.

Bathymetry:
Bathymetric data was collected all survey without problems using the 12 kHz echo-sounder. The 3.5 KHz Raytheon echo-sounder / profiler was not used during the survey.

SEISMIC ACQUISITION SYSTEM

The seismic acquisition system for SNOWS-II consisted of a Fjord Instruments analogue streamer, BMR designed and built amplifier/filters, Phoenix analogue-to-digital converter with instantaneous floating point (IFP) converter, and a Microvax-3 based recording system. Data were recorded on Fujitsu 3480 cartridge tape drives.

Streamer Sub-system:
The seismic streamer configuration consisted (from front to back) of armoured tow leader (80-110 m deployed), tension cell, 3 x 50 m stretch sections, 48 x 100 m active sections (192 x 25 m active groups), a single 50 m stretch section, and an 'active' tailbuoy at the end of a 200 m rope. Thirteen remotely controlled cable levellers, each with a depth transducer, were deployed equi-spaced along the streamer to provide depth control. In addition, 4 compass birds were deployed after active channels 25, 73, 121, and 169 (channel 1 at the front of the cable). A PRESTEL (Pressure release Satellite Transmitter for Emergency Locations) device was also mounted on the streamer, as a security measure.

During streamer deployment, extensive effort was expended in reducing noise to the lowest practical level. Most sections had oil and lead added to them, where deflation was apparent, while sections with wrinkled skin were swapped out. The effort put in here was well worth while, with the streamer proving exceptionally quiet during the survey. The average noise level for all noise tests conducted in a variety of sea conditions was 0.9 microbars per channel (Figs 10, 11). At no time during the survey were more than 2 channels 'dead'.

Streamer depth controller was generally good, with the depth range along the streamer usually being less than +/-1 m. Depth was set at 10, 11, or 12 m, depending on sea conditions and the resultant streamer noise level.

Streamer problems were limited to the normal attrition associated with 3 weeks of shooting. Fish bights on active section 45 (2 dead channels) necessitated retrieval of the streamer and replacement of that section during line 110/8. Some problems were encountered with low batteries in cable levellers; these were replaced, as required. The tension cell between the tow leader and the first stretch section was replaced during line 110/8, when it was found to be giving erratic and largely meaningless tension data. On later inspection, the tension cell was found to be cracked and to have salt water contamination.

At the start of the survey, tests were carried out with a GPS-equipped tailbuoy, to assist development of a system that provides improved streamer positioning. The tests were successful and further development will proceed.

Amplifier and A/D Sub-system:
The BMR designed and built digitally controlled amplifier filters performed well during the survey. Full computer-controlled testing of gains, noise, and filters was carried out on all lines prior to and following shooting. The amplifiers displayed very little drift, with the output signal levels generally maintained to within +/-1 mV of 1023 mV. When an amplifier drifted more than 1 mV from the target output, that amplifier was re-calibrated during line changes. From time to time during the survey, individual amplifiers did generate electronic problems; these amplifiers were replaced.

The Phoenix A/D converter and IFP amplifier used during the survey performed reliably. Tests carried out at the start and end of the survey indicated high linearity and stability for the duration of recording.

Recording Sub-system:
The MicroVax-3 computer and Fujitsu 3480 cartridge tape drives performed reliably throughout the survey. The only significant problem occurred when a cartridge tape jammed in a drive during line 110/1; this necessitated suspension of acquisition while the tape was released and the sailing of a loop.

Minor software/hardware problems during the survey were rare and provided only minor interruptions to recording.

MECHANICAL

Pre-cruise preparation entailed three main tasks:

- Repair and replace sonar doppler and paddle log stems damaged previously;
- Repair of 15 active streamer sections;
- Thorough overhaul of rear deck equipment, including sleeve guns, air hose and firing line bundles, and compressors.

Seismic Source:

The maintenance work allowed for long lines of uninterrupted shooting. Only one 'loop' had to be sailed while on line to allow airgun repairs.

The seismic source for Survey 110 was provided by two arrays of sleeve guns, with 16 x 2.46 litre (150 cu in) guns in each array. During seismic recording, 10 guns were fired from each array, for a total volume of 49.2 litres (3000 cu in). The airguns were grouped in clusters of 4, 3, 2, and 1 guns in each array. On the last line (110/15), when airgun attrition became serious after 30+ hours of continuous shooting, two clusters of 4 guns were fired in one array while 2 clusters of 3 guns were fired in the other. As water depths were in excess of 3000 m at the time, it was considered that this configuration would cause no perceivable deterioration in source characteristic.

Both gun arrays were towed outboard at the stern from the ends of the towing booms. Lateral separation between the arrays was approximately 20 m. Towing depth for the gun arrays was 9 m +/- 1 m.

By the end of the survey, each gun had been fired for an average of 45000 shots. A total of 8 guns were removed from the arrays for servicing during the survey, but only two of these had any discernible faults. There was no evidence of damage to face seals or wear rings.

While the mechanical components of the gun arrays continued to operate satisfactorily, many parts are becoming very worn and will require maintenance. As the air hose / firing line bundles were reconditioned before the survey, their condition remained good throughout the survey. Some electrical problems were experienced, but these were generally quickly identified and repaired.

Gun Controller and Gun Selection Box:

While the gun controller generally worked well during the survey, there were intermittent timing problems. Some guns would run well for several hours and then begin to display bad timing. If the gun was switched off for a while then re-started, then the bad timing often disappeared. Subsequent testing indicates that the bad timing is a result of intermittent noise on the timing coil line, and may also be temperature-dependent. While this problem requires further investigation, gun firing times were kept within specification for the duration of the survey.

Compressors:

High pressure air at 1800-2000 psi was supplied by 4 Price 'Air Gun Master' compressors, typically operating at 1650 rpm. Of the 6 compressors normally available, one was inoperative for the duration of the survey, leaving only one compressor as a spare. All 5 operative compressors performed satisfactorily, with only one significant breakdown. Relatively low ambient air temperatures in the compressor room (32-38^{o}C) are considered to be the main contribution to the compressor reliability.

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APPENDIX 1
EXECUTIVE SUMMARY FROM SNOWS-I POST-CRUISE REPORT
(From BMR Record 1991/79)

While the northern Carnarvon Basin of the southern North West Shelf is one of Australia's most hydrocarbon-rich provinces, relatively little is known of its deep structure and the control this deep structure has on hydrocarbon occurrences. BMR *Rig Seismic* Survey 101 was designed to acquire deep-crustal seismic data along a series of dip and strike lines in the region, with the following aims:

- To determine the broad regional structural framework of the southern North West Shelf by examining the boundaries between the major structural elements;
- To determine the deep crustal structure of the southern North West Shelf and its relationship to the development of the continental margin; and
- To assess the control of deep structure on the development of the major hydrocarbon fields and plays in the region, and in particular the structural and depositional effects resulting from reactivation of these structures.

It is recognised that at least two cruises of deep-crustal seismic acquisition are needed to address these problems adequately on the southern North West Shelf (northern Carnarvon Basin and offshore Canning Basins). Survey 101, which departed Port Hedland on May 11 and arrived in Fremantle on June 10, 1991, was concentrated in the northern Carnarvon Basin. Technical difficulties prevented extension of the cruise into the offshore Canning Basin, as was originally intended.

During Survey 101, a total of 1654 km of presumably high-quality deep seismic data were recorded along 6 dip and 4 strike lines in the Dampier, Barrow, and Exmouth Sub-basins. These lines were tied to 20 exploration wells, thereby providing valuable modern regional ties of the principal seismic horizons throughout the region.

The seismic data were recorded from a 4800 m streamer, configured with 192 x 25 m active groups. The record length was 16 seconds, and the sample interval 4 msec. The seismic source consisted of dual 'sleeve' airgun arrays with a total volume of 50 l (3000 in^3). Shots were fired every 50 m at a ship speed of 4.5 knots, giving 48-fold coverage. Both streamer and airguns were towed at 10-11 m depth. Streamer noise levels were uniformly low, being generally less than 5-6 microbars for the first 32 channels, and less than 3 microbars for channels 33-192.

Navigation for the survey was provided by differential Global Positioning System (DGPS), using a shore reference station at Broome and a real-time satellite data link. DGPS data were recorded for 95.4% of the survey; during almost all the remaining time, stand-alone GPS was available. While detailed analysis of the navigation data has not yet been done, it is estimated that absolute positional accuracy should be better than +/- 10 metres.

In the Dampier Sub-basin, three dip lines were recorded, in the northwest, centre, and southwest of the sub-basin. These lines extended from the southern basin boundary to the inner Exmouth Plateau. Two dip lines were recorded across the Barrow Sub-basin, with one of the lines being extended to Jupiter-1 on the crest of the Exmouth Plateau. Shallow water at the near-shore ends of these lines precluded their being continued to the landward basin margin. In the Exmouth Sub-basin, a single dip line was recorded from the southern Exmouth Plateau to North West Cape, parallel to, and south of the Long Island Transfer Fault. Three linked strike lines were recorded from the Exmouth Sub-basin along the length of the Barrow and Dampier depocentres into the Beagle Sub-basin, to tie together the dip lines and to image the generally NW-SE cross trends at depth; these cross-trends (transfer fault direction) have probably had a major influence on the present-day structure of the southern North West Shelf. Advantage was taken of available transit time to record a second, shorter tie line from the Kangaroo Syncline to the deep-water Exmouth Sub-basin.

As the Tertiary carbonates on the North West Shelf make the area notoriously difficult for the recording of seismic data, particularly in shallow water, it was anticipated that only gross structural information would be visible in the monitor sections. This turned out to be the case and, while definite primary reflections can be identified down to 5-6 seconds TWT on some lines, strong water column and interbed reverberations generally overwhelm any deep information in the unprocessed data. The only open-file deep seismic data from the northern Carnarvon Basin (two lines across the central Dampier Sub-basin) show reflections down to 10-12 s TWT, with a shorter streamer and smaller seismic source than were used in Survey 101. We are therefore confident that, given the low streamer noise levels prevailing during the survey, the processed data should reveal valuable information the basin-forming structures in the region.

APPENDIX 2
BARROW SUB-BASIN SHALLOW WATER SEISMIC PROPOSAL
(From BMR Record 1992/40)

In mid-1991, the Bureau of Mineral Resources (BMR) commenced a program of deep seismic acquisition on the southern North West Shelf with the intention of providing a regional framework data set for explorers in this highly prospective segment of Australia's continental margin. In particular, the program has the following aims:

- To determine the broad regional structural framework of the southern North West Shelf by examining the boundaries between the major structural elements;
- To determine the deep crustal structure of the region;
- To assess the control of deep structure on the development of the major hydrocarbon fields and plays, and in particular the structural and depositional effects resulting from reactivation of these structures; and
- To acquire a set of high-quality seismic tie lines linking the deeper exploration wells throughout the region to allow regional seismic correlations.

To address these aims, a multi-cruise program has been devised during which deep seismic data (4800 m streamer; 16 sec record length; 3000 cu in seismic source) are being recorded. During the first cruise, SNOWS-I (for Southern North West Shelf), completed in June 1991, 1654 km of seismic data were acquired aboard the BMR's research vessel *Rig Seismic* along 10 widely spaced lines tied to 20 exploration wells in the Barrow, Dampier, and Exmouth Sub-basins, and on the inner flank of the Exmouth Plateau. Processing of the data was arranged through a commercial contractor. The data were processed by the second quarter of 1992, and frequently show basin structure down to a depth of at least 10 s TWT (>20 km); these are the first data recorded on the southern North West Shelf that show such deep structures.

SNOWS-II, programmed for June-July 1992, is intended to acquire up to 2765 km of deep seismic data tied to 22 exploration wells (of which 4 were also tied on SNOWS-I), while SNOWS-III, scheduled for mid- to late-1993, will carry out similar work in the offshore Canning Basin.

As the *Rig Seismic* is a deep-water research vessel, the data recorded so far is restricted to water depths of more than 20 metres. However, within the Barrow Sub-basin, in particular, the basin-forming structures landward of the main depocentre axis are frequently located in water depths of less than 20 metres. Since the landward basin-bounding faults in continental margin rift basins are critical to understanding the gross basin framework and the tectonic evolution it is important that data be collected in these areas, for maximum program effectiveness.

To overcome this problem, BMR is proposing to contract a commercial shallow-water seismic vessel to record extensions to the SNOWS-I and SNOWS-II lines across the basin-bounding faults of the Barrow Sub-basin, where possible. The proposed program comprises 405 km of data along 7 lines which also tie 11 exploration wells. These lines will largely be in waters that are under the jurisdiction of the state of Western Australia.

At this stage, the specific recording parameters will be dependent on the capabilities of available shallow-draft vessels. While it is expected that it will be impractical to record data with the same parameters used on SNOWS-I and SNOWS-II (particularly with regard to streamer length), the contract will require the largest source and longest streamer length commensurate with operating in restricted waters.

APPENDIX 3
STRUCTURE, STRATIGRAPHY, AND HYDROCARBON ACCUMMULATIONS OF THE NORTHERN CARNARVON BASIN

STRUCTURE

The gross structure of the North West Shelf comprises a series of generally NE-SW trending rifted Mesozoic depocentres overlying Palaeozoic NW-SE trending basins that may have constituted failed arms of a previous rift valley (Veevers, 1988). Within the northern Carnarvon Basin, the four principal shelf and upper slope depocentres - the Exmouth, Barrow, Dampier, and Beagle Sub-basins (Fig. 12) - accumulated most of their sedimentary fill in the Triassic and Jurassic, before the rift system aborted with the separation of Australia from (?)Greater India along a parallel rift system along the northwest and northern margins of the Exmouth Plateau. Although the four sub-basins have frequently been treated as separate entities in the literature, this is largely due to the concentration of individual exploration companies in one or other of the sub-basins. In fact, the sub-basins are very closely related, particularly in the case of the Barrow and Dampier Sub-basins, and any analysis of the basin-forming mechanisms of the area should consider all of them together.

RELATIONSHIPS BETWEEN SUB-BASINS

The relationships between the sub-basins of the southern North West Shelf are complex and not, as yet, well-imaged or well-understood. In the southwest, the Exmouth Sub-basin is in *en echelon* arrangement with the Barrow Sub-basin (see, for example, Barber [1988], figure 2), with the boundary between the two usually being taken as the southern extension of the Rankin Trend (Alpha Arch) and the E-W trending Long Island Fault System. It is likely that the Long Island Fault System is a strike-slip or transfer fault zone. The junction between the Barrow and Dampier Sub-basins, northeast of Barrow Island, is defined largely on the basis of a change in strike of the main depocentres, from NNE-SSW in the Barrow Sub-basin to NE- SW in the Dampier Sub-basin. This junction, which is both complex and not imaged at depth, probably overlies a broad NW-SE trending transfer fault zone extending from the confluence of the Deepdale and Hauy Faults, northeast of the Monte Bello Islands, and through the bend in the Rankin Trend at the northeastern end of the Gorgon Structure. By virtue of the extremely thick Mesozoic sediment pile in the Barrow and Dampier Sub-basins, this boundary will probably be the most difficult to image with seismic techniques.

In the northeast, the boundary between the Dampier and Beagle Sub-basins is taken at a feature that has been referred to as the 'De Grey Nose'. It is likely again that this feature is a transfer fault, or complex of transfer faults 'closing off' the northeast end of the Dampier Sub- basin. To the northeast, the Beagle Sub-basin, as with the Exmouth Sub-basin, is relatively poorly known, mainly because of the lack of exploration success and the commensurate lack of modern high-quality seismic data. It appears from published tectonic elements maps and papers that the Mesozoic trend of this basin is strongly influenced by underlying orthogonal trends of the Offshore Canning Basin, and in some reports it has been considered to be a

Mesozoic sub-basin of the Canning Basin, as with the Rowley and Bedout Sub-basins. The Beagle Sub-basin is separated from the Bedout Sub-basin, Bedout High, and Rowley Sub-basin to the east and northeast by the N-S trending North Turtle Hinge.

