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Deep structure of the offshore Canning Basin, North West Shelf: Snows-3 (Survey 120) Post Cruise Report

by

*H.M.J. Stagg & Survey 120 Shipboard Party**

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DEEP STRUCTURE OF THE OFFSHORE CANNING BASIN, NORTH WEST SHELF: SNOWS-3 (SURVEY 120) POST-CRUISE REPORT.

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EXECUTIVE SUMMARY

In mid-1991, the Bureau of Mineral Resources (BMR; now the Australian Geological Survey Organisation, AGSO) 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. This program is part of a wider program that is acquiring a regional grid of deep-seismic data along the length of the North West Shelf. In particular, the program aims to:

- Determine the broad regional structural framework of the southern North West Shelf by examining the boundaries between the major structural elements;

- Determine the deep crustal structure of the region;

- 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

- 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 during which deep-seismic data are being recorded. The first survey, SNOWS-1 (for Southern North West Shelf; AGSO Survey 101) was concentrated in the Barrow and Dampier Sub-basins and inner Exmouth Plateau. 1654 km of good-quality seismic data tied to 20 exploration wells were recorded and processed; these data frequently show basin structure down to a depth of at least 10 s two-way time (TWT). The second survey, SNOWS-2 (AGSO Survey 110), acquired more than 2800 km of high-quality deep seismic data along 13 lines in the Beagle, Dampier, and Barrow Sub-basins, and over the full width of the Exmouth Plateau in mid-1992. These lines were tied to 21 exploration wells, of which 3 were also tied during SNOWS-I, and again show reflections down to 12 s TWT.

The third survey in the program, SNOWS-3 (AGSO Survey 120), took place in July-August 1993, and acquired a total of 4052.5 km of high-quality deep-seismic data along 14 lines, tied to 6 exploration wells (of which 2 were also tied on SNOWS-2) and Ocean Drilling Program Site 765 in the offshore Canning Basin, northeast extremity of the Carnarvon Basin, and Argo Abyssal Plain. SNOWS-3 ties in with the SNOWS-2 survey to the southwest and with the Browse Basin deep-seismic survey (AGSO Survey 119, acquired in June, 1993) to the northeast.

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 tuned airgun arrays with a total volume of 49 litres (3000 cu in). Shots were fired every 50 m at an average ship speed of 5 knots, providing 48-fold coverage. Streamer noise levels were low, with the average noise levels on acceptable channels generally being less than 1.5 microbars.

Navigation for the survey was provided by two differential Global Positioning Systems

(DGPS), using shore reference stations in Dampier and Broome, adjacent to the survey area. Full differential coverage was achieved for all but a few minutes of the survey. Positional accuracy is estimated to be probably better than +/- 10 metres.

The offshore Canning Basin is a complex amalgam of a WNW-ESE trending Early Palaeozoic intra-cratonic basin overlain by a NE-SW trending Late Palaeozoic to Mesozoic passive margin basin (the Westralian Super-basin). The survey lines were programmed to cross these conflicting trends to maximum advantage, and can be considered in five main groups, as follows:

NE-SW oriented lines that constitute Early Palaeozoic dip lines nearshore and Late Palaeozoic-Mesozoic strike lines further offshore (5 lines; 1578.3 km). Two of these lines provide the final link in a set of tie lines that extend for the full 2500 km length of the North West Shelf and which have been collected on 8 different surveys since late 1990.

NW-SE oriented lines that are Early Palaeozoic strike lines nearshore and Late Palaeozoic-Mesozoic dip lines further offshore (4 lines; 1338.6 km). Two of these lines provide full transects of the continental margin from Early Palaeozoic basins and shallow basement near the coast out to the oceanic crust of the Argo Abyssal Plain.

A single E-W oriented line (349.6 km) that extends from the Broome Platform westwards into the Beagle Sub-basin, crossing an major N-S dislocation in the Mesozoic basin system at the junction of the Beagle and Rowley Sub-basins.

Lines in the Bedout Sub-basin (3 lines; 450.8 km) that provide additional dip transects of the sub-basin together with a strike line that links the Early Palaeozoic Wallal Embayment to the southeast with the Beagle Sub-basin to the northwest.

A single NW-SE line that links the Bedout High to the northeast Exmouth Plateau, via the Beagle Sub-basin (335.2 km). This line fills in a significant gap in the SNOWS-2 data in the Beagle Sub-basin and, by extending on to the northeast Exmouth Plateau, it provides a start to the proposed Canning Basin - Exmouth Plateau in-fill program (SNOWS-4), scheduled for late 1993 or 1994.

As with the earlier SNOWS-1 and SNOWS-2 surveys, only gross structural and stratigraphic information is visible in the field monitors, particularly in shallow water where extensive primary and interbed multiples generated from Late Cretaceous and Tertiary carbonates mask the deeper section. However, as the two earlier surveys have provide high-resolution data in the upper section, as well as strong reflections down to at least 10 s TWT, we are confident that the SNOWS-3 data will prove to be of very high standard when processed.

As an addition to the conventional deep-seismic program, analysis of on-line shot records for refraction events was carried out during the survey by Sydney University. This analysis of some 600 refraction records yielded extensive velocity informatiom which is expected to prove of assistance in processing the reflection seismic data as well as provide new information on the shallow geological section.

With the acquisition of the SNOWS-3 data set, there is now available a regional grid of 8574 km of AGSO deep-seismic data in the northern Carnarvon and offshore Canning Basins.

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The success achieved on SNOWS-3 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*, Andy Codrington.

We would also like to acknowledge the contributions of companies who made suggestions during the planning phase of the survey, particularly:

Amoco Production Company
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Stirling Resources NL
Western Mining Corporation Ltd

INTRODUCTION

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 800 000 km^2 (Fig. 1). The principal sedimentary basins are, 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 hydrocarbons 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. 1989 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 Australian Geological Survey Organisation (AGSO), 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 our understanding of the linkages between the major structural elements and allowing revision of the gross structure of the region. This information is considered to 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 deep-seismic surveys using the AGSO research vessel *Rig Seismic* have been planned during a 4-year period. The program is as follows:

1. Vulcan Sub-basin 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-1) - 1654 km of deep seismic data - completed May-June, 1991 (Stagg, Brassil, & others, 1991; Appendix 1).

4. Northern Carnarvon Basin (Beagle-Dampier-Barrow Sub-basins; Exmouth Plateau; SNOWS-2) -2868 km of deep seismic data completed in June-July, 1992 (Stagg & Survey 110 Shipboard Party, 1992; Appendix 2).

5. Timor Sea - 3611 km of deep-seismic data acquired in January-March 1993 (Pigram, 1992b). 730 km of this survey were shot in the Timor Sea Australia-Indonesia Zone of Cooperation Area A for Nopec Australia.

6. Bonaparte Basin (Malita Graben and Petrel Sub-basin) - 3602 km of deep-seismic data, acquired during May, 1993 (Pigram, 1992a).

7. Browse Basin - 3460 km of deep-seismic data acquired during June, 1993 (Symonds, 1993).

8. Offshore Canning Basin (SNOWS-3) - 4052.5 km of deep-seismic data acquired during July-August, 1993 (subject of this report).

9. Western Canning Basin and Exmouth Plateau in-fill (SNOWS-4) - 3000+ km of deep-seismic data, scheduled for recording in late 1993 or 1994.

9. Northern North West Shelf in-fill program - 3000+ km of deep-seismic data, scheduled for recording in late 1993 or 1994.

10. Northern Scott Plateau - Roti Basin-Browse Basin - 3000+ km of deep-seismic data scheduled for recording in 1994.

By the end of the survey program outlined here, there will be available a network of up to 30000 km of deep-seismic data (recorded at up to 16 seconds TWT) for all of the major basins of the North West Shelf, from North West Cape to the Timor Sea. Two major features of this network will be the multiple margin 'strike' lines that extend for the full length of the North West Shelf and a number of margin 'dip' transects across all the major basins from nearshore out to the abyssal plain or plate boundary.

PREVIOUS EXPLORATION

The most intense exploration on the North West Shelf has been in the northern Carnarvon Basin and in the Timor Sea, where a number of significant oil and gas fields have been discovered. The discovery of giant gas fields in the Dampier Sub-basin of the northern Carnarvon Basin by the Woodside-Burmah Group in 1971 greatly spurred the exploration effort.

In the offshore Canning Basin there have been three phases of petroleum exploration, with activity peaks in the early 1970s and early 1980s; the third round of activity commenced in 1987.

SEISMIC

Compared to the northern Carnarvon Basin and Timor Sea, the offshore Canning Basin has only been sparsely explored with somewhat more than 40 000 km of multichannel seismic (MCS) data being recorded since the late 1960s. Few of these surveys extend into deep water. The early seismic surveys were conducted by BOCAL from the 1960's to the early 1970's, and subsequently by AMAX, BP, Esso, and Hematite. The early exploration phase mainly comprised regional seismic acquisition with a few detailed surveys. The early 1980s exploration phase included some high-quality seismic surveys in the nearshore areas, especially on the flanks of the Fitzroy Trough, but only limited exploration further offshore. Two regional seismic surveys by the Japan National Oil Corporation in 1987 and 1988 have provided a valuable regional seismic grid of some 10500 km in the offshore Canning Basin (Japan National Oil Corporation [JNOC], 1988, 1989; Fig. 2).

EXPLORATION WELLS (Fig. 3)

Six wells were drilled between 1970 and 1973 during the first exploration phase and a further seven wells were drilled between 1980 and 1984 in the second phase. The drilling targets were Mesozoic and Late Palaeozoic clastic reservoirs within the largest known potential traps. Of the seven wells drilled in the second exploration phase, four tested potential carbonate plays and three tested clastic intervals. The only wells in the offshore Canning Basin to provide any encouragement to exploration were Perindi-1 in the nearshore part of the Fitzroy Trough (minor oil show in a Permian reservoir) and Phoenix-1 on the Bedout High (minor gas show in a Triassic reservoir). Phoenix-2, sited to further delineate the Phoenix-1 shows, was unsuccessful.

DREDGING (Fig. 4)

The continental margin adjacent to the offshore Canning Basin is steep and, north of the Exmouth Plateau, deeply incised by canyons. The sedimentary section was sharply cleaved at the time of margin breakup, and this, in combination with the physiography, makes the margin an attractive target for seabed dredging. Since the late 1970s, four research cruises have successfully sampled this margin, as follows:

1979 Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR) *Sonne* Research Cruise SO-8 (von Stackelberg & others, 1980; Exon & others, 1982): northern margin of the Exmouth Plateau.

1986 BMR Survey 56 (Exon & Williamson, 1988; von Rad & others, 1990): northern margin of the Exmouth Plateau.

1990 BMR Survey 95 (Exon & Ramsay, 1990): northern margin of the Exmouth Plateau.

1990 BMR Survey 96 (Colwell, Graham, & others, 1990): margins of the Rowley Terrace and Scott Plateau.

In addition to the reports referred to above, a major geological synthesis of the margin is currently underway at AGSO, with the results due to be published in a forthcoming issue of the AGSO Journal of Australian Geology & Geophysics.

OCEAN DRILLING PROGRAM (Fig. 3)

During 1988, Legs 122 and 123 of the Ocean Drilling Program (ODP; von Rad, Haq & others, 1992; Gradstein, Ludden & others, 1992) both drilled sites on the northwest Australian continental margin that are relevant to the SNOWS-3 program.