INTERNAL SUB-BASIN STRUCTURES (Figs 13, 14)

To the southeast, the main depocentres of the rift are bound by the Flinders Fault System in the south and the *en echelon* Rosemary Fault System in the north. However, the main rift-bounding faults are more properly the Scholl Island Fault in the south and the Hauy Fault in the north. Between these two fault systems (Flinders-Rosemary and Scholl Island-Hauy), is a complex fault zone (Peedamullah Shelf and Enderby Trend) which principally includes Triassic and Permo-Carboniferous sediments. This area of the North West Shelf is one of the few areas where the Triassic-Jurassic section is thin enough that basin-forming structures can be distinguished with conventional seismic data.

Oceanwards of the Flinders and Rosemary Fault Systems and partially overlying them, is a complex zone where Cretaceous reactivation of pre-existing structures has caused extensive faulting and buckling of the Mesozoic section. This zone hosts the Saladin, Roller, and Yammaderry Fields in the Barrow Sub-basin and includes the oil-prone Legendre Trend in the Dampier Sub-basin.

The major Mesozoic depocentres include the sinuous and generally NNE-SSW trending Barrow Depocentre in the Barrow Sub-basin and the more linear NE-SW trending Lewis Trough in the Dampier Sub-basin. Both depocentres have expression as deep (~3 km Tertiary-Cretaceous and >5 km Jurassic, underlain by an unknown thickness of Triassic and Palaeozoics) essentially unfaulted downwarps.

The seaward boundary of the Barrow-Dampier rift is formed by the structurally high Rankin Platform and its associated structures, the Kendrew Trough (or Kendrew Terrace) and positive Madeleine Trend. The Rankin Trend itself is the southeastern border zone of the Exmouth Plateau/Rankin Platform megacrustal block (Woodside, 1988). The Rankin Platform has the strongest gravity signature on the southern North West Shelf (Fig. 4) and is obviously a fundamental structure of the rift system, as well as being host to the largest hydrocarbon reservoirs. For much of its length, the Rankin Platform is strongly fault-segmented, consisting of a series of NNE-trending pivotal Triassic horsts and grabens, again in an *en echelon* arrangement, suggesting that the trend formed in response to strike-slip movements (Woodside, 1988). Woodside further suggest that the entire complex area lying between the Rankin Trend and the Madeleine Trend formed above a deep-seated wrench zone.

In the southwest, offshore from the Barrow Sub-basin, the Rankin Platform swings round to the south, where it becomes known as the Alpha Arch (which includes the large Gorgon gas field). While the deep structure of the Alpha Arch is probably less-known than that of the Rankin Trend, its gravity expression is as strong as that of the Rankin Platform, and it also appears to be the expression of a fundamental basin-forming structure.

The southeast boundary of the Exmouth Sub-basin is formed by the Rough Range Fault, while the northwest boundary is ill-defined, due to the scarcity of seismic data northwest of Northwest Cape. The deep structure of the Exmouth Sub-basin consists of a series of east-tilted fault blocks that are down-thrown to the west by as much as 3000 m in the pre-Cretaceous and show evidence of some reverse movement in the late Miocene (Parry & Smith, 1988).

As with the Exmouth Sub-basin, the Beagle Sub-basin is inadequately defined and mapped. The sub-basin is a transitional area between the northern Carnarvon Basin and the Offshore Canning Basin, and contains trends that are common to both of these basins (Crostella & Barter, 1980). In the west, the two principal identified elements are the NE- SW trending Cossigny Trough and Picard Trend, which are probably fairly straightforward equivalents of the Lewis Trough and Rankin Platform, respectively. In the eastern half of the sub-basin, the dominant trend becomes N-S, as represented by the Thouin Graben and North Turtle Hinge.

AGE AND STYLE OF FAULTING

Etheridge & others (1991) consider that formation of the northern Carnarvon Basin has been influenced by four main stages of faulting. In descending age, these are as follows:

1. Crustal extension primarily in the (?Early) Permian (Yeates & others, 1987) along NE-trending normal faults separated by NW-trending transfer faults. These faults have probably determined the structural grain of the North West Shelf for the remainder of its history. The Scholl Island Fault is a relatively well-documented example of an extensional fault of this age (see, for example, Bentley [1988] figs 5 & 7).

2. Late Triassic to Early Jurassic faulting is widespread, particularly on the Rankin Trend and the Exmouth Plateau. This faulting has traditionally been interpreted as extensional and has been referred to frequently as 'rift onset'; however, the steep dips on these faults, the unsystematic fault block rotations on the Rankin Trend, and fault discontinuity all point to strike-slip faulting, interpreted to be in a left-lateral sense. Faulting of this age has produced most of the large gas fields of the North West Shelf (North Rankin, Goodwyn, West Tryal Rocks, Gorgon).

3. Middle to Late Cretaceous faulting is again largely restricted to NE-trending high-angle zones that are complexly-structured. This phase of faulting has formed many of the structures on the oil-rich trend from Saladin to Talisman. Fault geometries again indicate dominantly left-lateral wrench motion.

4. In the Miocene, a final episode of wrench reactivation occurred, probably with right- lateral sense and in response to the collision of Australia with Timor. This activity is still evident today, particularly in the Timor Sea, where some faults reach seabed.

It is clear that these four episodes of faulting (one of normal extension, two of left-lateral wrenching, and one of right-lateral wrenching) have contributed heavily to the structural complexity of the North West Shelf today. Also, it is likely that much of the reactivation faulting seen in the upper part of the section is concentrated above the original basin- forming structures, themselves the loci of inherent crustal weakness. It seems logical that the ability to trace the basin-forming structures will enable a better definition of the most active areas of reactivation, and hence hydrocarbon reservoir development.

STRATIGRAPHY

While the work set out in this cruise proposal is primarily directed at solving structural problems on the southern North West Shelf, for completeness of background the following summary of general stratigraphy is given (Fig. 15). Given that the North West Shelf is well-explored by Australian standards, the stratigraphy is relatively well-documented, particularly in the Barrow and Dampier Sub-basins. This section is based upon the studies of Parry & Smith (1988) and Woodside (1988).

PALAEOZOIC

Because of the great thickness of Mesozoic sediments beneath much of the northern Carnarvon Basin, Palaeozoic sediments have only been sampled infrequently. Carboniferous and Devonian rocks have been penetrated in Rough Range-1 and at shallower depth in wells on the Peedamullah Shelf, between the Flinders Fault System and the Scholl Island Fault. The Permian Byro Group has been documented in several wells on the Peedamullah Shelf and to the south, where it includes dark shale and siltstone with some sandstone. Parry & Smith (1988) believe that this sequence deserves more attention, given that there is a distinct possibility that shales in the group have generated hydrocarbons at some time and the fact that good-quality reservoir sandstones are present in the overlying Upper Permian Chinty Formation.

MESOZOIC-CAINOZOIC

Mesozoic sedimentation commenced with the deposition of the Scythian to Ladinian Locker Shale. This sequence consists of a basal transgressive coarse paralic sandstone and a thin shelfal limestone overlain by sandy shales. The bulk of this sequence consists of a thick marine section of interbedded claystone and minor siltstone with a thin regressive sandy sequence at the top.

The Locker Shale grades upwards into the Late Triassic Mungaroo Formation, a dominantly fluvial sandstone sequence, with some coals. This sequence is the principal reservoir for the major gas accumulations of the Rankin Trend. The coarse clastics in the sequence were probably deposited in a braided channel or fluvio-estuarine environment, whereas the interbedded claystones and coals represent flood-plain deposits with minor marine influences. At the top of the Mungaroo Formation there appears to be a return to a more marine environment, and there are widespread Rhaetian shelf carbonates along the northern margin of the Exmouth Plateau (von Rad, Haq, & others, 1992).

Overlying the Mungaroo Formation across most of the Dampier Sub-basin is a widespread Hettangian-Sinemurian sandstone sequence (North Rankin Beds; Woodside [1988]). These consist of marginal marine and fluvial sandstones interbedded with minor marginal marine and estuarine claystone, and was deposited in a nearshore/shoreline environment.

During most of the Jurassic, the thick Dingo Claystone was deposited across the southern North West Shelf. This formation is divided by Woodside (1988) into three sub-units - the lower, middle, and upper Dingo Claystone. Lateral equivalents include the more coarse-grained siliciclastic Biggada, Dupuy, Legendre, and Angel Formations. The base of the lower Dingo Claystone is marked by a transgression and an abrupt lithologic change from clastics to carbonates; this generated a basin-wide seismic marker. With deepening of the basin, the carbonates were succeeded by inner shelf calcareous claystones. In the Bajocian-Bathonian, a regional regression led to the deposition of westwards-prograding deltaic sediments across the northern Barrow-Dampier Sub-basins. This regression reached its maximum extent towards the end of the Middle Jurassic, coincident with a major phase of tectonic movement. This led to the formation of the ubiquitous 'Main Unconformity' ('MU'), separating the middle and upper Dingo Claystones, which has historically been interpreted as the expression of final continental breakup in the Argo Abyssal Plain. Much of the southern North West Shelf was emergent at this time; marine conditions persisted only in the rapidly-subsiding areas of the Lewis Trough and the Madeleine Trend.

The remainder of the Jurassic saw sedimentation in a true divergent margin setting with predominantly fine-grained mixed clastic sediments (upper Dingo Claystone) being rapidly deposited in the Lewis Trough. Within the uppermost part of the Dingo Claystone, a marine sandstone unit (Dupuy Sandstone Member) was deposited in moderate to deep water in the vicinity of Barrow Island and possibly also around the edges of the Rankin Platform.

The Dingo Claystone is disconformably overlain by the Barrow Group, a generally northwards-prograding regressive sequence of clastics of mainly Neocomian age. Three units have been named within the Barrow Group - the Malouet and Flacourt Formations, respectively comprising the bottomsets and foresets/topsets of the delta, and the Flag Sandstone (Kopsen & McGann, 1985), a massive submarine fan sandstone that is a facies equivalent of the Malouet Formation. The relationship between these three formations is shown diagrammatically in Howell (1988, fig. 8) and Barber (1988, fig. 7).

A major transgression beginning in the late Valanginian initiated the deposition of the units of the Winning Group (successively, the Birdrong Sandstone, Muderong Shale, Windalia Sandstone Member, Windalia Radiolarite, Gearle Siltstone and Haycock Marl). It is likely that this transgression was in response to margin breakup adjacent to the Perth Basin. The basal transgressive unit consists of the Birdrong Sandstone along much of the Peedamullah Shelf, and the mid- and outer-shelf Mardie Greensand to the south of Barrow island. Both units consist of quartzose sandstone; the Birdrong also contains minor interbedded siltstone, while the Mardie Greensand is heavily glauconitic. The basal sands were succeeded by the Muderong Shale, a widespread unit of marine claystones which provides a regional seal for most of the hydrocarbon accumulations in the Barrow and Dampier Sub- basins. A minor regressive phase is indicated by the deposition of the Windalia sandstone Member, a storm-winnowed shelf sand, at the top of the Muderong Shale.

In the Aptian, a marked environmental change and a rise in sea level led to the deposition of the widespread Windalia radiolarite, composed of radiolarite grading basinwards to radiolarian claystone, siltstone, and chert. The Windalia Radiolarite was succeeded by the Gearle Siltstone in the Barrow area and the Haycock Marl in the Dampier Sub-basin, with these units being deposited in open ocean settings.

Extensive carbonate sedimentation commenced in the Turonian with the deposition of the Toolonga Calcilutite. During the remainder of the Cretaceous, sedimentation was fairly evenly split between open marine carbonates and claystones (Korojon Calcarenite, Withnell Formation, and Miria Marl). Most of the Tertiary sequences on the North West Shelf are the result of out- and up-building of the continental shelf during a series of transgressive/regressive sea-level pulses, with the dominant sediment type being carbonate.

HYDROCARBON ACCUMULATIONS

The hydrocarbon fields of the southern North West Shelf fall into two categories (Vincent & Tilbury, 1988) - those reservoired in the pre-'Main Unconformity' (pre-MU) section, and those reservoired in the post-MU section (Appendix 5).

The pre-MU fields are characterised by the fault blocks of the Rankin Trend, which host several giant gas/condensate fields - most notably North Rankin, Goodwyn, and Gorgon. These fields are sub-unconformity traps and have in common reservoirs of the fluviatile Mungaroo Formation and are sealed by the Cretaceous Muderong Shale (much of the intervening Jurassic-Cretaceous section is absent through non-deposition or erosion). Sourcing is interpreted to be from the immense thickness of lower Dingo Claystone in the Lewis Trough, and possibly also from the Triassic (Pre-Mungaroo Formation) Locker Shale. The fault blocks are frequently tilted or triangular in outline, with varying degrees of rotation and, as discussed previously, appear to be wrench reactivations of older structures.

The post-MU hydrocarbon fields are generally much more subtle than the Rankin Trend fault blocks and they tend to be oil-prone. With some exceptions (Barrow Island and, more recently, Wanaea-Cossack) the field sizes have tended to be quite small. There is a greater variety of traps than with the pre-MU fields, with trap types including drape, anticlines (some faulted), rollover into faults, and fault-controlled (Appendix 2). As with the pre-MU fields, most, if not all of these fields are the result of reactivation of older structures. Hydrocarbons are primarily reservoired in three sections - Jurassic Angel Formation, Cretaceous Barrow Group (including Flag Sandstone), and Cretaceous Winning Group (particularly Windalia Sandstone Member and Mardie Greensand). In general, the Jurassic reservoirs are gas-rich and found on the Rankin Trend and in adjacent structures, while the Cretaceous reservoirs are oil-rich and found within the basins (eg Barrow Island) or along the southeast basin flank. As with the pre-MU fields, sourcing is probably from the Dingo Claystone.

In the literature, until recently, there has typically been reference to an 'inner oil trend' and an 'outer gas trend'. Until the late 1980's this was generally true, with hydrocarbon discoveries on the outer flank of the rift (Rankin Trend) being predominantly gas/condensate, while oil was the principal discovery within the rift or on the inner flank. However, with the successes at Chinook/Griffin/Ramillies and Wanaea/Cossack, on the Alpha Arch and the Madeleine Trend, the distinction between oil and gas trends is breaking down.

APPENDIX 4
SNOWS-I - PRELIMINARY RESULTS
(From BMR Record 1992/28)

During the SNOWS-I (Survey 101) cruise, a total of 1654 km of high-quality deep seismic data were recorded along 6 dip and 4 strike lines in the Dampier, Barrow, and Exmouth Sub-basins, and on the inner flank of the Exmouth Plateau. These lines were tied to 20 exploration wells throughout the region.

The SNOWS-I data consistently show unequivocal reflections down to 10 seconds (15-15 km), particularly offshore from the Rankin Platform and beneath the Exmouth Plateau. Deeper reflectors at 10-13 s are also observed; however these reflectors generally have low continuity and their correlation through the region is somewhat suspect.

At the time of writing (April, 1992), the processed data have only just become available. Consequently, the following notes are based on a preliminary and somewhat cursory examination of the major features observed in the data. Locations of lines are shown in Figure 5.

LINE 10

Dip line at the northeast end of the Dampier Sub-basin, from the Lambert Shelf, across the Enderby Trend, Rosemary Fault System, Legendre Trend, Lewis Trough, Madeleine Trend, Kendrew Trough, Rankin Trend, and Victoria Syncline, out to the Brigadier Trend. Ties to Lawley-1, Legendre-1, Lambert-1, and Brigadier-1.

Comments: A strong band of reflectors at the southeast end of the line, beneath the shallow basement of the Lambert Shelf, at a depth of 9.5-11.3 s (~25 km) are probably from laminated lower crust. It is noted that this type of reflection is observed beneath shallow basement in the region, but never when there is a thick sedimentary section. The Lewis Trough contains sediment down to at least 6.5 s and unlike other crossings of the feature, sediments are quite flat-lying down to at least 4 s and extensively faulted on the southeastern flank, adjacent to the Legendre Trend. The Rankin Platform is poorly defined, probably due to extensive faulting, in contrast to the Victoria Syncline and Brigadier Trend which are well-imaged down to at least 9 s. A moderately strong, though discontinuous reflector at about 9 s (referred to in this report as Horizon B) appears to mark the lower limit of well-layered probable sedimentary rocks.