ODP Sites 759-761 and 764, drilled on the Wombat Plateau (on the northern margin of the Exmouth Plateau) were designed to evaluate the syn-rift and post-rift structural and palaeoenvironmental evolution of eastern Gondwanaland (von Rad & others, 1992). Of partciular relevance to exploration on the North West Shelf was the coring of an Upper Triassic (Rhaetian) reef complex in Site 764 (Williamson & others, 1989), a discovery which potentially opens up an entirely new range of plays for rocks of this age on the North West Shelf.

ODP Site 765, on the southeast corner of the Argo Abyssal Plain, was drilled with multiple objectives (Appendix 3); the most relevant of the objectives to the SNOWS-3 program was determination of the age of onset of sea-floor spreading. Initial biostratigraphy from sediments overlying basement gave an Early Cretaceous age, 20 Ma younger than expected (Gradstein, Ludden, & others, 1990). However, subsequent re-analysis and modelling of the magnetic lineations, radiometric age dating of the basement basalts, and further biostratigraphic studies have resulted in the onset of sea-floor spreading now being interpreted at shortly prior to anomaly M26 time (163 Ma), approximately at the Callovian-Oxfordian boundary (Fullerton & others, 1989; Sager & others, 1992). Site 765 will be tied by deep-seismic lines during SNOWS-3.

PHYSIOGRAPHY

CONTINENTAL SHELF

The continental shelf of the southern half of the North West Shelf has an arcuate outline bounded by the coastline and the slope break at about 200m depth (Fig. 3). The shelf is approximately 200 km wide in the southwest and narrows to approximately 150 km north of Broome. Between Dampier and Broome, the continental shelf is relatively featureless, forming a gently sloping plain with slopes generally less than 0.25^{o}. The De Grey River, which discharges near Port Hedland, has had relatively little effect on the bathymetry of the continental shelf. Northwest of Broome, the shelf shallows onto the Leveque Platform. In this region, the bathymetry is more complex, reflecting the structural control of the basement faults associated with the Leveque Platform. On the western edge of the platform, slopes exceeding 0.25^{o} are interpreted as the seafloor expression of the Beagle Bay Fault.

CONTINENTAL SLOPE

The width of the continental slope varies between 150 and 200 km. Stagg and Exon (1981) divided this region into an upper slope between the 200 and the 3000 m isobaths, termed the Rowley Terrace, and a lower slope between the 3000 and the 5000 m isobaths with gradients of up to 20^{o}. The Rowley Shoals is a prominent physiographic feature of the Rowley

Terrace. These three coral cays (Mermaid, Clerke, and Imperieuse Reefs) have developed as present-day pinnacle reefs, with diameters of about 20 kilometres in water depths exceeding 300 m, on the upper continental slope.

The Swan Canyon is another major physiographic feature of this part of the continental slope, separating the Rowley Terrace from the Emu Spur on the northeastern Exmouth Plateau. This north-trending canyon debouches onto the Argo Abyssal Plain and has an axial slope of up to 6° and side-wall slopes in excess of 20°.

CONTINENTAL RISE AND ARGO ABYSSAL PLAIN

Oceanward of the offshore Canning Basin, the continental rise is extremely narrow, particularly northwest of the Rowley Shoals and east of the Swan Canyon. In this region, the Argo Abyssal Plain comes closest to the coastline, separating the Scott Plateau to the northeast from the Exmouth Plateau to the southwest. The Argo Abyssal Plain is generally flat, with a gentle southeasterly slope of about 0.02°. The deepest portion (5730 m) is adjacent to the continental rise in the southeast (Stagg & Exon, 1981).

GEOLOGY OF THE OFFSHORE CANNING BASIN

REGIONAL SETTING (Fig. 1)

The gross structure of the North West Shelf comprises a series of NE-SW trending passive margin rift basins of Late Palaeozoic and Mesozoic age (comprising the Westralian Super-basin; Yeates & others, 1986) that overlie three major NW-SE intra-cratonic basins of mainly Early Palaeozoic age (the Carnarvon, Canning, and Bonaparte Basins). The Canning Basin is by far the largest of the Early Palaeozoic basins, and occupies a central position along Australia's northwest margin. While most of the basin lies onshore, seismic data confirm its presence beneath the continental shelf, although the full offshore extent is unknown due to the oceanwards-thickening Mesozoic section.

This report will continue to use the name 'offshore Canning Basin' in describing the region; however, it should be acknowledged that we are in fact dealing with 'stacked' basins. The boundary between the intra-cratonic and passive margin systems can probably best be taken in the Late Carboniferous at the time of the Alice Springs Orogeny.

STRUCTURAL ELEMENTS (Fig. 5)

The main structural elements of the offshore Canning Basin can be most simply separated into those belonging to the intra-cratonic and the passive margin systems.

Intra-cratononic:

- **Fitzroy Trough:** This major sedimentary sub-basin has in the past also been referred to as the Fitzroy Graben, a name which has caused some confusion with regard to its geological origins. Detailed analysis of modern and deep seismic data show that the Fitzroy Trough is an asymmetrical WNW-trending rift that formed by periods of crustal extension in the latest Middle to Late Devonian, the Carboniferous, and the Permian (Drummond & others, 1991). The Fitzroy Trough is bounded on its northeastern flank by the Lennard Shelf and the Precambrian Kimberley Basin onshore, and by the shallow basement of the Leveque Platform offshore, and to the southwest by the Jurgurra Terrace and the shallow Broome Platform. Along strike, the Fitzroy Trough is contiguous with the Gregory Sub-basin to the southeast, while to the northwest its limits are uncertain. The total sediment fill is at least 10-12 km, most of which had accummulated by the end of the Permian.

- **Broome Platform** (also known as the Broome Swell or Broome Arch): This is a major WNW-trending, largely unfaulted, intra-basin high that separates the major Fitzroy Trough to the northeast from the minor Wallal and Samphire Depressions and Willara Sub-basin to the southwest. Along strike to the southeast, the Broome Platform is contiguous with the Crossland Platform, which separates the Gregory Sub-basin to the northeast from the Kidson Basin to the southwest. As with the offshore limits of the Fitzroy Trough, the northwestern boundary of the Broome Platform is over-printed by the northeasterly fault trends of the Westralian Super-basin. Sediment cover over the Broome Platform is generally less than 2000 m.

- **Willara Sub-basin; Samphire Depression; Wallal Depression:** These three small sub-basins or depressions in the southwest Canning Basin contain relatively minor thicknesses of Palaeozoic sediments. Offshore they are overlain by the Mesozoic Bedout Sub-basin, while to the southeast they merge with the major Kidson Sub-basin of the southernmost Canning Basin.

Passive Margin (Westralian Super-basin)

The principal passive margin elements of the offshore Canning Basin are the Bedout and Rowley Sub-basins and the intervening Bedout High (which may be a continuation of the Broome Platform). To the southwest, the boundary with the Beagle Sub-basin is somewhat arbitrary, but is usually taken at a down-to-the-west system of faults, the North Turtle Hinge. In the northeast, the boundary of the Rowley Sub-basin with the Browse Basin is also arbitrary, being taken at the narrowing of the rift system between the Leveque Platform to the southeast and the shallow basement of the southern Scott Plateau to the northwest.

The tectonics and structure of the Bedout and Rowley Sub-basins are quite different (Horstman & Purcell, 1988). The Bedout Sub-basin was a depocentre that was active in the Permian and Triassic, as well as during the Mesozoic and Tertiary, and the structures within it were principally caused by Triassic tectonism. This sub-basin is largely 'enclosed', by the Broome Platform to the northeast, by thinning onshore to the southeast and southwest, and by the Bedout High to the north.

In contrast to the Bedout Sub-basin, while the Rowley Sub-basin may also have been accumulating significant amounts of sediment in the Permo-Triassic, it is primarily a Jurassic-Cretaceous feature. The sub-basin is bounded by structurally high areas to the south (Bedout High), southeast (Broome Platform), and north (Scott Plateau), but is open to the northeast (Browse Basin), southwest (Beagle Sub-basin), and to the northwest where the sub-basin was breached at the time of margin breakup in the Jurassic. While this lack of present-day enclosure may appear to reduce the possibility of good-quality source rocks accummulating, it is possible that, prior to breakup, the basin was bounded to the northwest by a structural high which was subsequently rifted away, in which case pre-breakup palaeoenvironments may have been restricted. Although modern high-quality seismic data are sparse in the Rowley Sub-basin, the data that are available indicate that structuring in the centre of the basin is relatively subdued, while the basin margins are extensively faulted and folded, indicating that the region has been subjected to both extension and compression or strike-slip movement.

TECTONIC EPISODES

Horstman & Purcell (1988) described three tectonic episodes that can be recognised in the history of the offshore Canning Basin, as follows:

1. In the **Late Carboniferous**, as part of the Alice Springs orogeny, faulting established a basin system in which thick Permo-Triassic sediments subsequently accumulated. While this period of deposition is principally known from the Bedout Sub-basin, it is quite possible that similar sediments were also deposited in the Rowley Sub-basin.

2. A second major tectonic episode, in the **Late Permian to Early Triassic**, involved extensive uplift, faulting, and volcanism. This episode has been named the 'Bedout Movement' (Forman & Wales, 1981), since it is most pronounced in the Bedout Sub-basin and on the Bedout High. It has also been interpreted as the onset of the final rifting phase that culminated in the breakup of Australia from an unknown northern landmass in the Middle Jurassic. A similar faulting episode probably occurred along much of the North West Shelf; however, elsewhere it is probably largely obscured by the large thickness of sediment that accumulated in the Westralian Super-basin during the Triassic and Jurassic.

3. The final significant phase of tectonism that affected the offshore Canning Basin occurred in the **Jurassic** and was associated with final margin breakup. In the Early Jurassic, the 'Fitzroy Movement' produced some faulting and an erosional surface at the top of the Triassic that provides a regional seismic marker. Otherwise, the Bedout Sub-basin appears to have been relatively stable throughout the Jurassic, and the so-called Callovian 'breakup unconformity', prominent elsewhere on the North West Shelf, is not apparent in seismic data over large areas of the basin (although it is evident in some wells, such as Lacepede-1 and East Mermaid-1). The Jurassic rifting that is evident both in the northern Carnarvon Basin and in the Browse Basin, is also evident on the eastern margin of the Rowley Sub-basin, where faulting of this age is interpreted to abruptly terminate the underlying, orthogonal Early Palaeozoic trends.

STRATIGRAPHY (Fig. 6)

For the purpose of discussion in this pre-cruise report, the geological sequences of the offshore Canning Basin have been divided into ten units, based on well correlations and onshore geological data (Brown & others, 1984; Forman & Wales, 1981) and the JNOC studies (JNOC, 1988, 1989).

The following unconformities are common (but not ubiquitous) in the wells in the offshore Canning Basin:

- Devonian to Carboniferous
- Lower to Upper Carboniferous
- within the Lower Permian
- Permian to Triassic
- Triassic to Jurassic
- Middle to Upper Jurassic
- Cretaceous to Tertiary.

In the offshore Fitzroy Trough, wells have penetrated the Devonian section, but elsewhere offshore wells have seldom drilled pre-Triassic rocks.

Basement.

Although no Precambrian rocks have been sampled in wells in the offshore Canning Basin, Precambrian basement rocks have been drilled in several wells in adjacent areas. These basement rocks fall into two categories: metamorphic and volcanic. Banded iron formation and basic igneous rocks were intersected in the south Bedout Sub-basin and north Turtle Arch (Forman & Wales, 1981). Goldwyer-1 on the Broome Platform encountered volcanic basement rocks, and Leveque-1 on the Leveque Platform bottomed in gabbroic basement. Metamorphic basement was encountered in the Tappers Inlet-1, Meda-1 and Napier-4 wells on the Lennard Shelf and in the Thangoo-1 and Parda-1 wells onshore on the Broome Platform.

Ordovician

The Lower Ordovician section consists of clastics (Nambeet and Goldwyer Formations) and carbonates (Willara and Nita Formations). This shallow marine sequence has been intersected in several onshore wells, and is thought to have been distributed widely in the onshore Canning Basin where it has a maximum drilled thickness of at least 3000 m. However, regional southeastwards tilting of the basin in the Late Ordovician to Devonian resulted in erosion and extensive removal of the upper part of this sequence.

Silurian to Early Devonian

The Early Devonian section in the onshore Canning Basin is dominated by continental sediments of the Carribuddy Formation (evaporites) and the Tandalgoo Red Beds; these formations are mainly restricted to the Kidson Sub-basin, the Broome Platform, and the southern flank of the Fitzroy Trough. The overlying marginal marine sandstone and siltstone of the Poulton Formation is restricted to the Fitzroy Graben and Lennard Shelf.

Late Devonian - Early Carboniferous

Late Devonian sediments are characterised by the platform reef complex of the Pillara Limestone and the Nullara carbonate cycles within the onshore Canning Basin (Playford, 1984). Offshore, the Pillara Limestone has been intersected in three wells on the offshore extension of the Lennard Shelf (Kambara-1, Perindi-1, and Minjin-1), and seismic data suggest that this sequence is also developed within the offshore Fitzroy Trough.

Early Carboniferous rocks were intersected in three wells in the offshore Canning Basin (Pearl-1, Lacepede-1A, and Wamac-1). This sequence is the equivalent of the regressive clastic Fairfield Group and Anderson Formation onshore. In Pearl-1, the Early Carboniferous sequence consists wholly of shale, whereas in the other wells, the sequence is a non-marine sandstone characterised by a high content of calcareous matrix.

Onshore this sequence correlates with the well-known reef complexes of the Lennard Shelf, where reef development was fault-controlled; the associated lithologies include evaporites, shale, siltstones, sandstones, and carbonates.

Late Carboniferous to Late Permian

The Grant Formation consists of a substantial thickness of Late Carboniferous to Early Permian glacial fine- to coarse-grained sandstones. These are thickest in the Fitzroy Trough where the maximum thickness exceeds 2 km. The Early to Middle Permian post-glacial Poole Sandstone and Noonkanbah Formation, and the Late Permian Liveringa Group, are dominantly composed of sandstones and siltstones with minor limestone, and have major depocentres in the Fitzroy Trough (>2000 m) and in the Kidson Sub-basin. Sediments of this age are also interpreted to underlie the Bedout Sub-basin (Lipski & Beattie, 1992). Offshore this sequence has been sampled by Perindi-1. Deposition was interrupted in the Late Permian by igneous and tectonic activity.

Triassic

Within the Fitzroy Trough, the Early to Middle Triassic is represented by the marine Blina Shale and the deltaic Erskine Sandstone. Further offshore, the time-equivalent Locker Shale and Keraudren Formation (which correlates with the Mungaroo Formation of the northern Carnarvon Basin) have a maximum thickness of about 2000 m. A major depocentre developed offshore in the Triassic, but a substantial thickness of this sequence has been subsequently removed by erosion. The Late Triassic is areally more restricted, and onlaps onto the Leveque and Broome Platforms. The sequence was drilled in Barcoo-1 in the Rowley Sub-basin, where it consists largely of claystone and limestone, and also in the Bedout Sub-basin, where it is dominantly composed of deltaic or fluvial sandstone (Lipski & Beattie, 1992).

Early to Middle Jurassic

This interval is widely distributed in the offshore Canning Basin as a fluvial to deltaic sandstone with minor coal, mudstone, and limestone (the Bedout Formation of Lipski & Beattie, 1992). It correlates with the Wallal Sandstone in the onshore Canning Basin. Age equivalents of this sequence are generally absent in the northern Carnarvon Basin.

Late Jurassic to Early Cretaceous

The Late Jurassic sequence in the offshore Canning Basin consists dominantly of fine clastic sediments (siltstones and claystones) and is correlated with the Jarlemai Siltstone in the onshore Canning Basin. The Early Cretaceous sequence consists of a range of argillaceous sediments (claystones, siltstones, and sandstones) deposited in the marine environment of the newly formed ocean. The Mermaid Formation is dominated by sandstones on the Lennard Shelf, where it correlates with the Broome Sandstone (maximum drilled thickness of 300 m onshore), whereas mudstones dominate the Early Cretaceous sequence in the Rowley Sub-basin.

Late Cretaceous

The Late Cretaceous sequence consists of calcareous claystones and limestones, with interbedded sandstones. This sequence thickens northwestwards with a maximum drilled thickness of 1091 m in East Mermaid-1 in the Rowley Sub-basin. Two units have been identified offshore. The lower unit, the Toolonga Calcilutite, is an argillaceous limestone that was deposited in a middle to outer shelf marine environment. The upper unit, the Miria Formation, is a calcareous mudstone which was deposited in a shallow marine to littoral environment subsequent to a late Campanian to early Maastrichtian regression.

Paleocene to Holocene

Monotonous carbonates dominate the Cainozoic section on the North West Shelf, with calcareous mudstones and limestone being the main lithologies in the offshore Canning Basin. This unnamed sequence progades oceanwards and exceeds 1000 m thickness in the Rowley Sub-basin. Knowledge of the Oligocene to Holocene is scant, due to lack of cored samples. The ODP drill holes yielded such cores, but lie outside the basin.

HYDROCARBON POTENTIAL

In contrast to neighbouring North West Shelf basins, the majority of Canning Basin exploration activity has taken place onshore with Palaeozoic traps being the principal targets. Although more than 200 wells have been drilled in the basin, only 13 of these have been drilled offshore. Apart from minor oil staining in Permian sediments in Perindi-1 in the Fitzroy Trough and in Triassic sediments in Phoenix-1 on the Bedout High, all the offshore wells have been dry. Onshore, there have been 8 minor oil discoveries, the largest of which (and also the first) was at Blina-1 on the northern flank of the Fitzroy Trough in 1981 (Passmore, 1991).

While the hydrocarbon potential of the offshore Canning Basin does not currently generate high interest, this is not entirely justified, given the very low level of exploration in the region, particularly with regard to wells drilled. Although there has been a dearth of hydrocarbon indications in wells in the basin, the recent encouragement provided by the sub-economic oil discovery in Nebo-1 in the Beagle Sub-basin (the first significant hydrocarbon discovery in that sub-basin) should re-generate exploration interest in the offshore Canning Basin, particularly in the west.

Compared to the other basins of the North West Shelf, the offshore Canning Basin includes a wide variety of geological settings and a commensurate variation in potential hydrocarbon play types. These settings include:

- Offshore Fitzroy Trough: a Palaeozoic continental rift basin, with plays that are close analogies to the onshore Fitzroy Trough.

- Offshore Broome Platform: a large area of relatively shallow basement; successful plays need to invoke migration over considerable distances from the deeper parts of the basin and stratigraphic or structural traps on the platform margins.

- Offshore Wallal/Samphire Depressions: Palaeozoic depocentres of limited depth and areal extent and low hydrocarbon potential.

- Bedout Sub-basin: a largely Mesozoic 'enclosed' sub-basin that is underlain by an unknown thickness of Palaeozoic rocks and has potential for both structural and stratigraphic traps.

- Bedout High: structurally positive area of Mesozoic rocks, also underlain by an unknown thickness of Palaeozoic rocks.

- Rowley Sub-basin: a major Mesozoic depocentre, probably with underlying Palaeozoic rocks. While the the present-day configuration of the basin is breached, this may not have been the case prior to Jurassic margin breakup. The Rowley Sub-basin is the only part of the offshore Canning Basin that bears a close resemblance to the the main hydrocarbon-bearing Mesozoic sub-basins elsewhere on the North West Shelf. Late Triassic bioherm rocks, dredged from the outer margin, suggest a possible reef play.

Given the differences between the offshore Canning Basin and other basins of the North West Shelf, it is obvious that straightforward application of play concepts from adjacent areas is inappropriate.

The lack of wells drilled in the offshore Canning Basin (5 in the offshore Fitzroy Trough, 1 in the Rowley Sub-basin, 1 in the Bedout Sub-basin, and 4 on the Bedout High; Fig. 3) makes assessment of the hydrocarbon potential of the basin very speculative. The following summary of the source, reservoir, and seal distribution and quality is compiled from those few wells and should be therefore treated with caution.

SOURCE ROCKS & MATURITY

Four Palaeozoic and four Mesozoic units have been assessed by JNOC for hydrocarbon source potential (JNOC, 1989). These units are of Ordovician, Devonian, Lower Carboniferous, Upper Carboniferous to Permian, Triassic, Lower to Middle Jurassic, Upper Jurassic, and Cretaceous ages.

No offshore wells penetrate the Ordovician section in the region. Onshore, however, the

Goldwyer Formation and the Devonian reefs are considered to be good source rocks. The Devonian rocks generally have low TOC values, but may be extensive in the offshore Fitzroy Trough, where their source rock potential is unknown.

Offshore, the Lower Carboniferous equivalent of the Laurel Formation has higher TOC values but the kerogen content is mainly gas-prone. The Upper Carboniferous to Permian equivalent of the Grant Formation has relatively poor TOC values. Although the overlying Noonkanbah Formation was not evaluated by JNOC, extrapolation from onshore suggests that this formation may provide a good potential source, if it has been preserved with sufficient thickness in the deeply subsided parts of the Fitzroy Trough and Rowley Sub-basin.

The source potential of the Triassic Locker Shale and Keraudren Formations has been assessed on the basis of analyses of samples from the Keraudren-1 and Phoenix-1 and -2 wells. The Locker Shale consists of sandstones and mudstones from a shallow marine environment, and has relatively high TOC values. The Keraudren Formation (a lateral equivalent of the Mungaroo Formation in the northern Carnarvon Basin) is sandstone-dominated and was deposited in deltaic and fluvial environments. The Keraudren Formation has poor TOC values and is gas prone.

The Lower to Middle Jurassic sandstones and mudstones were deposited in a deltaic to fluvial environment. The shale ratio is interpreted to increase seawards, and the mudstones have relatively high TOC values with gas-prone kerogens. However, the lithology is dominantly sandstone, which limits the source volume.

The thick marine Upper Jurassic claystones which are a prolific source rock over most of the North West Shelf are also assessed to have good to excellent source rock potential in the offshore Canning Basin. However, in this region the sequence is generally thin, reducing the capacity of the sequence to generate hydrocarbons. In the near-shore wells, the Upper Jurassic is sandstone-dominated.

The Lower Cretaceous section of marine claystones and sandstones, contrasts with the Upper Cretaceous section of limestones and calcareous claystones. The claystones generally have fair to good TOC values, with the Lower Cretaceous being particularly rich, but gas prone.