LINE 9

Dip line across the central Dampier Sub-basin, from the Lambert Shelf, across the Enderby Trend, Rosemary Fault System, Legendre Trend, Lewis Trough, Madeleine Trend, Kendrew Trough, and Rankin Trend out to the Kangaroo Syncline. Ties to Strickland-1, Hampton-1, Rosemary-1, and Goodwyn-7.

Comments: Banded lower crustal reflectors are again visible at the SE end of the line beneath the Lambert Shelf and Enderby Terrace, down to 13 s (~30 km). Shallow crustal reflectors beneath the Enderby Terrace (better imaged on the GSI deep seismic lines to the northeast) appear to be detachment surfaces on which the Enderby Terrace faults sole out. The Lewis Trough is strongly synclinal (cf line 10) and sedimentary rocks can be seen down to >6.5 s. Imaging of the Goodwyn Block is excellent (Fig. 16), with the landward fault dipping SE beneath the Lewis Trough, probably soling out in the lower crust beneath the Enderby Terrace. In contrast, the seaward-bounding fault of the Goodwyn Block is high angle. Sedimentary rocks within the Goodwyn Block have a synclinal form and can be clearly distinguished down to about 8.5 s, where they overlie a strong (?basement) reflector (Horizon B). This reflector shows good continuity for a deep event, and can be traced beneath much of the outer shelf.

LINE 8

Dip line at the southwest end of the Dampier Sub-basin, from the landward flank of the Mermaid Fault, across the Mermaid Nose, Rosemary Fault System, Lewis Trough, Parker Terrace, and Rankin Trend. Ties to Arabella-1 and Parker-1.

Comments: This line is near the junction (and change in trend) of the Dampier and Barrow Sub-basins, which may account for the rather confused structuring. Basement at the SE end of the line is down-faulted northwestwards and Permian and older sediments (dated at Arabella-1) are strongly rotated, indicating a major episode of extension in the Palaeozoic (Fig. 17). Banded reflectors are again visible in the lower crust down to >12 s. The Lewis Trough is poorly defined on this line, and it may be that the movement that produced the large 'hole' into which Jurassic clastic sediments were dumped, has transferred into the Barrow depocentre, to the west. The sedimentary section beneath the outer shelf is again underlain by Horizon B at depths of 7-10 s.

LINE 7

Dip line across the central Barrow Sub-basin, from southwest of Barrow Island, across the Barrow depocentre, Gorgon structure, and Kangaroo Syncline, to the crest of the Exmouth Plateau. Ties to Robot-1A, Gorgon-1, and Jupiter-1.

Comments: Due to rapidly decreasing water depths, this line (and lines 6 & 5) had to be terminated at the Barrow depocentre. This depocentre is seen as a structural inversion with about 1s (~1.5 km) of positive relief at the Early Cretaceous level and about 1 s (~2 km) of negative relief at the base of the visible sedimentary section; most of this 'pod' of sediments is interpreted to be of Jurassic to Early Cretaceous age. Deep structural details of Gorgon Block are not immediately obvious; however, its development appears to be tied in with a major ?adjacent wrench-related anticline beneath the continental slope (Fig. 18). This anticline has its roots in dislocations in the underlying Horizon B and has been strongly eroded, probably in the Late Triassic or Early Jurassic. Horizon B can be traced through much of the Kangaroo Syncline and there are indications of its presence beneath the Exmouth Plateau Arch. If Horizon B marks the base of the sedimentary section, then there is more than 8 s of sediment underlying the Kangaroo Syncline; of this thickness, at least 6 s is Triassic and older.

LINE 6

Dip line across the southern Barrow Sub-basin, from the Barrow Depocentre, across the Alpha Arch, to the Kangaroo Syncline. Ties to Rosaliy-1A and Zeepard-1.

Comments: As with line 7, the Barrow Depocentre appears as a thick 'pod' of Jurassic sediments underlain, in this case, by a possible basement reflector at about 10 s. Horizon B is not readily identified on this line, though there are several indications of mid-crustal reflectors beneath the Exmouth Plateau. Careful analysis is required to determine which of these reflectors are primary events. Of particular interest on this line is the Triassic block on which Zeepaard-1 was drilled. This block has a strong synclinal form, both internally and at its upper surface on which Jurassic sediments are ponded. The southeast flank appears to be a compressional structure, while the northwest flank (site of Zeepaard-1) shows listric faulting.

LINE 16

Strike line joining the ends of lines 6 and 5, approximately along the axis of the Kangaroo Syncline. Ties to Zeewulf-1.

Comments: The principal features of interest on this line are two prominent mid-crustal reflectors that extend along most of the line, deepening from southwest to northeast. The upper reflector. at 7-9 s depth, is a detachment upon which faulting in the ?Palaeozoic to Triassic section soles out. The deeper reflector, at 9-10 s (Fig. 19), possible corresponds to the Horizon B, seen beneath the outer shelf and inner Exmouth Plateau.

LINE 5

Dip line across the northern end of the Exmouth Sub-basin, extending on to the southwest Exmouth Plateau. No direct well ties but it does tie to line 4, close to Jurabi-1.

Comments: This line is very different in character to the previous dip lines. The southeast end of the line is underlain by a band of strong crustal reflectors that deepen northwestwards from 8 to 10 s. The overlying Palaeozoic-Mesozoic section shows strong growth with the faults dipping to the southeast. In contrast the offshore end of the line, beneath the Exmouth Plateau, shows strong growth across faults dipping to the northwest. This polarity reversal may occur across an extension of the Long Island Fault, pointing to that fault being a transfer or accommodation zone.

LINES 4-2

Strike line from the northern end of the Exmouth Sub-basin, along the depositional axes of the Barrow and Dampier Sub-basins, into the southwest end of the Beagle Sub-basin. This line also includes the westernmost 50 km of line 1 of the cruise proposal (Stagg & Willcox, 1991). Ties to Jurabi-1, Bowers-1, Robot-1A, Tryal Rocks-1, and Angel-3.

Comments: It was anticipated that a strike line along the axes of the sub-basins would image the cross trends responsible for segmentation of the northern Carnarvon Basin. These cross-trends are probably present; however, their delineation will required detailed analysis of these lines in conjunction with examination of industry data.

APPENDIX 5
NORTHERN CARNARVON BASIN - OIL & GAS FIELDS
(Summarised from Cockbain, 1989)

Field	Year	Company	Age	Trap[1]	Orig. Reserves[2] Gas	Cond.	Oil
			PRE-BREAKUP FIELDS				
Barrow Deep	1973	Wapet	Ju	A	8	-	-
Dockrell	1979	Woodside	Tr	TiFB	-	-	0.8
Eaglehawk	1972	Woodside	Tr	HB	-	-	0.2
Goodwyn	1971	Woodside	Tr, Ju	TiFB	131	40	2
Goodwyn South	1973	Woodside	Tr	TrFB	-	-	3
Gorgon	1981	Wapet	Tr	HB	234	2	-
North Rankin	1971	Woodside	Tr, Ju	HB	225	1	-
N Rankin West	1972	Woodside	Ju	FB	7	1	-
Rankin	1971	Woodside	Tr	TiFB	6	-	-
Tidepole	1975	Woodside	Tr	TiFB	15	2	1
West Tryal Rocks	1973	Wapet	Tr	HB	81	4	-
Wilcox	1983	Woodside	Tr	FB	10	3	-
			POST-BREAKUP FIELDS				
Angel	1972	Woodside	Ju	D	36	11	-
Bambra	1982	Bond	Cret	A	1	-	-
Barrow Island	1964	Wapet	Ju, Cret	A	5	0.4	42
Campbell	1986	Bond	Cret	A	2	-	-
Chervil	1983	WMC	Cret	FA	-	-	0.7
Dixon	1984	Woodside	Ju	D			
Egret	1973	Woodside	Ju	F-C	-	-	1
Harriet	1983	Bond	Cret	F-C	1	-	6
Lambert	1974	Woodside	Ju	R			
Legendre	1968	Woodside	Cret	FA			
North Herald	1983	WMC	Cret	FA			
Rosette	1987	Bond	Cret	A	1	-	0.3
Saladin	1985	Wapet	Cret	F-C	0.6	-	8
Scarborough	1979	Esso	Cret	Dome	350	-	-
South Chervil	1983	WMC	Cret	FA			
South Pepper	1983	WMC	Cret	FA	-	-0.5	
Spar	1976	Wapet	Cret	R	7	1	-
Talisman	1984	Marathon	Cret	F-C			
Tubridgi	1981	Otter	Cret	A	2	-	-

Notes

1 Trap types as follows -

A	Anticline
TiFB	Tilted fault block
HB	Horst block
TrFB	Triangular fault block
FB	Fault block
D	Drape
FA	Faulted anticline
F-C	Fault-controlled
R	Rollover

2 Units for reserves

Gas	x 10^9 m^3
Condensate	x 10^6 kL
Oil	x 10^6 kL

APPENDIX 6
WELLS TIED ON SNOWS-I

Well	Operator	Date	TD	Oldest Sequence	Status
Angel-3	Woodside/Burmah	1973	3780	U. Ju	Susp.; cond., gas
Arabella-1	Aust. Occidental	1983	2209	Lw. Perm	Dry
Bowers-1	Wapet	1982	4300	U. Tr	Dry
Brigadier-1	Woodside	1978	4292	Tr	Dry
Goodwyn-7	Woodside	1985	3446	U. Tr	Cond., gas
Gorgon-1	Wapet	1980	4401	U. Tr	Susp.; cond., gas
Hampton-1	Woodside/Burmah	1974	2584	Lw. Tr	Dry
Jupiter-1	Phillips	1979	4946	U. Tr	Dry
Jurabi-1	Esso	1982	3712	U. Tr	Dry
Lambert-1	Woodside/Burmah	1973	3700	Lw. Ju	Dry; o/g shows
Lawley-1	Hudbay Oil	1981	1120	M. Tr	Dry
Legendre-1	Burmah	1968	3473	M. Ju	Dry
Parker-1	Woodside	1979	4737	Lw. Ju	Dry
Robot-1A	BP	1988	3459	Lw. Cret	Dry
Rosaliy-1A	Wapet	1982	3066	Lw. Cret	Dry
Rosemary-1	Woodside/Burmah	1972	3909	Ju	Dry
Strickland-1	Hudbay Oil	1982	1050	Tr	Dry
Tryal Rocks-1	Wapet	1970	3695	Ju	Dry
Zeepard-1	Esso	1980	4215	U. Tr	Dry; show gas
Zeewulf-1	Esso	1979	3500	U. Tr	Dry; show cond/gas.

APPENDIX 7
WELLS TIED ON SNOWS-II

Well	Operator	Date	TD	Oldest sequence
*Brigadier-1	Woodside	1978	4292	Triassic
Bruce-1	Stirling	1979	2168	Middle Triassic
Cossigny-1	Woodside/Burmah	1972	3203	Middle Triassic
Delambre-1	Woodside	1980	5495	Late Triassic
Eendracht-1	Esso	1980	3410	Late Triassic
Gandara-1	Hudbay	1979	4361	Late Triassic
Investigator-1	Esso	1979	3745	Late Triassic
*Jupiter-1	Phillips	1979	4946	Late Triassic
Minilya-1	Woodside/Burmah	1974	2400	Jurassic
North Turtle-1	BP	1982	4420	Jurassic
Novara-1	Esso	1982	2753	Neocomian
Outtrim-1	Esso	1984	1725	Late Jurassic
Phoenix-1	BP	1980	4880	Middle Triassic
Picard-1	Woodside/Burmah	1972	4216	Middle Jurassic
Ramillies-1	BHP	1990	3151	
Ronsard-1	Woodside/Burmah	1973	2848	Early Jurassic
Saturn-1	Phillips	1980	4000	Late Triassic
Scarborough-1	Esso	1979	2360	Berriasian
Sultan-1	Wapet	1979	3620	Late Triassic
Venture	Wapet	1990	3324	
*Zeewulf-1	Esso	1979	3500	Late Triassic

* signifies well also tied during SNOWS-I (Survey 101).

APPENDIX 8
WAY POINTS FOR SNOWS-II

All positions are relative to the WGS84 datum

Line	SP	Latitude dd mm ss.s	Longitude ddd mm ss.s	Comments
110/1A	181	18 32 55.0	119 00 11.5	SOL
110/1A	670	18 38 02.2	118 47 11.7	Phoenix-1
110/1A	1206	18 43 34.4	118 33 08.2	EOL
110/1B	2002	18 42 19.1	118 36 19.9	SOL
110/1B	3178	18 54 30.4	118 05 20.3	North Turtle-1
110/1B	5321	19 16 36.5	117 08 42.4	EOL
110/2A	153	19 36 52.2	118 02 5.2	SOL
110/2A	832	19 22 26.6	117 55 46.1	Bruce-1
110/2A	1757	19 01 57.1	117 40 25.4	EOL
110/2B	2002	19 04 22.6	117 42 14.1	SOL
110/2B	2297	18 57 54.8	117 37 24.7	Picard-1
110/2B	4003	18 20 20.6	117 09 14.8	EOL
110/3	153	18 22 23.8	116 35 29.1	SOL
110/3	544	18 31 00.1	116 41 52.3	Delambre-1
110/3	2229	19 08 25.7	117 09 43.1	Ronsard-1
110/3	2732	19 19 48.4	117 17 30.4	Cossigny-1
110/3	4059	19 48 32.8	117 40 22.9	EOL
110/4	232	19 42 52.7	117 43 43.4	SOL
110/4	4287	17 53 42.0	117 55 03.0	EOL
110/5A	158	17 55 30.9	117 39 18.2	SOL
110/5A	1564	18 09 09.2	118 16 15.4	EOL
110/5B	1768	18 07 45.5	118 12 27.1	SOL
110/5B	2942	18 19 23.8	118 44 01.0	Minilya-1
110/5B	3460	18 24 16.1	118 57 14.9	EOL
110/6	158	18 12 14.2	118 51 24.5	SOL
110/6	1124	18 38 02.2	118 47 11.7	Phoenix-1
110/6	3048	19 29 24.7	118 37 28.7	EOL

110/7A	348	19 03 51.8	118 51 34.2	SOL
110/7A	1040	18 55 08.8	118 33 58.8	EOL
110/7B	1160	18 57 00.0	118 37 40.4	SOL
110/7B	4182	18 19 08.3	117 21 09.5	EOL
110/8A	148	18 21 10.7	117 43 40.2	SOL
110/8A	3879	19 05 44.0	116 08 13.9	Brigadier-1
110/8A	4001	19 07 15.2	116 05 07.0	EOL
110/8B	4276	19 04 01.9	116 11 53.3	SOL
110/8B	5191	19 16 26.1	115 49 19.5	Gandara-1
110/8B	7507	19 54 30.8	114 56 45.2	Saturn-1
110/8B	7690	19 57 32.0	114 52 34.4	EOL
110/9	180	19 36 28.0	114 25 32.6	SOL
110/9	1451	19 54 30.8	114 56 45.2	Saturn-1
110/9	2043	20 02 33.7	115 11 25.6	Sultan-1
110/9	2388	20 08 21.7	115 19 12.1	Venture-1
110/9	2657	20 12 30.1	115 25 22.5	EOL
110/10	200	19 52 38.3	114 59 39.7	SOL
110/10	325	19 54 30.8	114 56 45.2	Saturn-1
110/10	2599	20 29 12.2	114 02 40.9	EOL
110/11	323	20 55 36.2	113 17 53.8	SOL
110/11	1107	21 06 27.8	113 37 17.6	Zeewulf-1
110/11	2201	21 21 21.2	114 04 34.6	Novara-1
110/11	3067	21 31 47.9	114 27 07.1	Outtrim-1
110/11	3212	21 33 34.4	114 30 55.6	EOL
110/12A	208	21 22 47.6	114 49 39.8	SOL
110/12A	743	21 15 25.5	114 36 10.4	Ramillies-1
110/12A	4670	20 21 01.9	112 58 05.9	Investigator-1
110/12A	5008	20 16 01.2	112 49 54.8	EOL
110/12B	6025	20 18 13.3	112 53 32.2	SOL
110/12B	7629	19 54 24.2	112 14 39.7	Eendracht-1
110/12B	7944	19 49 43.0	112 07 02.6	EOL
110/13	232	20 16 06.0	112 39 21.6	SOL
110/13	1569	19 53 01.9	113 08 49.0	Scarborough-1
110/13	2624	19 34 48.2	113 32 02.4	Jupiter-1
110/13	3900	19 12 31.5	113 59 30.4	EOL

110/14	178	19 14 38.4	113 50 08.7	SOL
110/14	1751	19 37 56.9	114 28 00.0	EOL
110/15	197	19 37 47.7	113 7 13.4	SOL
110/15	411	19 34 48.2	113 2 02.4	Jupiter-1
110/15	6601	18 07 28.7	111 1 21.3	EOL

APPENDIX 9
SEISMIC TAPE LISTING

Line	FSP	FGSP	LGSP	LSP	First tape	Last tape
1A	102	181	1206	1206	1	17
1B	2002	2002	5321	5403	18	70
2A	102	153	1757	1760	71	96
2B	2002	2002	4003	4041	97	128
3	102	153	4059	4100	129	190
4	102	232	4287	4326	191	255
5A	102	158	1564	1596	256	278
5B	1702	1768	3460	3549	281	309
6	102	158	3048	3085	310	355
7A	101	348	1040	1052	356	369
7B	1102	1160	4182	4220	370	417
8A	102	148	4001	4002	418	478
8B	4202	4276	7690	7753	479	533
9	102	180	2657	2705	534	574
10	102	200	2599	2612	578	616
11	102	323	3212	3245	617	665
12A	102	208	5008	5041	666	741
12B	6004	6025	7944	8004	742	772
13	102	232	3900	3933	773	831
14	118	178	1751	1803	832	857
15	102	197	6601	6667	858	958

Note:
FSP = first shot-point
FGSP = first good shot-point
LGSP = last good shot-point
LSP = last shot-point

APPENDIX 10
NON-SEISMIC DATA ACQUISITION CHANNELS

The following is a list of channel allocations for the non-seismic data of Survey 110.

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 from DAS computer clock	(sss.ddd)
2	Acquisition GMT from DAS computer clock	(.hhmmss)
3	Acquisition GMT from master clock	(.hhmmss)
4	Latitude, best estimate	(radians)
5	Longitude, best estimate	(radians)
6	Speed, best DR estimate	(knots)
7	Course, best DR estimate	(degrees)
8	Magnetometer # 1	(nT)
10	Depth from 12 kHz echo sounder	(metres)
12	F/A Magnavox sonar doppler	(3920 counts/nm)
13	P/S Magnavox sonar doppler	(3920 counts/nm)
16	Paddlelog wheel	
18	Instrument room Sperry gyro heading (synchro)	(degrees)
19	Bridge Sperry gyro heading	(degrees)
20	Instrument Room Sperry gyro heading (stepper)	(degrees)
25	Racal dGPS #2 UTC time	(hhmmss)
26	Racal dGPS #2 latitude	(radians)
27	Racal dGPS #2 longitude	(radians)
28	Racal dGPS #2 height	(m)
29	Racal dGPS #2 course	(degrees)
30	Racal dGPS #2 speed	(knots)
31	Racal dGPS #2 number of satellites	
32	Racal dGPS #2 PDOP	
33	Racal dGPS #2 HDOP	
34	Racal dGPS #2 3-D position error	(m)
35	Racal dGPS #2 2-D position error	(m)
36	Racal dGPS #2 differential quality	(see below)
37	Racal dGPS #2 flag	(see below)
39	T-Set north std dev.	(m)
40	T-Set east std dev.	(m)
41	T-Set satellite numbers	
42	T-Set GMT time	(seconds)
43	T-Set DOP	
44	T-Set latitude	(radians)
45	T-Set longitude	(radians)
46	T-Set height above geoid	(m)

47	T-Set speed	(knots)
48	T-Set course	(degrees)
49	T-Set frequency bias	
51	Latitude from Dead Reckoning System 1	(radians)
52	Longitude from Dead Reckoning System 1	(radians)
53	Speed from Dead Reckoning System 1	(knots)
54	Course from Dead Reckoning System 1	(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	($m/sec^2 \times 10^{-3}$)
80	ACX	($m/sec^2 \times 10^4$)
81	ACY	($m/sec^2 \times 10^4$)
82	Sea state	
83	AGRF magnetic anomaly #1	(nT)
86	Shot time	(hhmmss)
87	Shot point number	
88	Northerly set/drift	(radians/10 seconds)
89	Easterly set/drift	(radians/10 seconds)
110	Racal #1 dGPS UTC time	(hhmmss)
111	Racal #1 dGPS latitude	(radians)
112	Racal #1 dGPS longitude	(radians)
113	Racal #1 dGPS height	(m)
114	Racal #1 dGPS course	(degrees)
115	Racal #1 dGPS speed	(knots)
116	Racal #1 dGPS number of satellites	
117	Racal #1 dGPS PDOP	
118	Racal #1 dGPS HDOP	
119	Racal #1 dGPS 3-D position error	(m)
120	Racal #1 dGPS 2-D position error	(m)
121	Racal #1 dGPS differential quality	(see below)
122	Racal #1 dGPS flag	(see below)

The **Transit satellite fix information** from both the MX1107 and MX1142 is saved in blocks of 20 floating point words when the fix data become available. The data from each satnav are 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	" " "	

Racal dGPS "flag" is a 5 digit number n1,n2,n3,n4,n5, as follows;

n1: Operating Mode	0 = no solution
	1 = 4 SV
	2 = 3 SV + altitude aiding
	3 = 3 SV + clock aiding
	4 = 2 SV + altitude aiding + clock aiding
	5 = all-in-view
n2: Receiver Code	7 = C/A, L1 only, carrier aided
n3: Receiver Dynamics	0 = static, 1...9 represents low...high
n4: Position Quality	0...9 represents bad...good
n5: Differential Quality	0 = no corrections, 1...9 represents bad...good

APPENDIX 11
SEISMIC ACQUISITION PARAMETERS

Seismic Cable Configuration

length -	4800 m
group length -	25 m
no. channels -	192
Towing depth -	10, 11, or 12 m, dependent on sea state

Seismic Source

Airgun capacity	50 litres (3000 cu in)
Airgun pressure	1800 psi (normal)
	1600 psi (minimum)
Towing depth	9 m +/- 1 m
Shot interval	50 m
Shot rate	19.4 s @ 5 kn
	21.6 s @ 4.5 kn

Fold 4800%

Recording Parameters

Record length -	16 s
Sample interval -	2 ms

APPENDIX 12
EQUIPMENT UTILISED ON SNOWS-II

FJORD Instruments seismic receiving array: 6.25 m, 12.5 m, 18.75 m, or 25 m group lengths; up to 288 channels; up to 6000 m active streamer length.

Syntron RCL-3 cable levelers; individual remote control and depth readout (x 13)

Syntron compass birds (x 4)

Haliburton Geophysical Service 32 x 150 cubic inch airguns in two 16-gun arrays; normal operating array is two x 10 guns, giving a total of 3000 cubic inches normal operating volume

Air compressor system: 6 x A-300 Price compressors, each providing 300 scfm at 2000 psi (62 litres/min at 14 MPa)

Digital seismic acquisition system designed and built by BMR and based on a DEC MicroVAX-3 computer: 16-bit floating point, SEG-Y output on cartridge tape

Raytheon echo-sounder; 12 KHz (2 kW) precision echo-sounder

Geometrics G801/803 magnetometer

Bodenseewerk Geosystem KSS-31 marine gravity meter

Racal 'Skyfix' differential GPS (x 2)

Magnavox T-Set stand-alone GPS receiver

Magnavox MX 1107RS and MX 1142 transit satellite receivers

Magnavox MX 610D dual axis sonar doppler; Ben paddle log

Sperry, Arma-Brown, and Robertson gyro-compasses

APPENDIX 13
COMPANIES CONSULTED DURING PROPOSAL PREPARATION

During preparation of this cruise proposal, the following exploration companies were contacted to provide input. We are grateful to staff of these companies for this input.

Ampol Exploration Ltd
Bridge Oil Ltd
BHP Petroleum Pty Ltd
BP Exploration
Command Petroleum Holdings NL
Conoco Australia Ltd
Crusader Ltd
Esso Australia Ltd
Gas and Fuel Exploration NL
Hadson Energy Ltd
Hardy Petroleum Ltd
Idemitsu Oil Development Co. Ltd
Kufpec Australia Pty Ltd
Lasmo Oil (Australia) Ltd
Marathon Petroleum Australia Ltd
MIM Petroleum Exploration Pty Ltd
Minora
Mobil Exploration and Producing Australia Pty Ltd
Norcen International Ltd
Petroz NL
Phillips Australian Oil Co
Sagasco Resources Ltd
Santos Ltd
Shell Development (Australia) Pty Ltd
West Australia Petroleum Pty Ltd
Western Mining Corporation Pty Ltd
Woodside Offshore Petroleum Pty Ltd

APPENDIX 14
CREW LIST - SURVEY 110

Scientific Crew

H. Stagg	Cruise Leader
E. Chudyk	Quality Control / Systems Expert
H. Miller	Quality Control / Systems Expert
M. Callaway	Electronics Technician
U. Reike	Electronics Technician
M. Alcock	Science Technician
J. Bedford	Science technician
C. Buchanan	Science Technician
P. Butler	Science Technician
A. Hunter	Science Technician
F. Stradwick	Science Technician
S. Wiggins	Mechanical Technician
S. Milnes	Mechanical Technician
J. Roberts	Mechanical Technician
D. Sewter	Mechanical Technician
J. Vickery	Mechanical Technician

Crew of the *Rig Seismic*

R. Hardinge	Master
L. Gillies	Mate
P. Robinson	Second Mate
B. Troke	Chief Engineer
T. Ireland	Second Engineer
W. Hanson	Electrical Engineer
D. Brown	Integrated Rating
J. Fraser	Integrated Rating
R. Johnson	Integrated Rating
M. Pitcher	Integrated Rating
H. Dekker	Chef
W. Leary	Assistant Chef
S. O'Rourke	Seaman/Steward
S. Stavely	Seaman/Steward

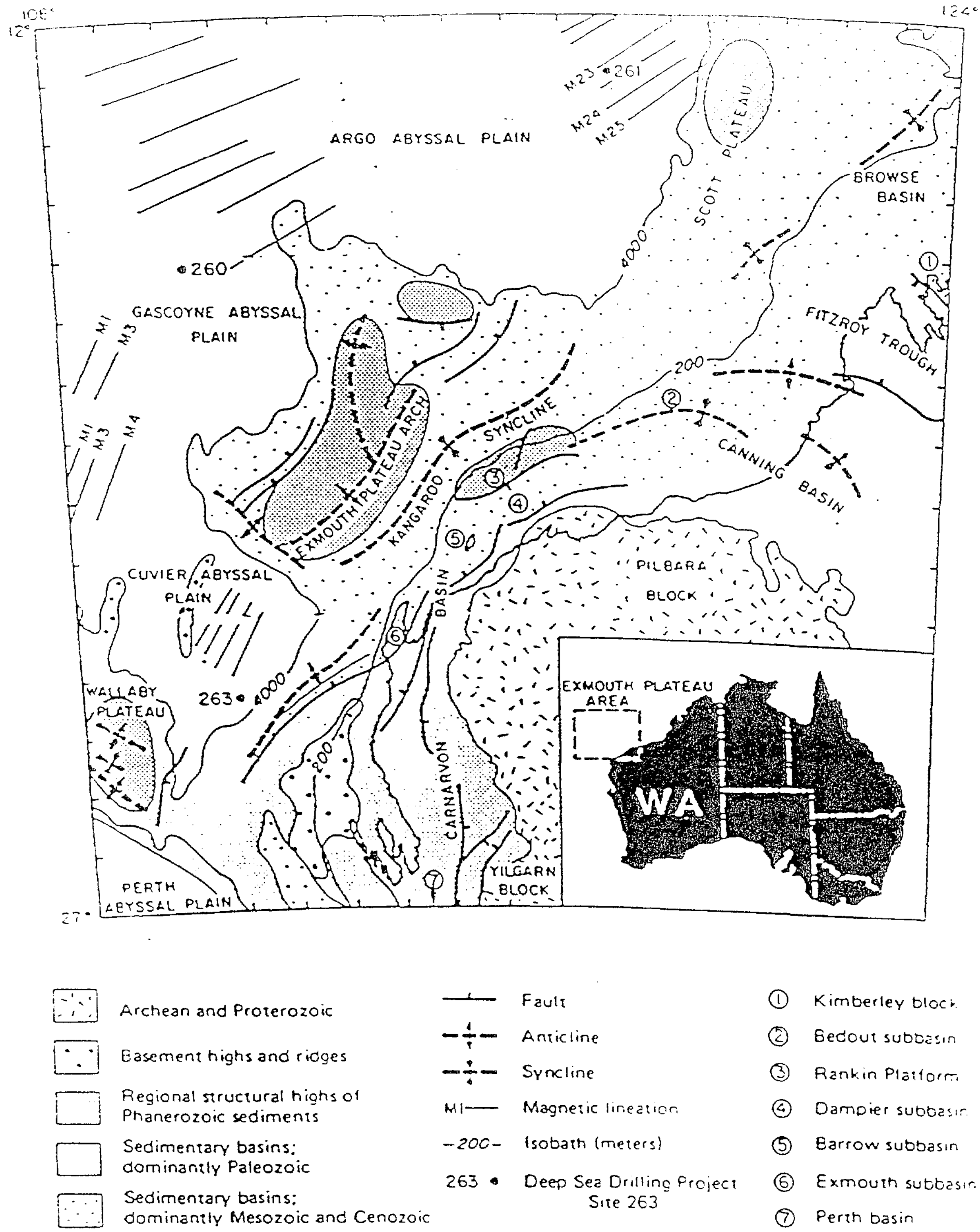

Figure 1: Location map for the southern North West Shelf and Exmouth Plateau (after Exon & Willcox, 1980).

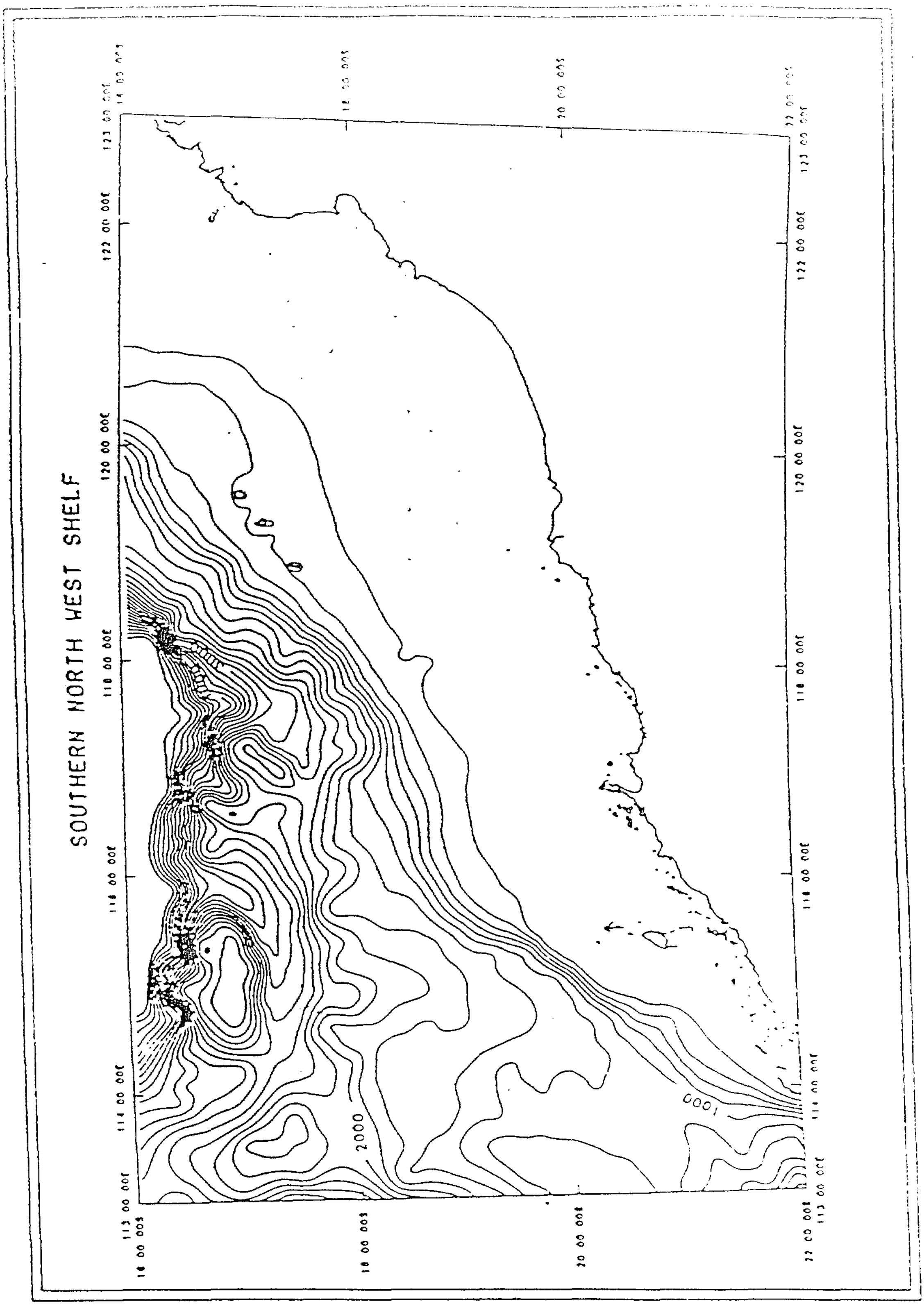

Figure 2: Bathymetry of the southern North West Shelf; contour interval 200 m.