The geothermal gradient tends to be lower in the offshore extension of the Fitzroy Trough and the Rowley Sub-basin (2.0 to 2.5°C/100m) and higher (3.0 to 4.0°C/100m) above shallow basement. The Cretaceous and Upper Jurassic sequences are generally considered to be immature. The Lower Jurassic is also immature, except in the Rowley Sub-basin where it is thought to be early mature due to the greater depth of burial. The Triassic sequence is considered to be mature where it occurs in the Rowley Sub-basin.

RESERVOIR AND SEAL

Commercial production from minor onshore hydrocarbon fields in the northern Canning Basin comes from Devonian carbonates and from Permian and Carboniferous sandstones. These sequences are also present in the nearshore part of the basin, where they were the targets of Perindi-1, Pearl-1, Kambara-1, and Minjin-1. Further offshore, Palaeozoic targets are probably too deeply buried to constitute a valid exploration target (Horstman & Purcell, 1988).

In the main offshore part of the basin, Late Palaeozoic and Mesozoic reservoirs are probably the main exploration targets. Permian (Liveringa Group), Triassic (Keraudren Group), and perhaps Jurassic sands appear to be widespread. The Keraudren Formation (equivalent of the Mungaroo Formation), in particular, appears to be a good prospect (Lipski & Beattie, 1992). Upper Cretaceous and Tertiary carbonates have good porosity and permeability, but are unlikely to be adequately sealed.

Adequate regional seals appear to be present. These seals include the Lower Triassic Locker Shale (also a potential source rock), the Early-Middle Jurassic Bedout Formation (the equivalent to this interval is usually absent elsewhere on the southern North West Shelf), and the Upper Tithonian to Neocomian Muderong Shale equivalent that was deposited in the margin-wide marine transgression after margin breakup.

GENERAL OBJECTIVES & SPECIFIC PROBLEMS

The broad objectives of the program are the same as those applied to SNOWS-1 and SNOWS-2, namely:

- ❒ To determine the regional structural framework by examining the boundaries between major structural elements along key transects of the shelf.
- ❒ To determine the deep crustal structure and its relationship to the development of the adjacent continental margin.
- ❒ 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, the following problems can be addressed by regional deep-seismic data in the offshore Canning Basin (Stagg & Leven, 1993):

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). Where are the primary detachment surfaces beneath the offshore Canning Basin, and what were the azimuths, ages, and amounts of extension in each phase of basin formation?

2. ***Interaction of extension episodes of different ages:*** Given that there are two separate and orthogonal extension episodes involved in the formation of the offshore Canning Basin (NE-SW in the ?Early Palaeozoic in the onshore and nearshore Canning Basin; NW-SE in the Late Palaeozoic-Mesozoic in the overlying Westralian Super-basin), how have these two detachment systems interacted? What are the similarities with the comparable situation in the Bonaparte Basin (Petrel Sub-basin and Malita Graben-Sahul

Platform) and can development in the two areas be related?

3. ***Strike-slip movements:*** Strike-slip motion and wrenching appear to have been major influences on the development of structures throughout the North West Shelf (for example, in the adjacent Beagle Sub-basin); can such structures also be identified in the offshore Canning Basin?

4. ***Limits of Palaeozoic sediments:*** What is the northwesterly extent of the Early Palaeozoic sediments that underlie the Rowley Sub-basin (Fitzroy Trough) and Bedout Sub-basin (Wallal and Samphire Embayments)?

5. ***Fitzroy Trough deep structure:*** BMR has previously acquired deep seismic lines across the onshore Fitzroy Trough and proposed a model for formation of the trough (Drummond & others, 1988). Is this model supported by deep seismic data in the offshore extension of the trough, or does it require modification (this has relevance to onshore exploration)?

6. ***Broome Platform deep structure:*** What is the deep structure of the Broome Platform, and how and why did such a major feature develop in the centre of the Canning Basin? Could the Broome Platform have developed into a marginal plateau if the Early Palaeozoic Canning Basin extension proceeded to continental breakup? Is there potential for stratigraphic traps for hydrocarbons on the flanks of the platform?

7. ***Development of Bedout Sub-basin:*** The Bedout Sub-basin is quite different in its setting to the other Late Palaeozoic-Mesozoic sub-basins of the North West Shelf. How and why did this sub-basin develop and what bearing does this development have on its hydrocarbon potential?

8. ***Development of the Bedout High:*** The Bedout High has apparently been structurally positive at least as far back as the Early Mesozoic. This structure is the site of a major dislocation in the Westralian Superbasin rift system and obviously has major significance. What are the origins of the Bedout High and what controlling influences has it had on basin development?

9. ***Control of Canning Basin on northern Exmouth Plateau margin:*** Extension of the trends of the Canning Basin offshore suggest that it has had a controlling influence on the subsequent development of the northern margin of the Exmouth Plateau. What is the nature of this control, if it is indeed real?

10. ***Rowley Sub-basin:*** The Rowley Sub-basin is the major Mesozoic depocentre in the offshore Canning Basin and therefore, by analogy with other basins on the North West Shelf, it should be the most prospective sub-basin in the area, albeit in deep water. Modern seismic coverage of this sub-basin is minimal and only one well has been drilled on the flank of the sub-basin. How did the Rowley Sub-basin form; how can this development be related to the formation of the Argo Abyssal Plain; and does the sub-basin have serious hydrocarbon potential? Why is the centre of the sub-basin only mildly structured, whereas the flanks show extensive structuring? The outer flank of the Rowley Sub-basin was 'breached' at margin breakup in the Middle Jurassic - was the basin restricted prior to this breaching?

11. *Argo Abyssal Plain:* What are the fundamental crustal structures that have caused the present-day configuration of the Argo Abyssal Plain, with its deep southeastwards indentation into the continental margin? What crustal structure has produced the sharp cleaving of the outer margin of the Rowley Sub-basin and the abrupt transition from continental to oceanic crust?

CRUISE NARRATIVE

The SNOWS-3 survey (AGSO Survey 120) departed from Port Hedland on July 9, 1993, and terminated in Fremantle on August 12. The following is a brief summary of the principal events; chronology is given as Julian day number and GMT hours and minutes.

190.1000	Depart from Port Hedland
190.2300	Commence streaming 4800 m seismic cable. 2 active sections swapped out and sections balanced for survey area.
192.0200	Commence system tests.
192.0632	First good shot-point (FGSP) line 120-0101 (ie Survey 120, line 01, part 01).
193.0633	Last good shot-point (LGSP) line 120-0101. Loop for gun-array maintenance.
193.1336	FGSP line 120-0102.
194.1734	LGSP line 120-0102. Loop to northwest for gun-array maintenance and re-position for line 120-0201.
194.2315	FGSP line 120-0201.
195.1509	LGSP line 120-0201. Loop to northeast for gun-array maintenance and re-position for line 120-0301.
195.2155	FGSP line 120-0301.
196.1400 (approx.)	Channel 159 goes noisy, then dead; cable leveller (bird) wing angles at this time indicate cable section holed.
196.2140	LGSP 120-0301. Loop for gun-array maintenance and streamer repairs. 2 active sections swapped, tailbuoy replaced, and all bird batteries replaced.
197.2203	FGSP line 120-0302.
198.0400 - 0840 (approx.)	Deterioration in weather; data marginally outside recording guidelines for swell noise.
198.1911	LGSP line 120-0302. Line terminated approximately 8 km before programmed end-of-line, due to rapid deterioration in weather.
199.0240	FGSP line 120-0401.
199.1050	LGSP line 120-0401. Loop for gun array maintenance.
199.1716	FGSP line 120-0402.
199.2037	LGSP line 120-0402. Waiting on weather.
200.1210	FGSP line 120-0403.
200.1659	LGSP line 120-0403. Waiting on weather.
201.1130	FGSP line 120-0404.
201.1624	LGSP line 120-0404. After 3 breaks due to bad weather on line 120-04, it was decided to try shooting in a different direction (SSW); this

	proved successful, with resultant noise levels very low.
202.0205	FGSP line 120-0501.
202.2038	LGSP line 120-0501. Gun-array maintenance during transit to next line.
203.0236	FGSP line 120-0601.
203.1929	LGSP line 120-0601. First 400 m of active streamer retrieved and birds 1-3 replaced. Birds 11 and 21, which were both displaying low battery voltages, were replaced using the Zodiac rubber dinghy.
204.0459	FGSP line 120-0405. (Weather conditions had moderated to the level such that line 120-04 could be completed.)
205.0132	LGSP line 120-0405.
205.0641	FGSP line 120-0701.
206.1259	LGSP line 120-0701. Loop for gun array maintenance.
206.1835	FGSP line 120-0702.
207.1444	LGSP line 120-0702. During the long transit to the next line, the Zodiac was used to replace 12 birds with low batteries and the Argos battery pack in the tailbuoy.
208.0930	FGSP line 120-0801.
209.0701	LGSP line 120-0801. Loop for gun array maintenance.
209.1253	FGSP line 120-0802.
210.0649	LGSP line 120-0802.
210.1418	FGSP line 120-0901.
211.0056 - 0157	Course change between Clerke and Imperieuse Reefs.
211.1325	LGSP line 120-0901.
211.1811	FGSP line 120-1001.
212.0813	LGSP line 120-1001.
212.1457	FGSP line 120-1101. The weather deteriorated during the first half of this line, and some swell noise was evident. However, recording was at all times comfortably within guidelines.
213.1917	LGSP line 120-1101. Commence 18 hour transit to northeast end of line 120-1201.
214.1620	FGSP line 120-1201. The start of this line was moved some 110 km to the southwest of the start-of-line in the cruise proposal. This was because of poorly charted banks and shoals at the proposed start-of-line, which were assessed to be too hazardous for operations.
216.0004	LGSP line 120-1201. Loop for preventative gun maintenance.
216.0554	FGSP line 120-1202.
216.2045	LGSP line 120-1202.
217.0255	FGSP line 120-1301. As the original cruise program was completed, lines 120-1301 and 120-1401 were additional lines proposed during the survey.
217.1744	LGSP line 120-1301.
218.0013	FGSP line 120-1401.
219.1059	LGSP line 120-1401.
219.1200 - 1945	Retrieve gun arrays and streamer. Some problems were encountered with streamer retrieval when a filler valve on an active section was found to be leaking. There was also minor fish bight near the end of the streamer which was repaired without the section being replaced.
219.2000	Commence transit to Fremantle.

223.0200 Arrive in Fremantle; end of Survey 120.

SEISMIC DATA RECORDED

REFLECTION DATA

The 14 seismic lines recorded during SNOWS-3 are shown in Figures 7 & 8. These lines total 4052.5 km and tie 6 exploration wells, of which one was also tied on SNOWS-2, and ODP Site 765 on the Argo Abyssal Plain. A brief outline of the location and function of each line is as follows (110/ prefix lines were recorded during SNOWS-2; 119/ prefix lines were recorded during the Browse Basin deep-seismic survey, Survey 119):

120-01: (Cruise Proposal line SNOWS3-H; 474.8 km; ties to Lagrange-1, ODP Site 765, lines 120/02, 04, 05, 06, 07, 12): Prime offshore Canning Basin transect, Samphire/Wallal Depressions - Bedout Sub-basin - Bedout High - Rowley Sub-basin - Argo Abyssal Plain.

120-02: (Cruise Proposal line SNOWS3-E; 145.1 km; ties to ODP Site 765, lines 120/01, 03): Short strike line on oceanic crust in southeast Argo Abyssal Plain between magnetic anomalies M25 and M26. Although of low priority from the exploration viewpoint, this line provides deep crustal data across a major oceanic fracture zone interpreted from sea-floor spreading magnetic lineations.