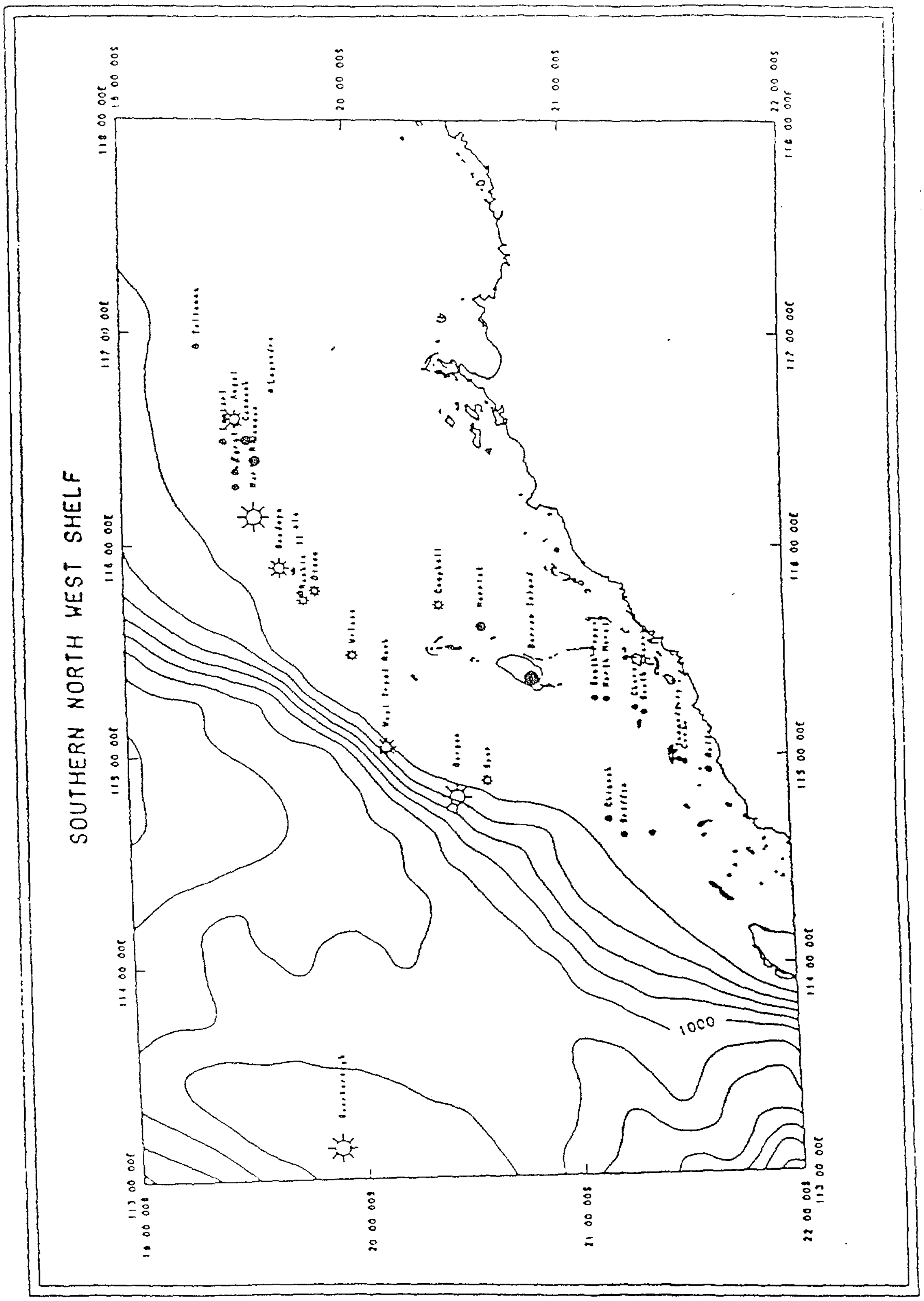

Figure 3: Locations of hydrocarbon accumulations on the southern North West Shelf. The size of the symbol is proportional to the approximate size of the field. bathymetry contour interval 500 m.

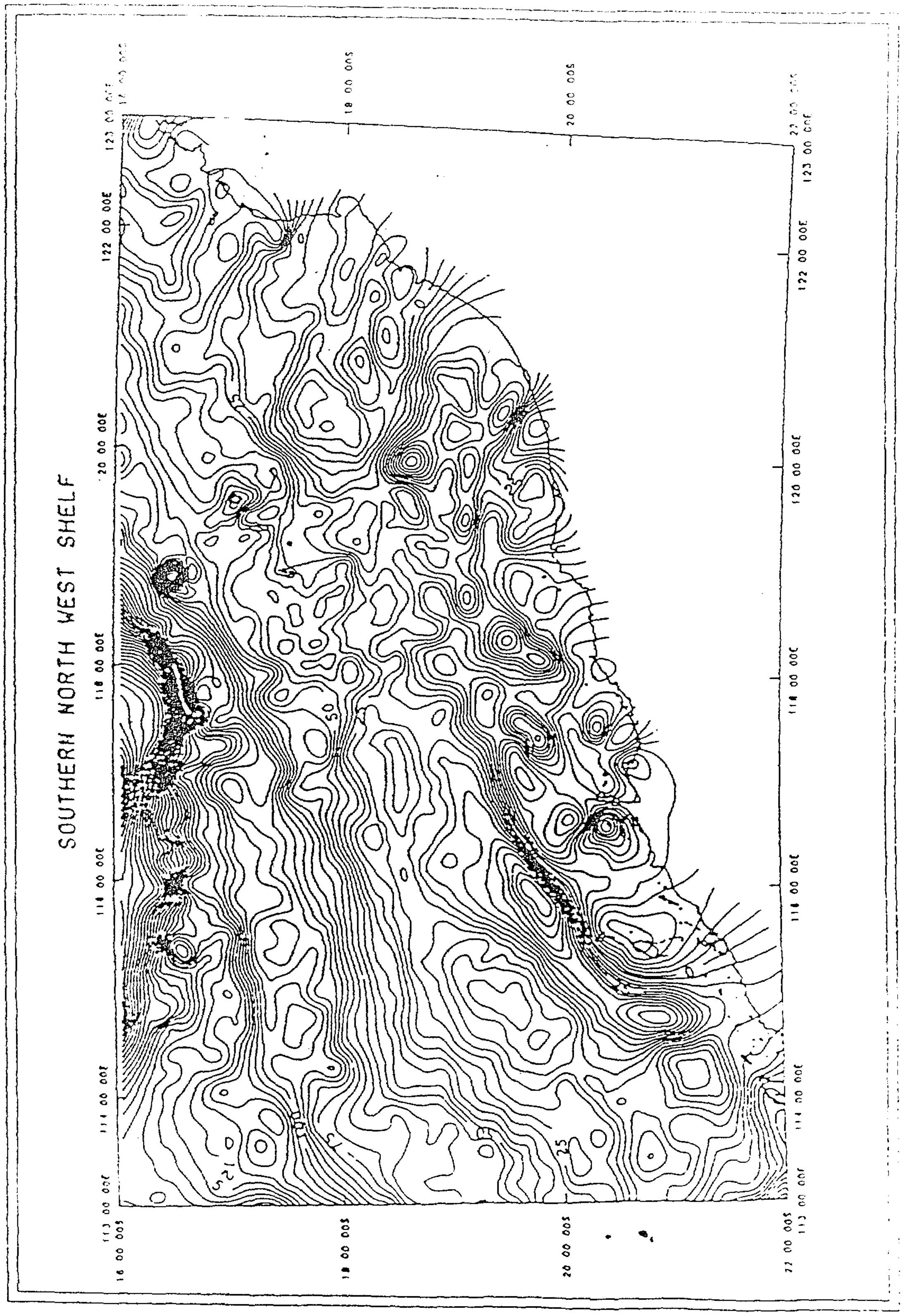

Figure 4: Bouguer gravity anomalies on the southern North West Shelf. Contour interval 5 mgals.

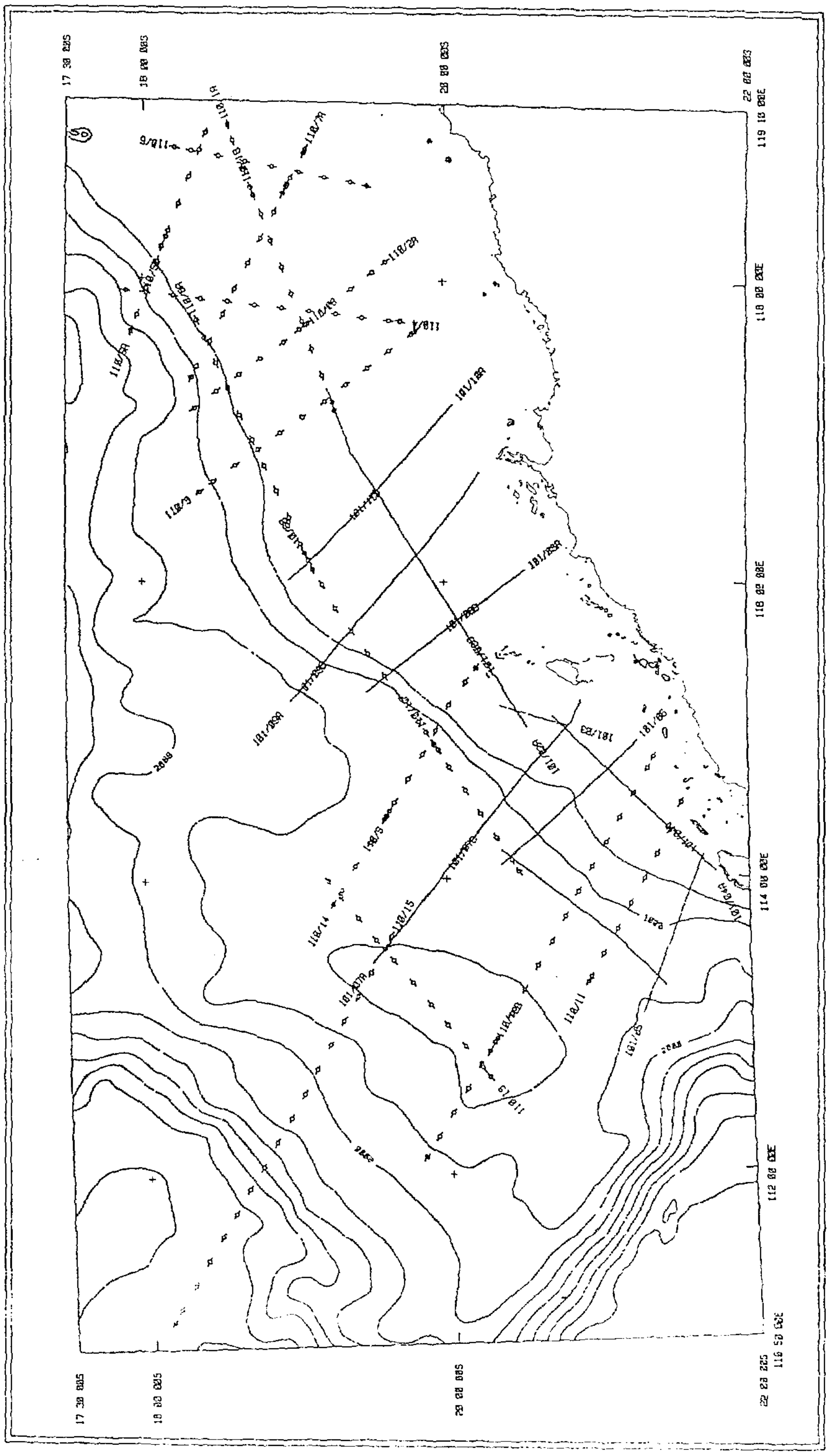

Figure 5: Location of SNOWS-I and SNOWS-II seismic lines on the southern North West Shelf. SNOWS-I lines are shown as solid lines; SNOWS-II lines shown by shot-point symbols.

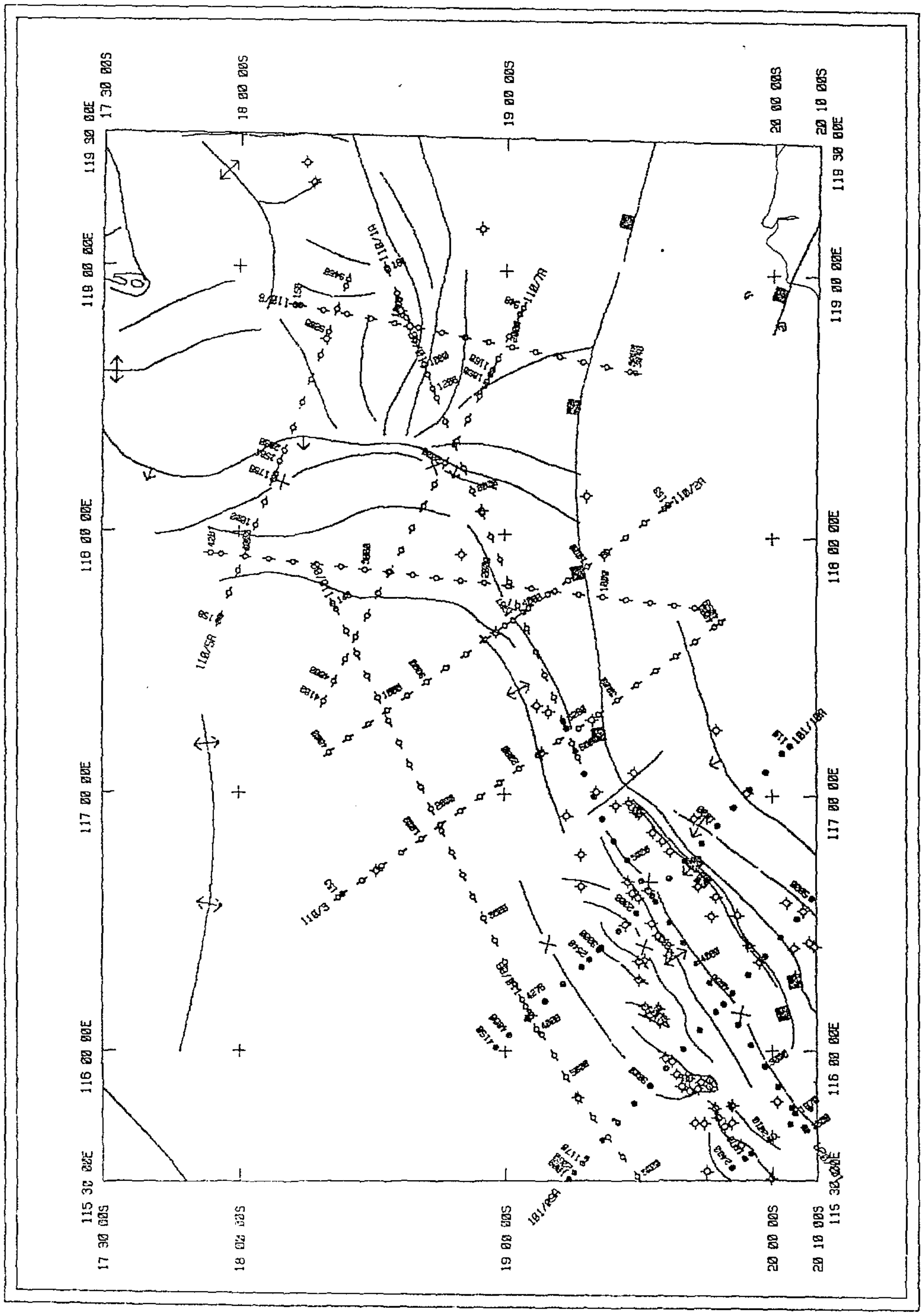

Figure 6: Location of SNOWS-I (101/ prefix) and SNOWS-II (110/ prefix) seismic lines in the Beagle Sub-basin.

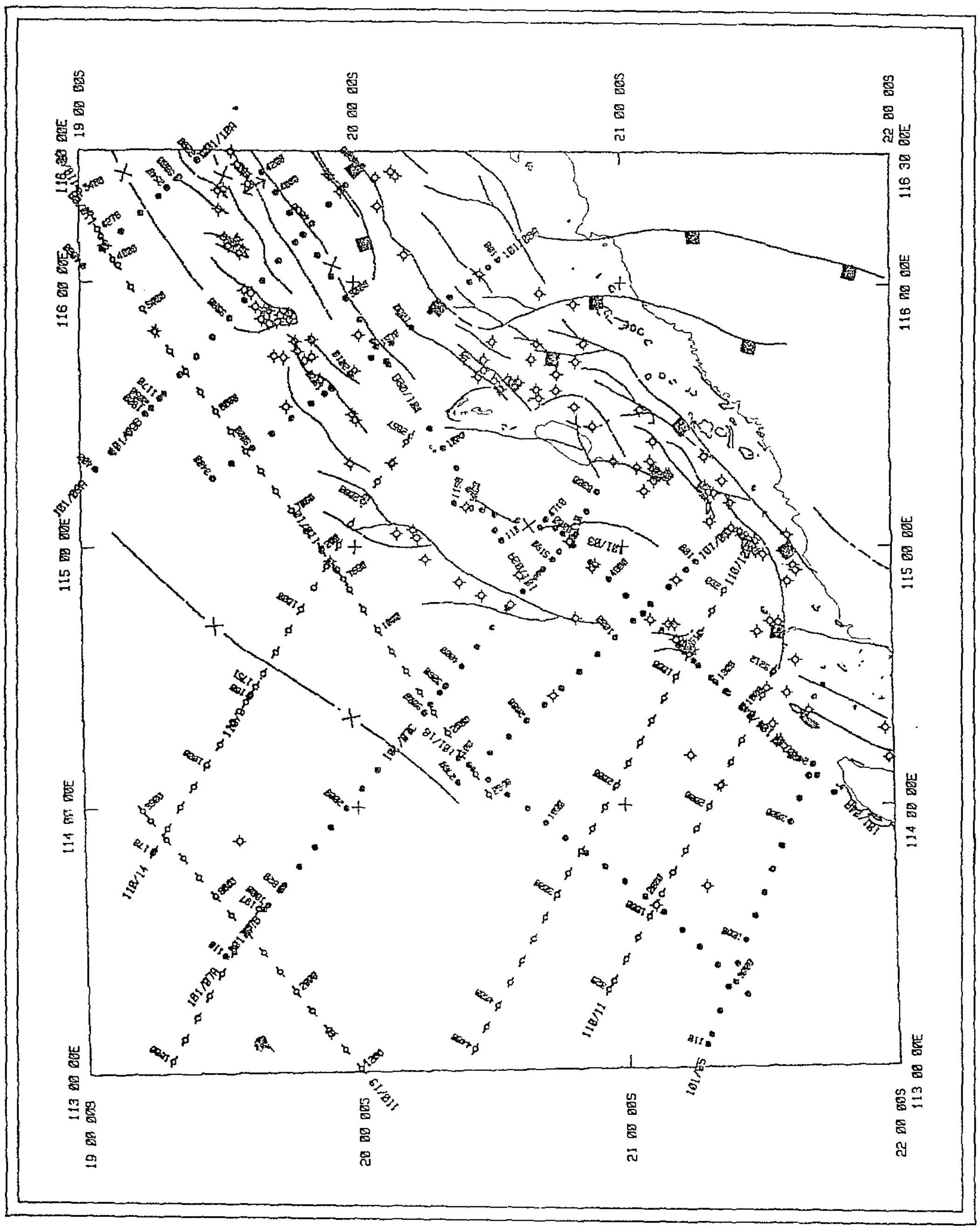

Figure 7: Location of SNOWS-I (101/ prefix) and SNOWS-II (110/ prefix) seismic lines in the Barrow and Dampier Sub-basins and inner flank of the Exmouth Plateau.

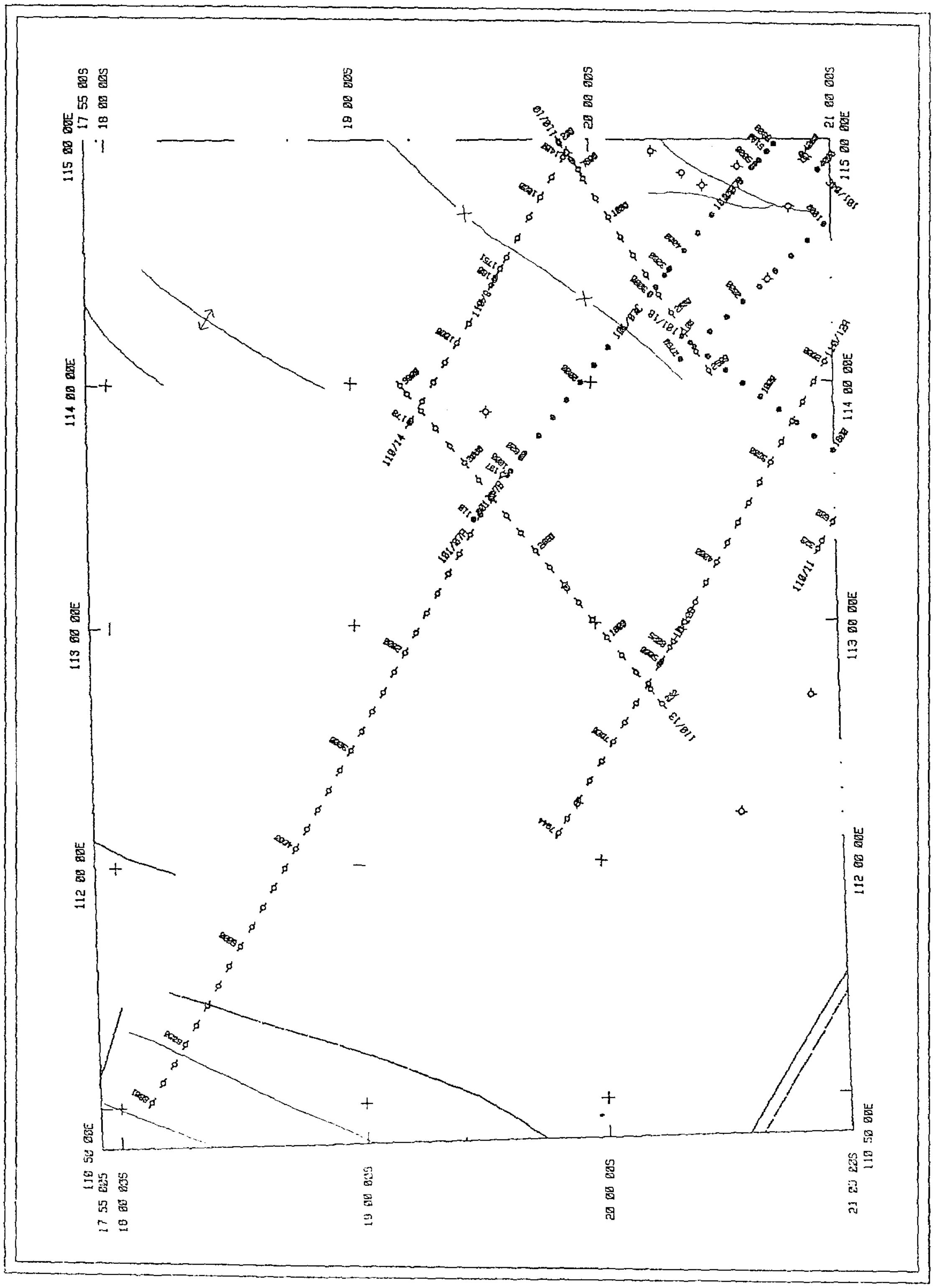

Figure 8: Location of SNOWS-I (101/ prefix) and SNOWS-II (110/ prefix) seismic lines on the Exmouth Plateau.

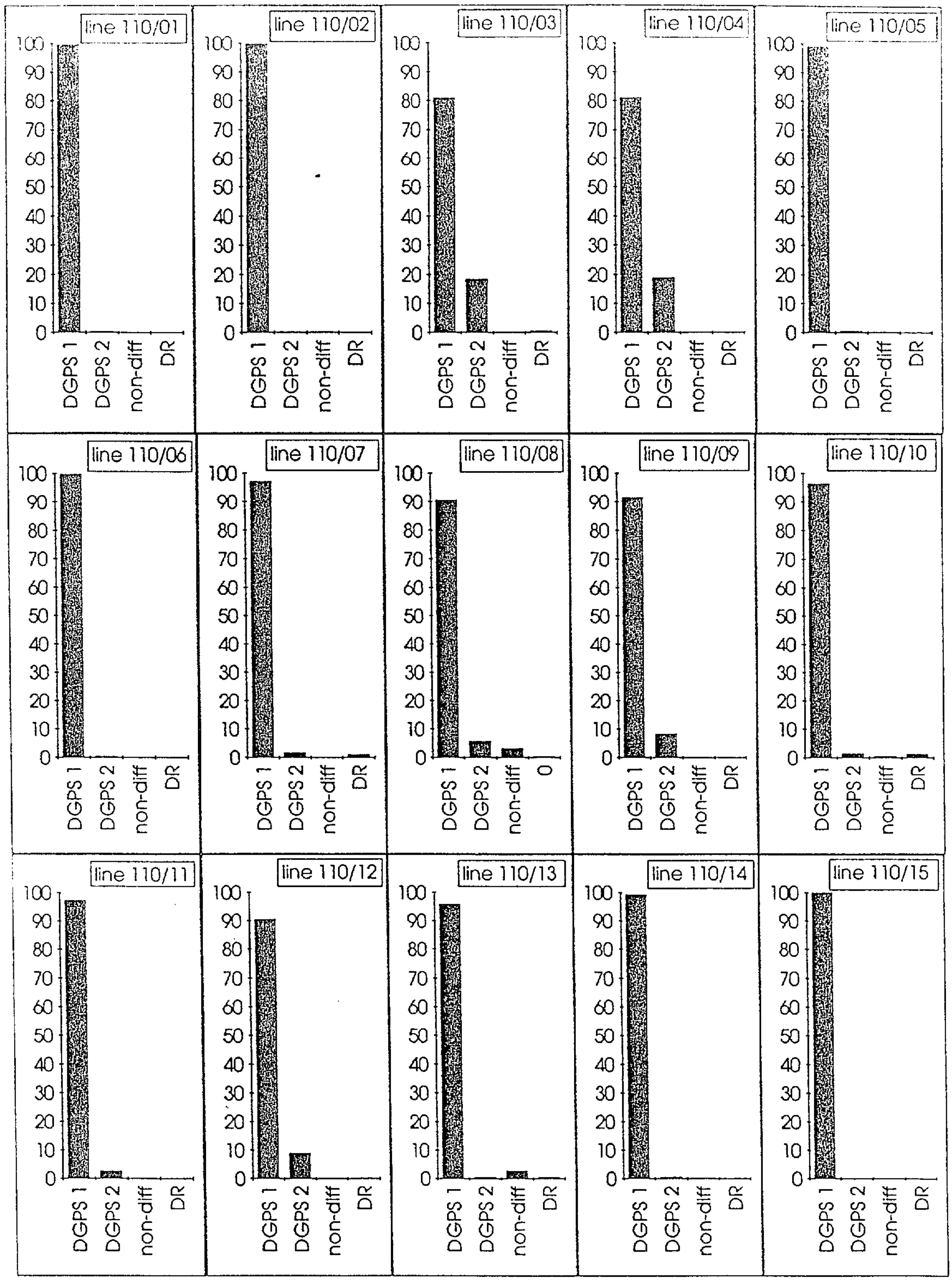

Figure 9: Proportion of each navigation system used on each seismic line during SNOWS-II.

CRUISE 110 NOISE TEST SUMMARY		
LINE NUMBER	MEAN RMS NOISE mV	MEAN RMS NOISE uBars
1	20.49	0.8
1	20.56	0.8
2	16.22	0.63
2	14.37	0.56
3	19.44	0.75
3	12.8	0.5
4	15	0.58
5	13.74	0.53
5	32.55	1.27
6	22.76	0.88
6	17.38	0.67
7	28.46	1.11
7	25.94	1.01
7	22.23	0.86
8	20.57	0.8
8	20.09	0.78
9	21.05	0.82
10	33.31	1.3
11	17.3	0.67
11	22.23	0.86
12	16.14	0.63
12	14.46	0.56
12	15.3	0.59
12	16.27	0.63
12	17.89	0.69
13	51.38	2
14	59.73	2.33
14	31.48	1.22
15	32.62	1.27
15	16.74	0.65
15	20.75	0.81
	Average noise for survey =	0.9 uBars

Figure 10: Summary of streamer noise tests from SNOWS-II.