120-03: (Cruise Proposal line SNOWS3-K; 383.8 km; ties to East Mermaid-1, lines 120/02, 04, 07, 08, 10, 12): Mesozoic dip line, Broome Platform - Rowley Sub-basin - Argo Abyssal Plain.

120-04: (Cruise Proposal line SNOWS3-G; 349.6 km; ties to Minilya-1, Lagrange-1, lines 110/04, 05, 06, 08, 120/01, 03, 05, 06, 07, 08, 12, 14): Beagle Sub-basin - Bedout High - Broome Platform. This line was designed to provide an orthogonal crossing of the major N-S trending structures that comprise the ?transform dislocation between the northern Carnarvon Basin (Beagle Sub-basin) and Rowley Sub-basin.

120-05: (Cruise Proposal line SNOWS3-F; 160.6 km; ties to Keraudren-1, Lagrange-1, lines 120/01, 04, 13): Mesozoic dip line, Bedout High - Bedout Sub-basin - Lambert Shelf.

120-06: (Cruise Proposal line SNOWS3-C; 151.5 km; ties to lines 120/01, 04, 08, 13): Palaeozoic dip line, Lambert Shelf margin - Wallal Depression - Samphire Depression - margin of Broome Platform.

120-07: (Cruise Proposal line SNOWS3-D; 484.8 km; ties to lines 110/04, 05, 07, 08, 119/01, 02, 120/01, 03, 04, 09, 11, 14,): Mesozoic strike and tie line from northern Beagle Sub-basin.northern Beagle Sub-basin - northern flank of Bedout High - Rowley Sub-basin - southwest extension of the Browse Basin. This line is the remaining link in the major strike line that extends for the length of the North West Shelf.

120-08: (Cruise Proposal line SNOWS3-B; 368.7 km; ties to lines 119/02, 10, 120/03, 04, 06, 09, 11): Palaeozoic dip line, Leveque Platform - Fitzroy Trough - Broome Platform. The northeast end of this line (and the southwest end of line 119/10 were both displaced to the southeast relative to the cruise proposal lines, due to inadequate mapping of shallow features in this area.

120-09: (Cruise Proposal line SNOWS3-I,J; combined length 231.1 km; ties to lines 120/07, 08, 10): Mesozoic dip line, outer Broome Platform - Rowley Sub-basin.

120-10: (Line not in original Cruise Proposal; 138.2 km; ties to lines 119/12, 120/03, 09, 11): Mesozoic strike line along the axis of the Rowley Sub-basin. A decision was taken to record this line when it became apparent that sufficient time remained to complete the proposed program. An unplanned extension to this line to the southern Scott Plateau was shot at the end of the Browse Basin deep-seismic survey.

120-11: (Cruise Proposal line SNOWS3-L; 248.9 km; ties to Wamac-1, lines 119/12, 120/07, 08, 10, 12): Palaeozoic strike and Mesozoic dip line, Fitzroy Trough - Rowley Sub-basin.

120-12: (Cruise Proposal line SNOWS3-A; 441.5 km; ties to lines 120/01, 03, 04, 11, 13): Palaeozoic dip line, Leveque Platform - Fitzroy Trough - Broome Platform - Samphire Depression - Wallal Depression. Due to shallow water depths at the northeast end of the line, the start-of line way point was displaced to the southwest relative to the start-of-line specified in the pre-cruise proposal. This meant that it was not possible to tie the line to the inshore Browse Basin strike line, nor was it practical to tie to Lacepede-1A. The deletion of the Lacepede-1A tie is not considered crucial as that well can be tied via the JNOC survey.

120-13: (line additional to Cruise Proposal; 138.7 km; ties to lines 110/07, 120/05, 06, 12): Palaeozoic strike line in the wallal Embayment and Mesozoic ?dip line in the Bedout Sub-basin. This line is co-linear with line 110/7, giving a 300 km line linking the Wallal Embayment to the outer Beagle Sub-basin.

120-14: (line additional to Cruise Proposal; 335.2 km; ties to Phoenix-1 and lines 110/01, 04, 06, 120/04, 07): Mesozoic dip line, Bedout High - North Turtle Hinge - Beagle Sub-basin - inner flank of the northeast Exmouth Plateau. While not in the original cruise proposal, this line forms a component of the proposed Canning - Exmouth Plateau in-fill survey.

REFRACTION ANALYSIS

As an adjunct to the recording of reflection data, automatic shot replays were generated every 100 shots (5 km) to provide data for analysis of refractions in the shallow section by D. Mihut of The University of Sydney. High-velocity carbonates in the Late Cretaceous and Tertiary section on the North West Shelf, and the velocity inversions beneath these carbonates, have long been recognised as the bane of the seismic processor in this region. The long seismic streamer used (4800 m) meant that refraction energy could be obtained from depths of up to about 3500 m. Systemmatic analysis of these refraction records provides the possibility of developing a velocity model for the shallow section which will both aid seismic processing and provide new geological information.

During the survey, some 620 shot records were examined and refraction events picked for velocity and depth; up to 5 separate refraction events could be picked, with velocities ranging from 1950 - 6000 $m.s^{-1}$. Post-cruise analysis of the data will include correlation of refraction velocity with processed reflection records and, possibly, the development of new geological models that are applicable to the Cretaceous-Tertiary section.

EQUIPMENT AND SYSTEMS REPORTS

NAVIGATION/GEOPHYSICAL DATA ACQUISITION (DAS)

The geophysical/navigation data acquisition system (DAS) ran without serious problems for the duration of Survey 120. As Survey 120 was the last survey to be acquired using the Hewlett-Packard-based DAS, no software or other modifications were made during the survey.

Navigation

As with all recent *Rig Seismic* surveys, the primary and backup navigation systems consisted of 2 physically identical differential Global Position Systems (DGPS), provided by Racal. Shore stations providing differential corrections were located at Dampier (primary system) and Broome (secondary system). No substantial signal loss was experienced during the survey, except for 30 minutes on Day 194 when differential corrections from the Perth base station had to be used, due to land-line transmission problems to Perth from the Dampier and Broome stations.

A tertiary navigation system was provided by Magnavox dual-axis sonar doppler velocity log and Sperry gyro-compass. This system is only intended to provide dead-reckoning navigation during very short periods (a few minutes or less), when full differential coverage may be lost for technical reasons.

Overall, full DGPS coverage by the primary system was achieved for 98.64% of the survey. Of the remaining avarge of 20 minutes per day when the primary DGPS was not available, the secondary DGPS provided an average of 15 minutes coverage. Navigational accuracies are estimated to be probably better than +/- 10 metres. An indication of the level of accuracy is that small magnetic anomalies are frequently recorded where seismic lines cross abandoned exploration wells.

Bathymetry

Both 3.5 kHz and 12 kHz Raytheon echo-sounders were fully functional for the duration of the survey. The digital data from both echo-sounders were of generally good quality, although the 12 kHz system was prone to losing track on a steeply descending seabed. On a number of occasions during the survey, the 3.5 kHz system produced up to 50-100 msec of sub-bottom penetration in shallow water.

Magnetics

The single-channel Geometrics proton precession magnetometer was deployed along all seismic lines, except the first part of line 120-0101, and on most transits between lines. The magnetometer was not deployed during the transit from Port Hedland to the survey area, nor from the survey area to Fremantle at the end of the survey.

Because of the typically shallow water depths, the sensor head was deployed at a distance of only 150 m astern. Noise levels were acceptable throughout the survey at +/- 1-3 nT.

Gravity

The Bodenseewerk Geosystem KSS-31 marine gravity meter was fully operational throughout the survey, including the transit to Fremantle. Gravity ties were completed in Port Hedland prior to the survey, and at Fremantle at the end of the survey.

SEISMIC DATA ACQUISITION

The seismic acquisition system ran very reliably for the entire survey, as confirmed by the high average daily productivity (> 149 $km.day^{-1}$). In addition to the full gamut of system tests run at the start and end of every line, end-of-record noise tests were run at regular intervals (and more often when recording conditions were marginal) along each line. Consequently, we are confident that system noise levels were, with two minor non-critical parts of lines, well within the parameters set down for AGSO deep-seismic acquisition.

Seismic Source

The seismic source for Survey 120 was provided by two identical arrays of sleeve guns, with 16 x 2.46 litre (150 cu in) guns in each array. The guns were clustered in groups of 6, 5, 3, and 2 guns in each array, with groups of 4, 3, 2, and 1 gun from each array being fired. The gun arrays were towed outboard from the magnetometer booms at the stern, approximately 30 m from the stern, with about 20 m separation between the arrays. The gun towing depth was 10 +/- 1.5 m.

High pressure air at 1800-2000 psi was supplied by 4 Price 'Air Gun Master' compressors, typically operating at 1650 rpm. Two compressors were normally available at any time as back-up units.Wear and tear on all units was normal for a survey of this type, and few serious problems were encountered. Probably the most serious problems were related to oil filters splitting on 2 compressors, resulting in the contents being pumped out on to the compressor room floor.

Seismic Streamer

A Fjord Instruments transformerless analogue seismic streamer was used for Survey 120. The streamer was configured with 192 x 25 metre active groups, to give a total active streamer length of 4800 m. Five equally spaced water break detectors were used to monitor cable offset. Cable depth was controlled at 10 +/- 1.5 m (usually 10 +/- 0.5 m) by means of 25 Syntron RCL-3 cable levellers ('birds') spaced every 200 m along the streamer.

Extensive effort was put in at the start of the survey, and during a cable retrieval after 4 days shooting, to ensure that the streamer was optimally balanced. The initial balancing was done on the basis of bird wing angles recorded during the Browse Basin survey and the water temperatures in the Browse and offshore Canning Basins, while the second balancing was done on the basis of bird wing angles recorded during the first 4 days of Survey 120; these wing angles indicated that the streamer was generally heavy. After the second balancing exercise, bird wing angles for the remainder of Survey 120 were generally in the range of 0 to -5°. These low wing angles were reflected in the low noise levels (typically 2-4 microbars) on the bird channels. The streamer balancing effort was also reflected in the overall noise levels on the streamer which, for good channels, could be summarised as 2-4 microbars for the first 200 m of the streamer, and 0.5 - 1.5 microbars for the remainder.

The number of 'bad' channels (ie channels outside recording guidelines) was minimal throughout the survey. Channel 101 was bad for the entire survey, for reasons still not clear, while channel 92 was bad for much of the survey. Channel 159 went dead on line 120-0301 after a fish bight allowed salt water ingress; the cable section containing this channel (section 40) was replaced at the end of line 120-0301. Channels 186 and 190 were consistently bad throughout the survey, with low frequency noise on both these channels being exactly in phase, indicating a common (?shorting) problem.

Cable positioning was monitored throughout the survey by 4 Syntron compass birds mounted after channels 36, 83, 132, and 180. The compasses functioned at all times during the survey. The GPS-positioning in the 'active' tailbuoy did not function satisfactorily during the survey, and requires additional development work. Data from the compass birds indicates that strong currents were prevalent throughout the survey area. Feather angles of up to 15°, either side of the ship's track were not uncommon, and on long lines these could be correlated with the ebb and flow of the tide. Feather angles were manually logged by the bridge from the radar throughout the survey.