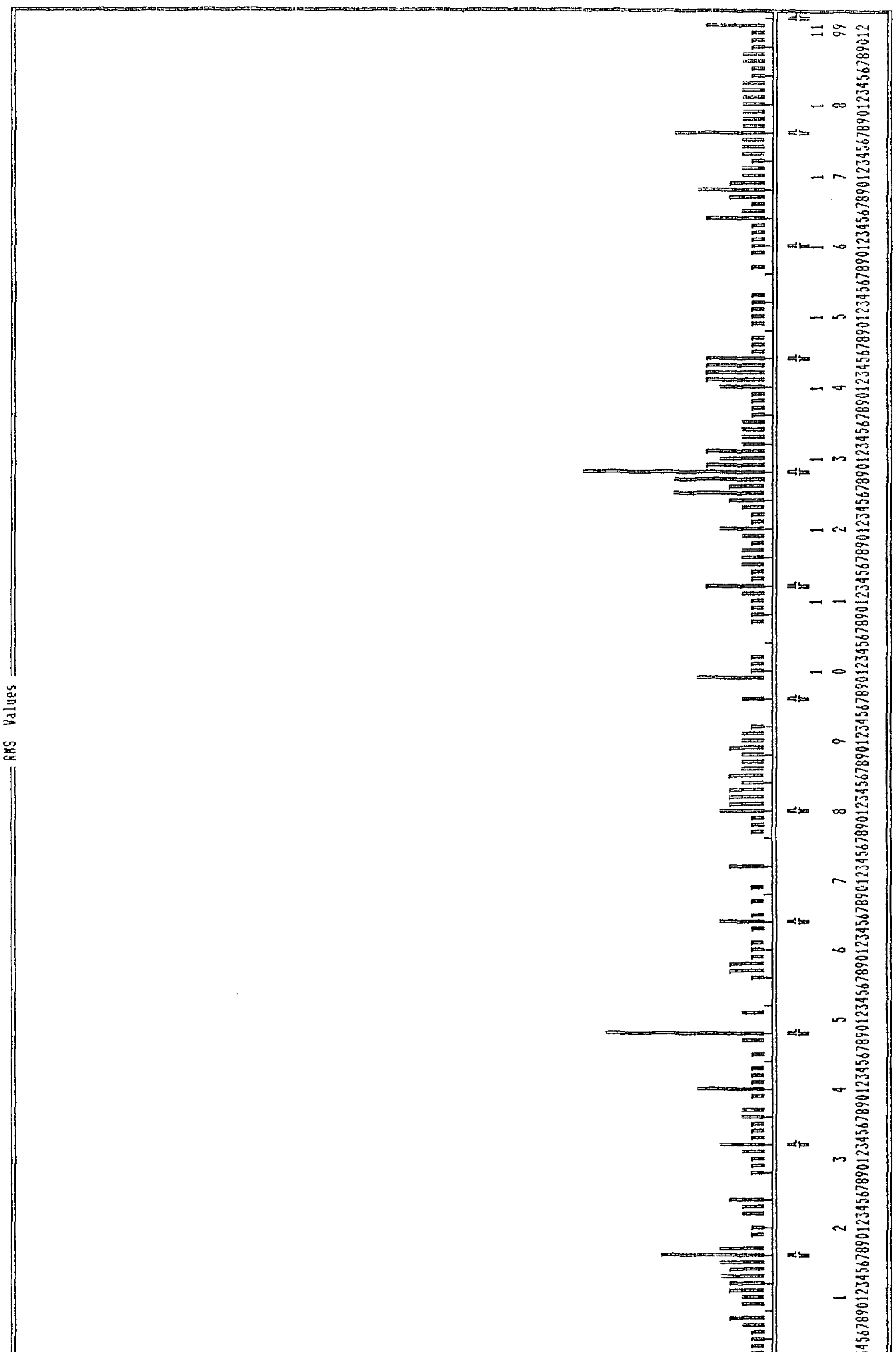

Figure 11: Typical streamer noise test from SNOWS-II. Vertical axis in microbars

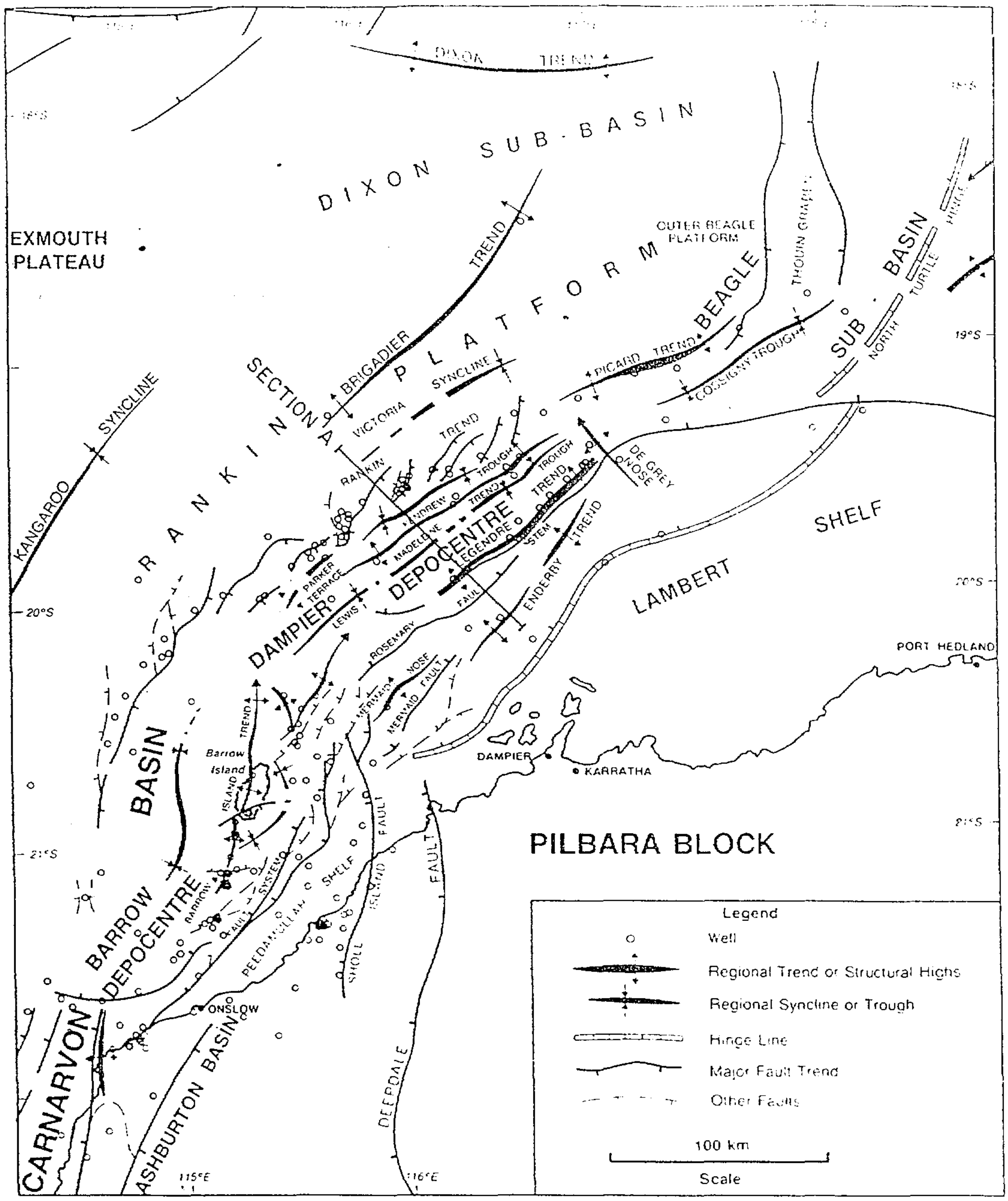

Figure 12: Tectonic elements of the southern North West Shelf (after Woodside, 1988).

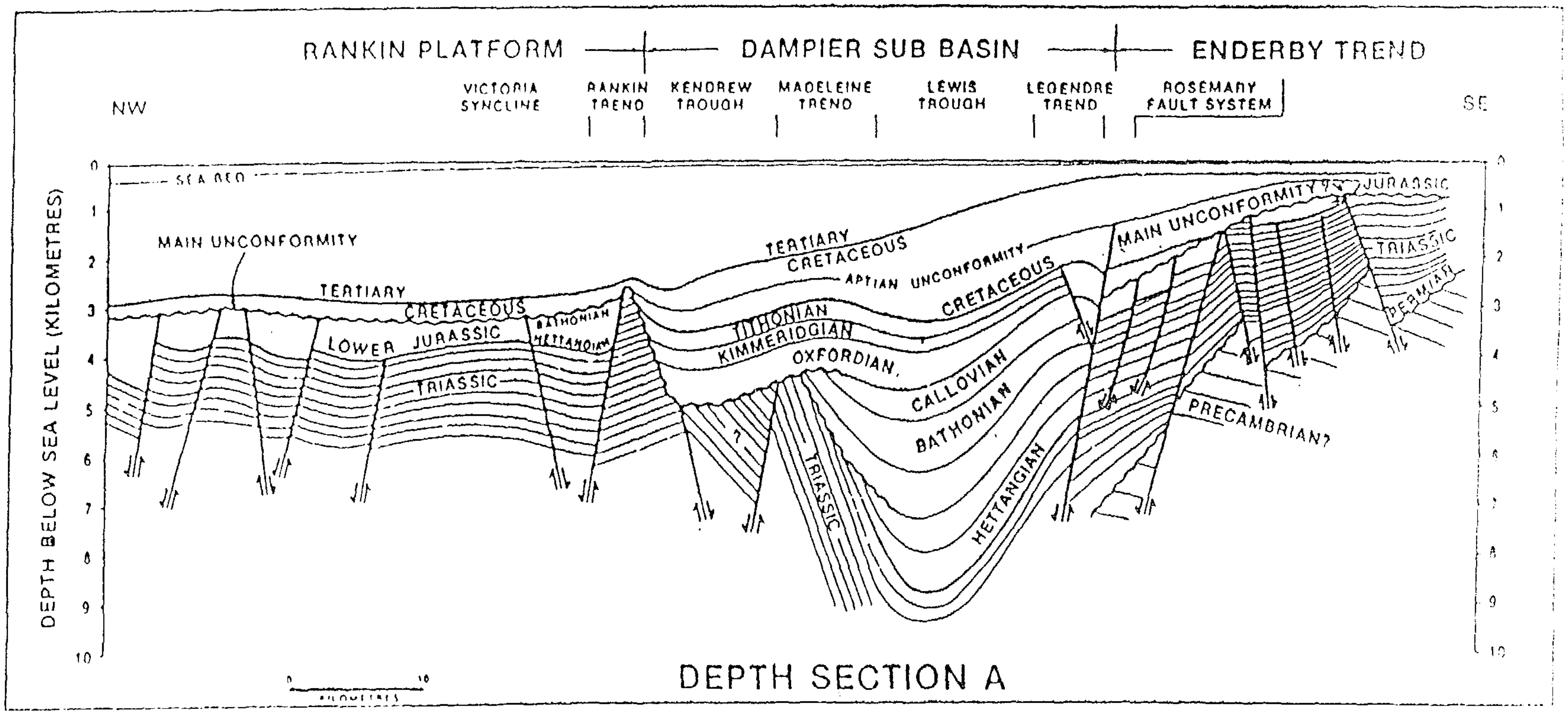

Figure 13: Depth profile across the Dampier Sub-basin (after Woodside, 1988).

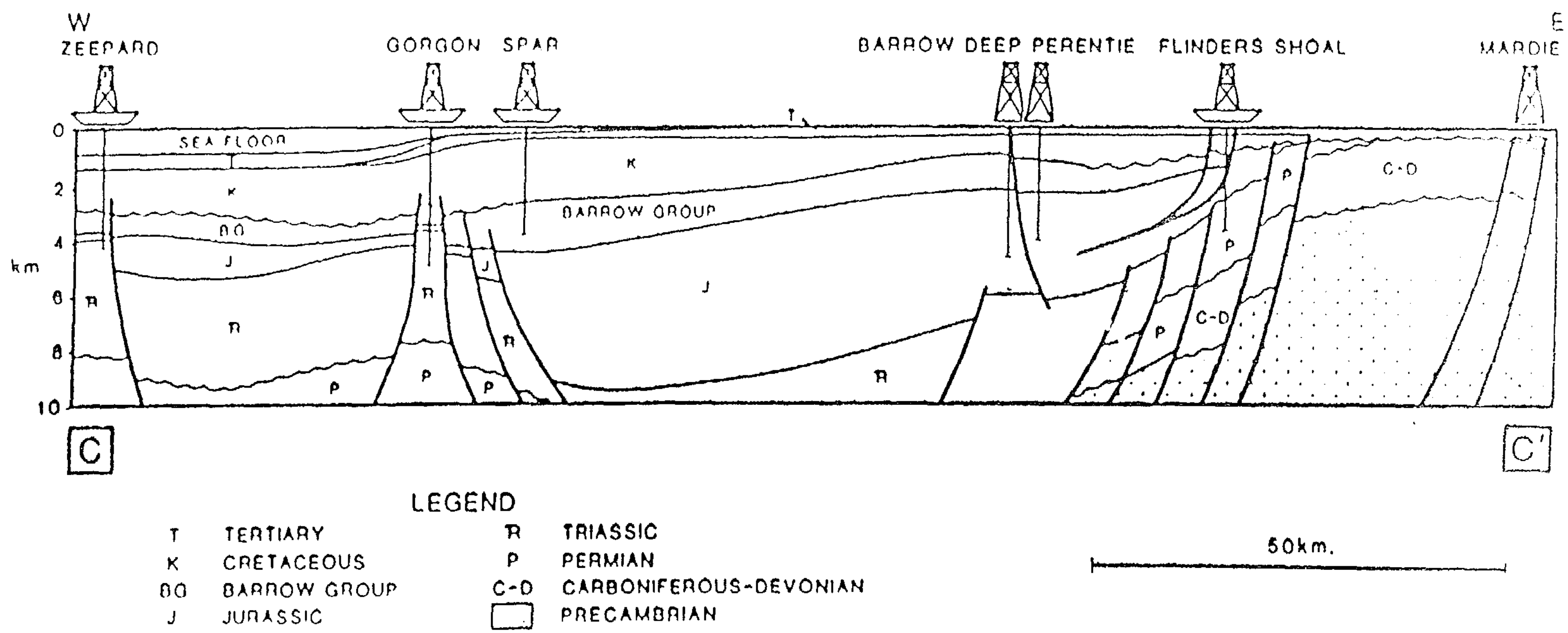

Figure 14: Depth profile across the Barrow Sub-basin (after Parry & Smith, 1988).

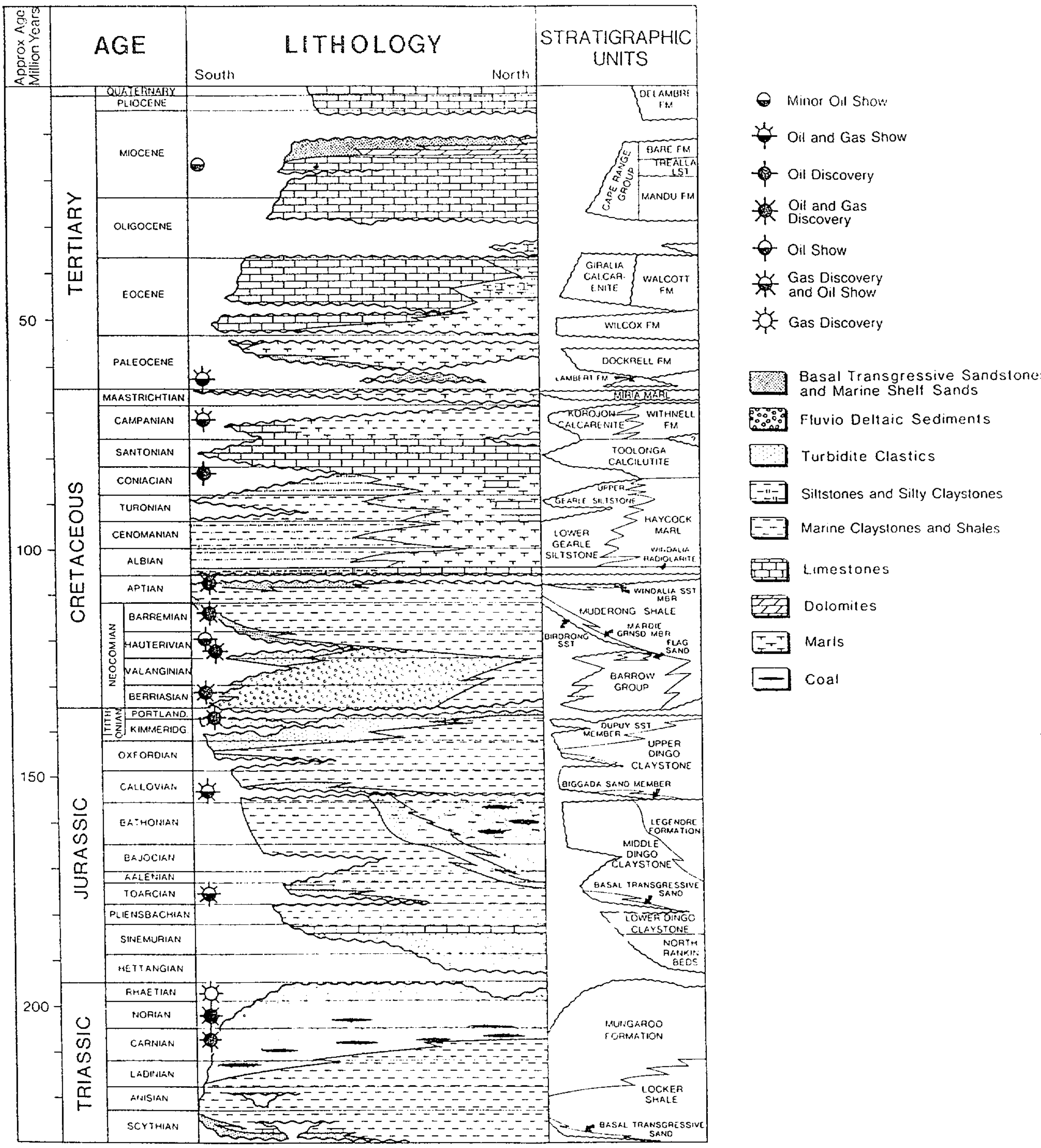

Figure 15: Stratigraphy of the southern North West Shelf (after Woodside, 1988).

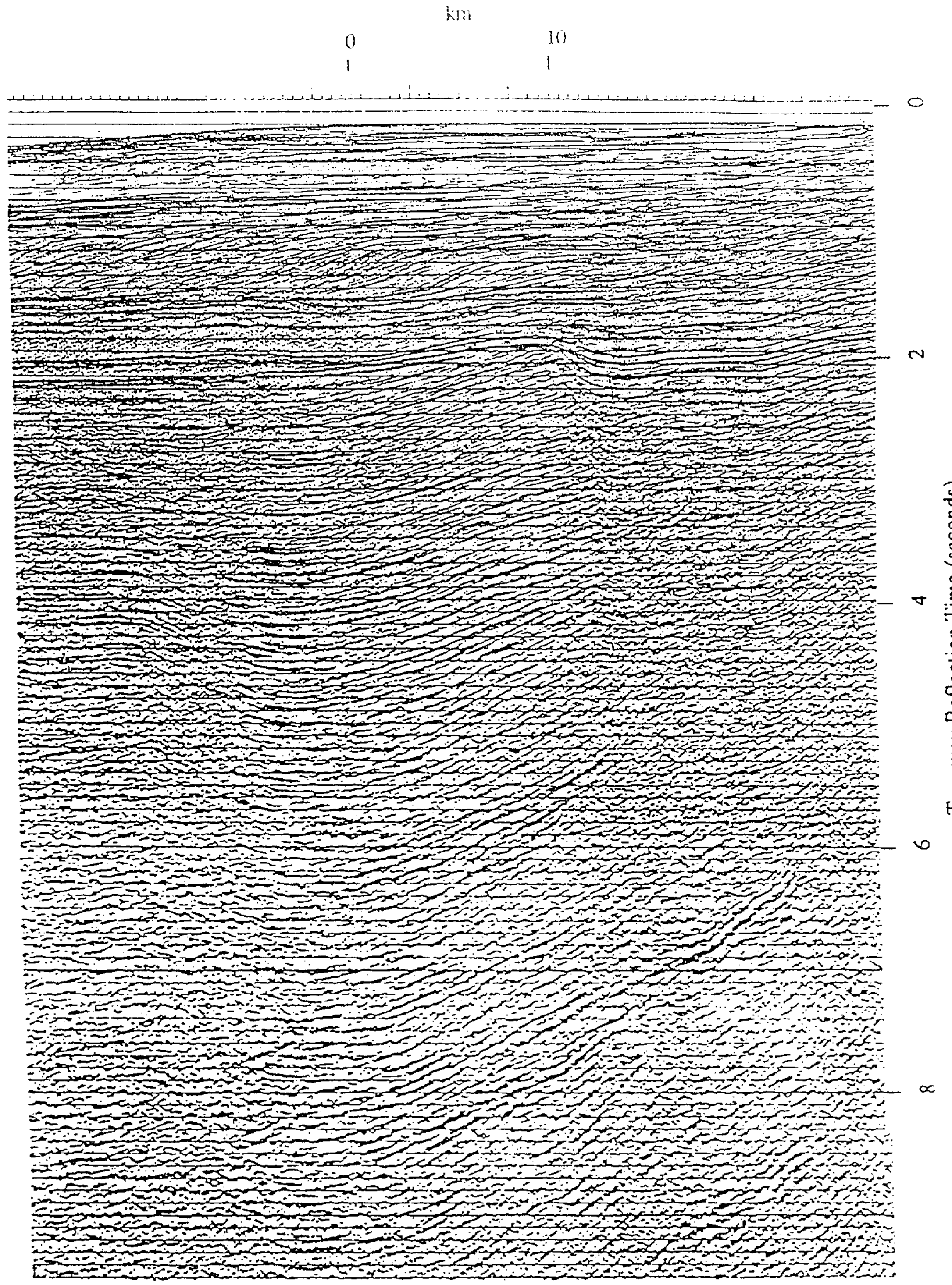

Figure 16: Portion of BMR seismic line 101/9, across the Goodwyn structure.

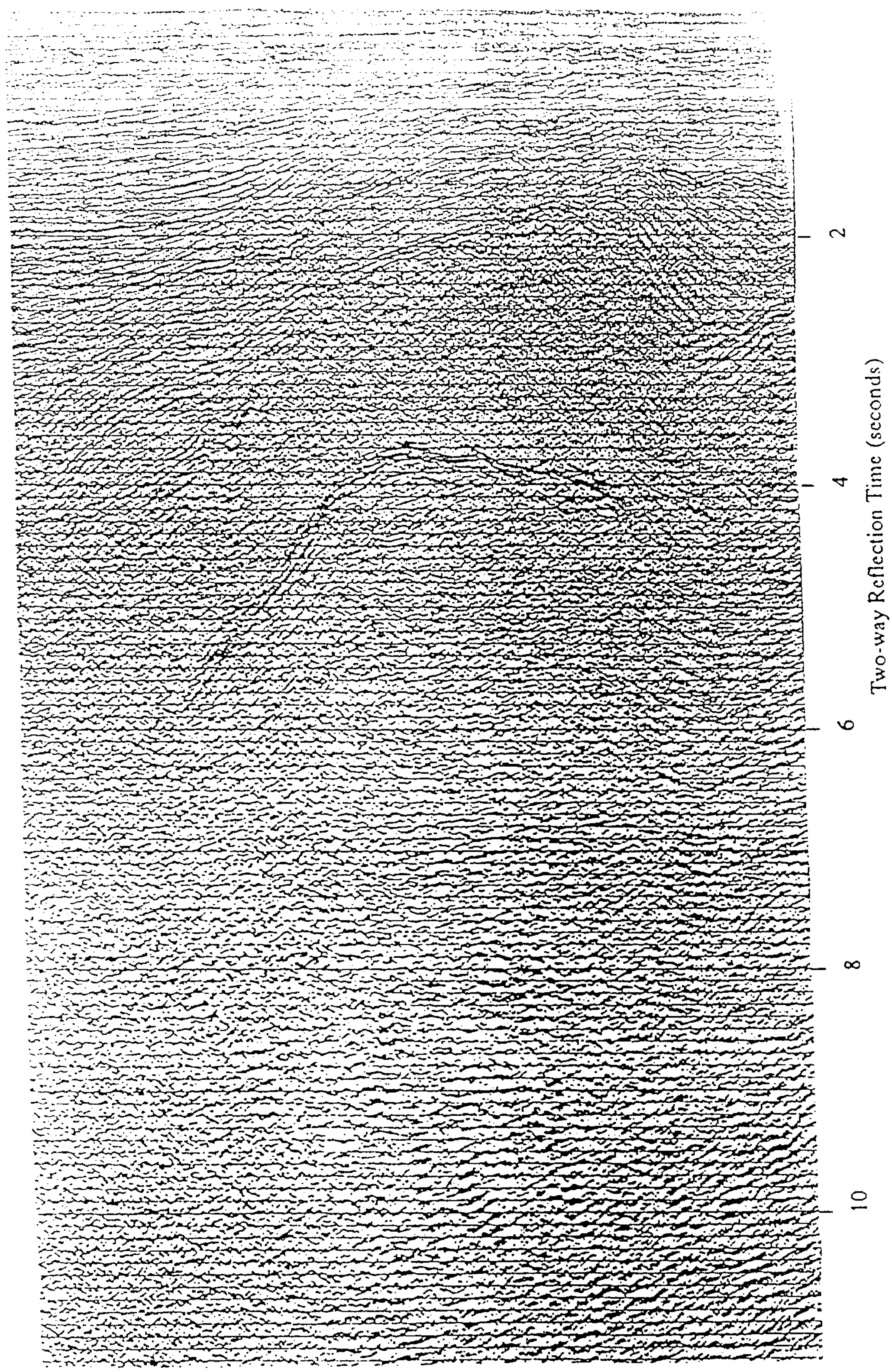

Figure 17: Portion of BMR seismic line 101/8 in the southwest Dampier Sub-basin showing the rotated Palaeozoic sediments above faulted basement at the Arabella structure. Note the banded reflectors in the crust below 7 s.

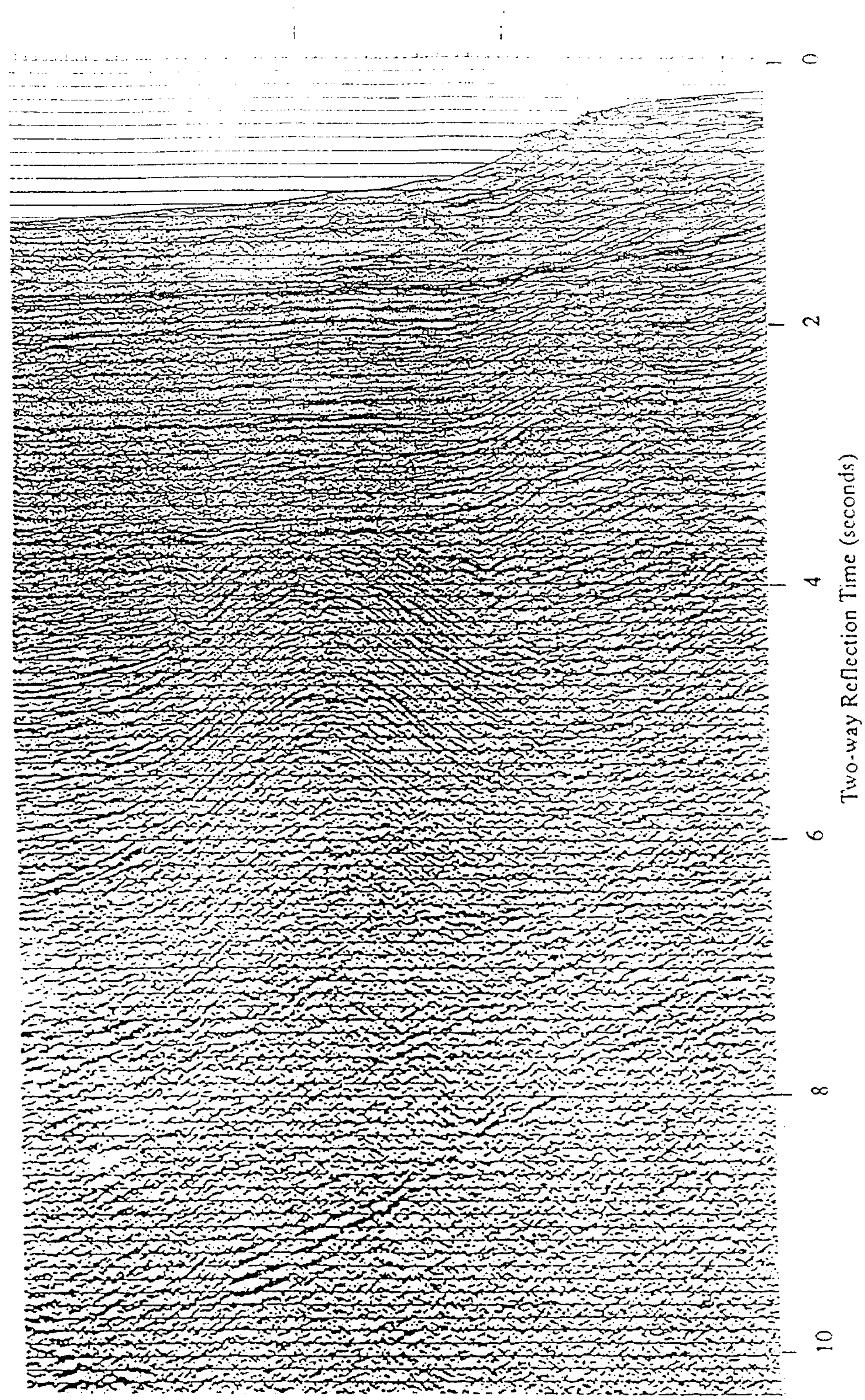

Figure 18: Portion of BMR seismic line 101/7 crossing the Gorgon gas field at the right of the section and the adjacent ?wrench anticline beneath the upper slope above the Exmouth Plateau. The strong reflector at about 9 s is Horizon B.

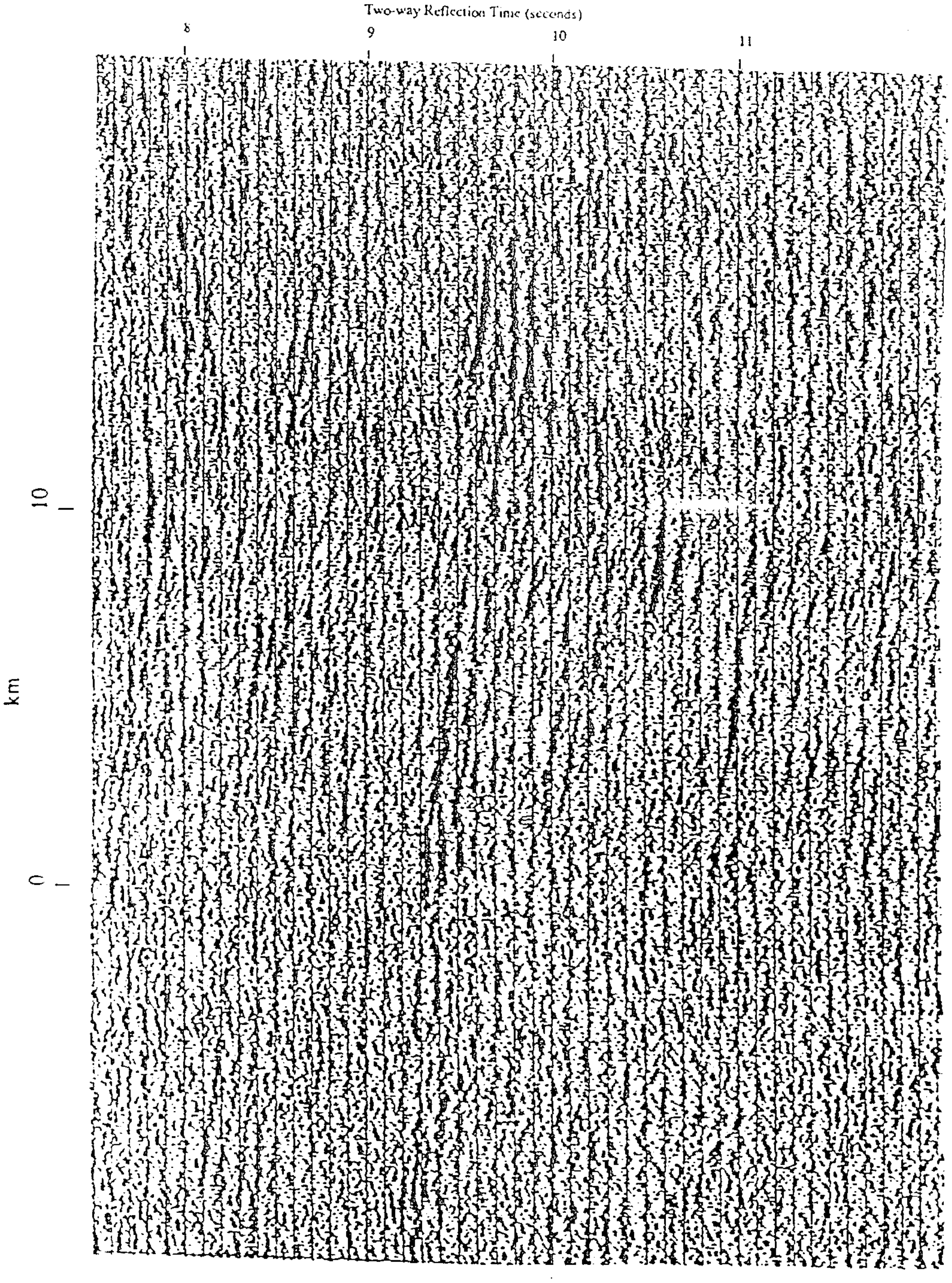

Figure 19: Portion of BMR seismic line 101/16 along strike in the Kangaroo Syncline, showing crustal reflectors at about 8.4 and 9.4 s TWT.