Seismic Amplifiers and A-to-D Converter

The AGSO-modified Phoenix analogue-to-digital converter (including IFP) and the AGSO-designed and built charge-coupled amplifiers functioned satifactorily during Survey 120. A full range of computer-driven amplifier tests was run at the start and end of every line, with the system performing fully within specification.

Seismic Acquisition System

The seismic data were acquired in demultiplexed SEG-Y format by the AGSO-designed acquisition system, built around a MicroVAX-3 computer. Data are recorded on cartridge tapes, and a wide variety of quality control measures were employed. No problems of any significance were encountered with the acquisition system during the survey.

Sonobuoys

Twelve refurbished Aquatronics sonobuoys were deployed during the survey, with only minor success. The only definite success was from Sonobuoy 10, which transmitted for 3 hours to a range of about 30 km. The data from this sonobuoy are recorded on tape, but have not yet been analysed.

REFERENCES

Brown, S.A., Boserio, I.M., Jackson, K.S., & Spence, K.W., 1984 - The geological evolution of the Canning Basin - implications for petroleum exploration. In Purcell, P.G. (ed.) *The Canning Basin, W.A.*, Proceedings of the Geological Society of Australia/Petroleum Exploration Society Australia Symposium, Perth, 1984, 85-96.

Bureau of Mineral Resources, 1989 - Australia's petroleum potential. In *Petroleum in Australia, The First Century*, Australian Petroleum Exploration Association Publication, 48-90.

Colwell, J.B., Graham, T.L., & others, 1990 - Stratigraphy of Australia's NW continental margin (Project 121-26) post-cruise report for BMR Survey 96. *Bureau of Mineral Resources Australia Record*, 1990/85 (unpub.)

Drummond, B.J., Etheridge, M.A., Davies, P.J., & Middleton, M.F., 1988 - Half-graben model for the structural evolution of the Fitzroy Trough, Canning Basin, and implications for resource exploration. *APEA Journ.*, 28(1), 76-86.

Drummond, B.J., Sexton, M.J., Barton, T.J., & Shaw, R.D., 1991 - The nature of faulting along the margins of the Fitzroy Trough, and implications for the tectonic development of the trough. *Exploration Geophysics*, 22, 111-116.

Exon, N.F., Colwell, J.B., Williamson, P.E., & Bradshaw, M.T., 1991 - Reefal complexes in Mesozoic sequences: Australia's North West Shelf region. *Proceedings of Indonesian Petroleum Association, 20th Annual Convention*, October 1991, 51-66.

Exon, N.F., von Rad, U., & von Stackelberg, U., 1982 - The geological development of the passive margins of the Exmouth Plateau off northwest Australia. *Marine Geology*, 47, 131-152.

Exon, N.F. & Ramsay, D.C., 1990 - BMR cruise 95: Triassic and Jurassic sequences of the northern Exmouth Plateau and offshore Canning Basin. *Bureau of Mineral Resources Australia Record*, 1990/57 (unpub.).

Exon, N.F. & Williamson, P.E., 1988 - Preliminary post-cruise report: Rig Seismic Research Cruises 7 & 8: sedimentary basin framework of the northern and western Exmouth Plateau. *Bureau of Mineral Resources Australia Record*, 1988/30 (unpub.).

Forman, D.J. & Wales, D.W. (Compilers), 1981 - Geological evolution of the Canning Basin, Western Australia. *Bureau of Mineral Resources Australia Bulletin*, 210.

Fullerton, L.G., Sager, W.W., & Handshumacher, D.W., 1989 - Late Jurassic - Early Cretaceous evolution of the eastern Indian Ocean adjacent to northwest Australia. *Journ. Geophys. Res.*, 94, 2937-2953.

Gradstein, F.M., Ludden, J.N., & others, 1990 - *Proceedings of the Ocean Drilling Program, Initial Reports*, 123. College Station, TX (Ocean Drilling Program). 716 pp.

Gradstein, F.M., Ludden, J.N., & others, 1992 - *Proceedings of the Ocean Drilling Program, Scientific Results*, 123. College Station, TX (Ocean Drilling Program), 846 pp.

Horstman, E.L. & Purcell, P.G., 1988 - The offshore Canning Basin - a review. In Purcell, P.G. & R.R. (Eds), *The North West Shelf, Australia,* Proceedings of Petroleum Exploration Society Australia Symposium, Perth, 1988, 253-257.

Japan National Oil Corporation, 1988 - Geological and geophysical study of the offshore Canning Basin in the Northwest Shelf of Australia. *Japan National Oil Corporation Report* (unpub.).

Japan National Oil Corporation, 1989 - Geological and geophysical study of the northeastern part of the offshore Canning Basin on the Northwest Shelf of Australia. *Japan National Oil Corporation Report* (unpub.).

Lipski, P. & Beattie, B., 1992 - A Triassic play in the eastern Bedout Sub-basin. *Oil & Gas Australia*, July, 1992, 24-26.

Lister, G.S., Etheridge, M.A., & Symonds, P.A., 1986 - Application of the detachment fault model to the formation of passive continental margins. *Geology*, 14, 246-250.

O'Brien, G.W. & Williamson, P.E., 1990 - Research cruise proposal. Vulcan Graben, Timor Sea: deep crustal structure, structural reactivation, aeromagnetics, and hydrocarbon migration. *Bureau of Mineral Resources Australia Record* 1990/91.

Passmore, V.L., 1991 - Promising hydrocarbon potential seen in Canning Basin off Australia. *Oil & Gas Journal*, Aug. 26, 1991, 65-70.

Pigram, C.J., 1992a - Deep structure of the east Malita Graben region - western Arafura and northern Timor Seas. *Bureau of Mineral Resources Australia Record,* 1992/94 (unpub.).

Pigram, C.J., 1992b - Deep structure of the Joint Development Zone and adjacent areas, Timor Sea: cruise proposal. *Bureau of Mineral Resources Australia Record,* 1992/95 (unpub.).

Poll, J., 1983 - On-shore Canning Basin - an historical perspective. *PESA Journal*, 3, 11-20.

Sager, W.W., Fullerton, L.G., Buffler, R.T., & Handschumacher, D.W., 1992 - Argo Abyssal Plain magnetic lineations revisited: implications for the onset of seafloor spreading and tectonic evolution of the eastern Indian Ocean. In Gradstein, F.M., Ludden, J.N., & others, *Proceedings ODP, Scientific Results,*123, College Station, TX (Ocean Drilling Program), 659-669.

Stagg, H.M.J., 1993 - Tectonic elements of the North West Shelf Australia, scale 1:2500000. *Australian Geological Survey Organisation*, Canberra.

Stagg, H.M.J., Brassil, F.M., & Survey 101 Shipboard Party, 1991 - Deep structure of the southern North West Shelf: post-cruise report. *Bureau of Mineral Resources Australia*

Record, 1991/79 (unpub.).

Stagg, H.M.J. & Exon, N.F., 1981 - Geology of the Scott Plateau and Rowley Terrace off northwestern Australia. *Bureau of Mineral Resources Australia Bulletin*, 213.

Stagg, H.M.J. & Leven, J., 1993 - Deep structure of the southern North West Shelf: offshore Canning Basin (SNOWS-3) pre-cruise report. *Bureau of Mineral Resources Australia Record*, 1993/48 (unpub.).

Stagg, H.M.J., & Survey 110 Shipboard Party, 1992 - Deep structure of the southern North West Shelf: SNOWS-II (Survey 110) post-cruise report. *Bureau of Mineral Resources Australia Record*, 1992/60 (unpub.).

Symonds, P.A., 1993 - Deep structure of the Browse Basin region, North West Shelf, Australia: cruise proposal. *Bureau of Mineral Resources Australia Record*, 1993/40 (unpub.).

von Rad, U., Exon, N.F., & Haq, B.U., 1992 - Rift-to-drift history of the Wombat Plateau, northwest Australia: Triassic to Tertiary Leg 122 results. In von Rad, U., Haq, B.U., & others, *Proceedings. ODP, Scientific Results*,122, College Station, TX (Ocean Drilling Program), 765-800.

von Rad, U., Haq, B.U., & others, 1992 - *Proceedings of the Ocean Drilling Program, Scientific Results*,122. College Station, TX (Ocean Drilling Program), 934 pp.

Von Rad, U., Schott, M., Exon, N.F., Mutterlose, J., Quilty, P.G., & Thurow, J.W., 1990 - Mesozoic sedimentary and volcanic rocks dredged from the northern Exmouth Plateau: petrography and microfacies. *BMR Journ. Aust. Geol. & Geophys.*, 11, 449-472.

von Stackelberg, U., Exon, N.F., von Rad, U., Quilty, P., Shafik, S., Beiersdorf, H., Seibertz, E., & Veevers, J.J., 1980 - Geology of the Exmouth and Wallaby Plateaus off northwest Australia: sampling of seismic sequences. *BMR Journ. Aust. Geol. & Geophys.*, 5, 113-140.

Willcox, J.B. & Ramsay, D.C., 1991 - Deep structure of the Bonaparte Basin region Petrel Sub-basin cruise: operational report. *Bureau of Mineral Resources Australia, Record*, 1991/45 (unpub.).

Williamson, P.E., Exon, N.F., ul Haq, B., von Rad, U., & Leg 122 Shipboard Scientific Party, 1989 - A North West Shelf Triassic reef play: results from ODP Leg 122. *APEA Journ.*, 29 (1), 328-344.

Yeates, A.N., Bradshaw, M.T., Dickins, J.M., Brakel, A.T., Exon, N.F., Langford, R.P., Mulholland, S.M., Totterdell, J.M., & Yeung, M., 1986 - The Westralian Superbasin: an Australian link with Tethys. *International Symposium on Shallow Tethys*, 2, 199-213.

APPENDIX 1
EXECUTIVE SUMMARY FROM SNOWS-I
(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 on the basin-forming structures in the region.

APPENDIX 2
EXECUTIVE SUMMARY FROM SNOWS-2
(From BMR Record 1992/60)

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-1 (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-2 (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-2 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-1 to the northeast, and also tied with the proposed SNOWS-3 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-1 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-1. 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-1. 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-1 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-1 data show crustal reflections down to at least 10 s TWT on several lines, we are confident that the SNOWS-2 data will be of at least the same standard at depth. In addition, the 2 ms sample period used on SNOWS-2 (vs 4 ms on the earlier survey) should ensure an improved shallow section.

With the acquisition and processing of the SNOWS-1 and SNOWS-2 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.

APPENDIX 3
SNOWS-3 PRE-CRUISE REPORT EXECUTIVE SUMMARY

In mid-1991, the Bureau of Mineral Resources (BMR; now the Australian Geological Survey Organisation, AGSO) 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 aims to:

- Determine the broad regional structural framework of the southern North West Shelf by examining the boundaries between the major structural elements;
- Determine the deep crustal structure of the region;
- 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
- 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 during which deep-seismic data are being recorded. The first survey, SNOWS-1 (for Southern North West Shelf; AGSO Survey 101; Stagg, Brassil, & others,1991) was concentrated in the Barrow and Dampier Sub-basins and inner Exmouth Plateau. 1654 km of good-quality seismic data tied to 20 exploration wells were recorded and processed; these data frequently show basin structure down to a depth of at least 10 s two-way time (TWT). The second survey, SNOWS-2 (AGSO Survey 110; Stagg & Survey 110 Shipboard Party, 1992), acquired more than 2800 km of high-quality deep seismic data along 13 lines in the Beagle, Dampier, and Barrow Sub-basins, and over the full width of the Exmouth Plateau in mid-1992. These lines were tied to 21 exploration wells, of which 3 were also tied during SNOWS-I, and again show reflections down to 12 s TWT.

In the second half of 1993, the Marine Geosciences and Petroleum Geology Program (MGPG) at AGSO will continue this program with the third survey in the area, to be known as SNOWS-3. The survey will be concentrated in the offshore Canning Basin, and will tie in with the SNOWS-2 survey to the southwest in the Beagle Sub-basin, and the 1993 Browse Basin survey to the northeast. The survey will tie the principal exploration wells in the region and is expected to acquire at least 3000 km of data along long regional lines; the program allows for up to 3500 km of data to be recorded. As part of the MGPG program of acquiring deep crustal transects across the margin adjacent to the North West Shelf, the opportunity will be taken to record at least one margin transect from near the coast out to Ocean Drilling Program Site 765 on the southeast Argo Abyssal Plain.

Recording parameters for the survey will include a 4800 m streamer, configured with 192 x 25 m active groups; the record length will be 16 seconds, and the sample interval 2 msec. The seismic source will be provided by tuned airgun arrays of total capacity 49 litres, fired every 50 metres to give 48-fold CDP coverage. These parameters are the same as were used on the SNOWS-1 and SNOWS-2 surveys.

Navigation for the survey will be provided by differential Global Positioning System (DGPS), using shore reference stations in Western Australia. Full differential coverage should be achieved for the entire survey and it is estimated that positional accuracy should be better than +/- 10 metres.

Proposed deep seismic profiles

The proposed lines for SNOWS-3 total 3491 km and tie 6 exploration wells, of which one was also tied on SNOWS-2, and ODP Site 765 on the Argo Abyssal Plain. A brief outline of the location and function of each line is as follows (110/ prefix lines are from SNOWS-2; BB/ prefix lines are the programmed lines for the Browse Basin deep-seismic survey):

SNOWS3-A: (555 km; ties to Lacepede-1A, lines SNOWS3-G, H, K, L, BB-F, G, H): Palaeozoic dip line, Leveque Platform - Fitzroy Trough - Broome Platform - Samphire Depression - Wallal Depression. Due to shallow water in the southwest, it will probably not be possible to continue this line on to the Lambert Shelf.

SNOWS3-B: (347 km; ties to lines SNOWS3-C, I, K, , BB-G, I): Palaeozoic dip line, Leveque Platform - Fitzroy Trough - Broome Platform.

SNOWS3-C: (150 km; ties to lines SNOWS3-B, G, H): Palaeozoic dip line, margin of Broome Platform - Samphire Depression - Wallal Depression - Lambert Shelf margin.

SNOWS3-D: (465 km; ties to lines SNOWS3-G, H, J, K, L, BB-J, 110/4, 5, 7, 8): Mesozoic strike and tie line from southwest extension of Browse Basin - Rowley Sub-basin - northern flank of Bedout High - northern Beagle Sub-basin. This line is the remaining link in the major strike line that extends for the length of the North West Shelf.

SNOWS3-E: (138 km; ties to ODP Site 765, lines SNOWS3-H, K): Short strike line on oceanic crust in southeast Argo Abyssal Plain between magnetic anomalies M25 and M26. Although of low priority from the exploration viewpoint, this line will provide deep crustal data across a major oceanic fracture zone.

SNOWS3-F: (159 km; ties to Keraudren-1, Lagrange-1, lines SNOWS3-G, H): Mesozoic ?dip line, Lambert Shelf - Bedout Sub-basin - Bedout High.

SNOWS3-G: (343 km; ties to Minilya-1, Lagrange-1, lines SNOWS3-A, C, D, F, H, K, 110/4, 5, 6, 8): Beagle Sub-basin - Bedout High - Broome Platform. This line is designed to provide an orthogonal crossing of the major N-S trending structures that comprise the ?transform dislocation between the northern Carnarvon Basin (Beagle Sub-basin) and Rowley Sub-basin.

SNOWS3-H: (480 km; ties to Lagrange-1, ODP Site 765, lines SNOWS3-A, C, D, E, F, G): Prime offshore Canning Basin transect, Samphire/Wallal Depressions - Bedout Sub-basin - Bedout High - Rowley Sub-basin - Argo Abyssal Plain.

SNOWS3-I, J: (combined length 222 km; ties to lines SNOWS3-B, D): Mesozoic dip line, outer Broome Platform - Rowley Sub-basin.

SNOWS3-K: (388 km; ties to East Mermaid-1, lines SNOWS3-A, B, D, E, G): Mesozoic dip line, Broome Platform - Rowley Sub-basin - Argo Abyssal Plain.

SNOWS3-L: (244 km; ties to Wamac-1, lines SNOWS3-A, B, D): Palaeozoic strike and Mesozoic dip line, Fitzroy Trough - Rowley Sub-basin.

APPENDIX 4
WELLS TIED ON SNOWS-3

Well locations are specified in WGS84.

Well: East Mermaid-1
Basin Element: Rowley Sub-basin
Location: 17° 09' 56.0" S 119° 49' 25.8" E
Operator: Shell Development (Australia) Pty Ltd
TD Date: 8 Oct 1973
TD Drilled: 4067 m
Water Depth: 399 m
Status: Dry
Shows: Dry
Objective: Anticline
Oldest Sequence Drilled: Lower Jurassic
Summary: East Mermaid-1 penetrated a section ranging in age from Recent to Lower Jurassic. Due to poor hole conditions and technical difficulties the well was suspended before it penetrated the 'IJ' seismic horizon. The absence of hydrocarbons in the well is attributed to the lack of source rocks within migration distance of the well.

Well: Keraudren-1
Basin Element: Bedout Sub-basin
Location: 18° 54' 22.4" S 119° 09' 19.9" E
Operator: Hematite Petroleum
TD Date: 12 Dec 1973
TD Drilled: 3844 m
Water Depth: 95 m
Status: Dry
Shows: Fluorescence, minor gas
Objective: Test of relatively complete Mesozoic-Tertiary section, overlying basement of inferred Permian rocks.
Oldest Sequence Drilled: Middle Triassic
Summary: Keraudren-1 penetrated a section ranging in age from Lower Tertiary or younger to early Middle Triassic. Wireline log interpretation indicates that the porous sandstones in the well are all 100% water-saturated. No significant hydrocarbon shows were recorded. Disappointing results and mechanical difficulties led to the decision to abandon the well prior to the planned total depth of 4600 m.

Well: Lagrange-1
Basin Element: Bedout High
Location: 18° 16' 22.5" S 119° 18' 11.9" E
Operator: BP Petroleum Devopment Australia Pty Ltd
TD Date: 4 Jan 1983
TD Drilled: 3260 m
Water Depth: 146.9 m
Status: Dry
Shows: Dry
Objective: Primary objective was to test sandstones of the Upper Triassic Upper Keraudren Formation. Secondary targets were the Lower to Middle Jurassic Depuch Formation and speculative Palaeozoic sediments below the Top Permian unconformity.
Oldest Sequence Drilled: Upper Permian
Summary: Neither the Upper Keraudren Formation objective nor the Depuch Formation contained hydrocarbons. The Palaeozoic target was not reached due to an unexpected thick volcanic section.

Well: Minilya-1
Basin Element: Bedout High
Location: 18° 19' 23.9" S 118° 44' 01.4" E
Operator: Woodside/Burmah Oil NL
TD Date: 30 Aug 1974
TD Drilled: 2400 m
Water Depth: 146 m
Status: Dry
Shows: Trace gas
Objective: Fault-controlled positive feature near the Bedout-Beagle hinge zone.
Oldest Sequence Drilled: Jurassic
Summary: Minilya-1 penetrated a sedimentary section ranging in age from Cainozoic to Jurassic (Bajocian). Only traces of gas were recorded from the Cretaceous and Jurassic sections and all porous intervals were found to be water-saturated. The Jurassic sandstones which were the principal objective showed variable but mainly good porosity, with the average porosity being 26%.

Well: Phoenix-1
Basin Element: Bedout High
Location: 18° 38' 02.2" S 118° 47' 12.1" E
Operator: BP Petroleum Development Australia Pty Ltd
TD Date: 30 May 1980
TD Drilled: 4880 m
Water Depth: 139 m
Status: Dry
Shows: Minor gas
Objective: NE-SW trending anticline intersected by NNE-SSW trending faults. Primary objective was Middle to Late Triassic sandstone; secondary objective was late Middle Jurassic sandstone.
Oldest Sequence Drilled: Middle Triassic
Summary: Thick sandstones below 4113 m yielded significant gas shows; however, a core confirmed that the reservoir quality was poor and the lack of liquid hydrocarbons.Further gas-bearing sandstones of Middle Triassic age were encountered and the well was deepened beyond the originally programmed TD of 4450 m. Drilling continued to the TD through a sequence of Middle Triassic mudstones, siltstones, and occasional thin, intra-formationally sealed, low-porosity, gas-bearing sandstones. Phoenix-1 was suspended without testing, for safety reasons.

Well: Wamac-1
Basin Element: Fitzroy Trough
Location: 17° 14' 20.9" S 121° 29' 34.2 E
Operator: Amax Petroleum
TD Date:8 Oct 1973
TD Drilled: 2764 m
Water Depth: 76 m
Status: Dry
Shows: Fluorescence, minor gas
Objective: Test of the sedimentary section on the Wamac structure (?fault block).
Oldest Sequence Drilled: Upper Palaeozoic
Summary: No hydrocarbon shows were recorded in the Mesozoic section due mostly to the lack of closed structure in the Mesozoic, and possibly also in the Upper Palaeozoic. Low porosity and negligible permeability may have been responsible for the lack of hydrocarbon indications in the Palaeozoic.

Well: ODP Site 765
Basin Element: Argo Abyssal Plain
Location: 15° 58' 32.4" S 117° 34' 29.4" E
Operator: Ocean Drilling Program
TD Date: September/October 1988 (multiple holes)
TD Drilled: 6919.2 m
Water Depth: 5717 m (average)
Objective: Elucidate palaeoceanography, sedimentology, and magmatic processes related to the rifting of the early Indian Ocean; constrain rift to drift history of one of the world's oldest oceanic basins; improve the Mesozoic time scale; provide a geochemical reference section of old oceanic crust.
Summary: The principal rsult from Site 765 that is relevant to the SNOWS-3 study is that the age of onset of spreading in the Argo Abyssal Plain is now estimated to be shortly prior to anomaly M26 time (163 Ma), approximately at the Callovian-Oxfordian boundary.

APPENDIX 5
WAY POINTS FOR SNOWS-3

Positions quoted are for first and last production shot-points and for intermediate way points. SOL means start-of-line; EOL means end-of-line.

Line	Way Pt	Latitude	Longitude	Comments
120-0101	1	19 18.498	120 06.612	SOL
120-0101	2	18 16.375	119 18.198	Lagrange-1
120-0101	3	17 41.794	118 48.210	EOL
120-0102	1	17 43.791	118 49.953	SOL
120-0102	2	17 39.458	118 46.197	course change
120-0102	3	15 58.542	117 34.488	ODP Site 765
120-0102	4	15 49.302	117 27.718	EOL
120-0201	1	16 02.269	117 25.417	SOL
120-0201	2	15 58.542	117 34.488	ODP Site 765
120-0201	3	15 29.674	118 40.864	EOL
120-0301	1	15 25.169	118 30.837	SOL
120-0301	2	16 58.704	119 43.389	EOL
120-0302	1	16 55.563	119 41.100	SOL
120-0302	2	16 58.000	119 43.000	course change
120-0302	3	17 09.933	119 49.430	East Mermaid-1
120-0302	4	18 13.689	120 38.696	EOL
120-0401	1	18 08.829	120 49.620	SOL
120-0401	2	18 12.310	120 07.431	EOL
120-0402	1	18 11.988	120 11.327	SOL
120-0402	2	18 13.452	119 53.660	EOL
120-0403	1	18 13.201	119 56.654	SOL
120-0403	2	18 15.191	119 32.468	EOL
120-0404	1	18 14.961	119 35.298	SOL
120-0404	2	18 16.375	119 18.198	Lagrange-1
120-0404	3	18 16.716	119 14.336	EOL
120-0405	1	18 16.165	119 20.550	SOL
120-0405	2	18 19.398	118 44.023	Minilya-1
120-0405	3	18 23.358	117 31.520	EOL

Line	Way Pt	Latitude	Longitude	Comments
120-0501	1	18 05.929	119 20.735	SOL
120-0501	2	18 16.375	119 18.198	Lagrange-1
120-0501	3	18 54.373	119 09.332	Keraudren-1
120-0501	4	19 31.605	118 59.400	EOL
120-0601	1	19 29.193	119 26.670	SOL
120-0601	2	18 10.537	119 54.778	EOL
120-0701	1	18 30.247	117 28.956	SOL
120-0701	2	16 46.913	119 38.932	EOL
120-0702	1	16 50.520	119 34.411	SOL
120-0702	2	15 50.000	120 50.000	course change
120-0702	3	15 44.068	121 01.870	EOL
120-0801	1	15 38.188	122 02.178	SOL
120-0801	2	15 50.312	121 49.742	course change
120-0801	3	17 03.611	120 50.759	EOL
120-0802	1	16 59.867	120 53.774	SOL
120-0802	2	18 16.816	119 54.465	EOL
120-0901	1	18 00.788	120 13.180	SOL
120-0901	2	17 31.607	119 16.902	course change
120-0901	3	16 40.909	118 36.286	EOL
120-1001	1	16 47.201	118 30.948	SOL
120-1001	2	16 20.293	119 44.948	EOL
120-1101	1	16 18.240	119 36.695	SOL
120-1101	2	17 14.348	121 29.570	Wamac-1
120-1101	3	17 20.309	121 42.661	EOL
120-1201	1	16 07.586	121 49.329	SOL
120-1201	2	18 12.000	120 35.000	course change
120-1201	3	18 30.454	120 23.767	EOL
120-1202	1	18 27.043	120.25.845	SOL
120-1202	2	19 35.391	119 44.088	EOL
120-1301	1	19 24.446	119 59.656	SOL
120-1301	2	19 02.740	118 50.000	course change
120-1301	3	19 00.925	118 42.990	EOL
120-1401	1	18 42.905	118 59.048	SOL
120-1401	2	18 38.036	118 47.202	Phoenix-1
120-1401	3	18 05.400	117 30.800	course change

Line	Way Pt	Latitude	Longitude	Comments
120-1401	4	17 18.052	116 09.923	EOL

APPENDIX 6
SEISMIC TAPE LISTING FOR SNOWS-3

Line	First Tape	Last Tape	First SP	Last SP	Start time	Stop time
120-0101	1	72	102	4781	192.0609	193.0703
120-0102	73	154	5691	10956	193.1312	194.1749
120-0201	155	203	103	3254	194.2240	195.1540
120-0301	204	273	102	4582	195.2118	196.2128
120-0302	274	330	5588	9265	197.2140	198.1931
120-0401	331	356	102	1751	199.0154	199.1109
120-0402	357	370	2851	3696	199.1655	199.2149
120-0403	371	388	4801	5964	200.1157	200.1825
120-0404	389	401	7002	7813	201.1116	201.1639
120-0501	402	454	103	3483	202.0128	202.2053
120-0601	455	504	102	3335	203.0156	203.1946
120-0405	505	565	8602	12522	204.0443	205.0144
120-0701	566	660	102	6247	205.0603	206.1314
120-0702	661	723	103	4173	206.1819	207.1459
120-0801	724	789	101	4353	208.0916	209.0745
120-0802	790	847	5355	9073	209.1232	210.0705
120-0901	848	921	102	4847	210.1357	211.1344
120-1001	922	967	102	3065	211.1747	212.0838
120-1101	968	1046	102	5219	212.1443	213.1928
120-1201	1047	1141	102	6276	214.1602	216.0016
120-1202	1142	1188	7279	10323	216.0530	216.2059

Line	First Tape	Last Tape	First SP	Last SP	Start time	Stop time
120-1301	1189	1234	102	3037	217.0234	217.1803
120-1401	1235	1340	103	6993	217.2353	219.1125

APPENDIX 7
SEISMIC ACQUISITION PARAMETERS

Seismic Cable Configuration

active streamer length	4800 m
group length	25 m
no. channels	192

Seismic Source

Airgun capacity	49.2 litres (3000 cu in)
Airgun pressure	1800 psi (normal) 1600 psi (minimum)
Shot interval	50 m
Shot rate	19.4 s @ 5 kn 21.6 s @ 4.5 kn

Fold

Standard	4800%

Recording Parameters

Record length	16 s
Sample interval	2 ms

APPENDIX 8
EQUIPMENT UTILISED ON SNOWS-II

Seismic System

Streamer	4800 metre Fjord Instruments programmable analogue seismic streamer, configured as 192 x 25 m groups, with 40 hydrophones per group.
Cable levellers	25 Syntron RCL-3 depth controllers with depth output; controllers spaced every 200 m.
Cable compasses	4 Syntron RCU-831 compasses equi-spaced along the streamer.
Active tailbuoy	Magnavox MX100 GPS receiver, modem, and radio transmitter.
Source arrays	32 Haliburton 150 cu in SG-2 sleeve guns, configured as 2 x 16-gun arrays; intra-gun spacing 0.5 m; inter-group spacing of 2.5 m; each array tuned by firing 10 groups in groups of 4, 3, 2, and 1.
Gun timing	AGSO 32 channel gun controller and 32 channel gun firing box.
Source sensors	8 Teledyne model 29330 gun signature hydrophones, with 1 hydrophone per gun group.
Depth sensors	8 Teledyne model 29360 gun depth sensors, with 1 sensor per gun group; 8 Teledyne model 28951 Digital Depth Indicator modules.
Cable loss alarms	2 cable strain gauges; 1 PRESTEL pressure release satellite transmitter for emergency location, located near the centre of the streamer; ARGOS PTT located on the tailbuoy.
Compressed air	1600-2000 psi compressed air supplied by 6 Price 300 SCFM compressors.
Recording system	AGSO-designed seismic acquisition system, MUSIC, running on a MicroVax-3 computer; AGSO 208-channel amplifier system; AGSO-modified Phoenix A-D converter; data format 12-bit mantissa and 4-bit exponent; 2 Fujitsu 3480 cartridge tape drives; all seismic data were recorded in an AGSO implementation of the SEG-Y format.
Playback system	AGSO-designed seismic playback system, running on a MicroVax-2 computer. Playback facilities include: shot replay, trace statistics, header and trace data dumps.

Non-Seismic Geophysical Data

Data acquisition system	AGSO-designed data acquisition system running on a Hewlett

	Packard 2117 F-Series computer system; data were recorded on 1600 BPI 9-track magnetic tape.
Bathymetry	One Raytheon 12 kHz deep-sea echo-sounder, with 2 kW output. One Raytheon sub-bottom profiler, with 2 kW output; output frequency swept from 2.5 - 4.5 kHz.
Gravity	Bodenseeqerk Geosystem KSS-31 marine gravity meter.
Magnetic	Geometrics G801/803 proton precession magnetometer.

Navigation Systems

Differential GPS	2 Trimble 4000DL GPS receivers; 2 satellite receiver dishes; 2 satellite data demodulators; 2 Compaq 386 PCs, running Trimble differential GPS software.
Stand-alone GPS	One Magnavox MX100 GPS receiver; one remote Magnavox MX100 receiver located on the seismic streamer tailbuoy.
Dead-reckoning 1	Magnavox MX610D sonar doppler dual axis ship velocity sensor; Sperry Mk 37 gyro-compass.
Dead-reckoning 2	Raytheon DSN-450 dual axis sonar doppler ship velocity sensor; Sperry Mk 37 gyro-compass.
Auxiliary equipment	Two GED digital clocks, used as the master time source; one AGSO gyro-log interface box; one AGSO digital multiplexer; one Ben paddle log ship velocity sensor.
DAS playback & processing	AGSO-designed playback and processing system, running on the DAS system. Playback/processing facilities include data replay, editing, and plotting.

APPENDIX 9
ORGANISATIONS CONSULTED DURING PROGRAM PLANNING

The following organisations were consulted during planning of the SNOWS-3 program. We are grateful to those organisations who responded.

Exploration Companies

Amoco Production Company (Australia and USA)
Ampol Exploration Ltd
Apache International
BHP Petroleum Pty Ltd
BP Developments Australia Ltd
Bridge Oil Ltd
Command Petroleum Holdings Ltd
Conoco Australia Ltd
Conoco Inc
Crusader Ltd
Esso Australia Ltd
Hadson Energy Ltd
Hardy Petroleum Ltd
Idemitsu Oil Development Co Ltd
Kufpec Australia Pty Ltd
Marathon Petroleum Australia Ltd
MIM Petroleum Exploration Ltd
Mobil Exploration & Producing Australia Pty Ltd
Norcen International Ltd
OPIC Australia Pty Ltd
Phillips Australian Oil Company
Sagasco Resources Ltd
Santos Ltd
Shell Australia Ltd
West Australian Petroleum Pty Ltd
Western Mining Corporation
Woodside Offshore Petroleum Pty Ltd

Government Bodies

Bureau of Resource Sciences
Department of Conservation & Land Management, WA
Petroleum Division, Department of Mines, WA
Petroleum Division, Department of Primary Industries & Energy

APPENDIX 10
SURVEY 120 - CREW LIST

Scientific Crew

H. Stagg	Cruise Leader / Ship Manager
E. Chudyk	Quality Control / Systems Expert
M. Alcock	Quality Control / Systems Expert
D. Cathro	Quality Control / Systems Expert
L. Miller	Electronics Technician
W. Wierzbicki	Electronics Technician
J. Bedford	Science Technician
T. McNamara	Science Technician
H. Reynolds	Science Technician
R. Robson	Science Technician
M. James	Mechanical Technician
A. Hogan	Mechanical Technician
S. Milnes	Mechanical Technician
R. Schuler	Mechanical Technician
D. Sewter	Mechanical Technician
D. Mihut	PhD student, University of Sydney

Crew of the R/V *Rig Seismic*

A. Codrington	Master
M. Gusterson	Mate
D. Watson	Second Mate
B. Troke	Chief Engineer
R. Heaton	Second Engineer
W. Hanson	Electrical Engineer
D. Brown	Integrated Rating
J. Fraser	Integrated Rating
M. Pitcher	Integrated Rating
R. Willis	Integrated Rating
H. Dekker	Chef
W. Leary	Assistant Chef
G. Lilja	Seaman / Steward
S. Sparrow	Seaman / Steward

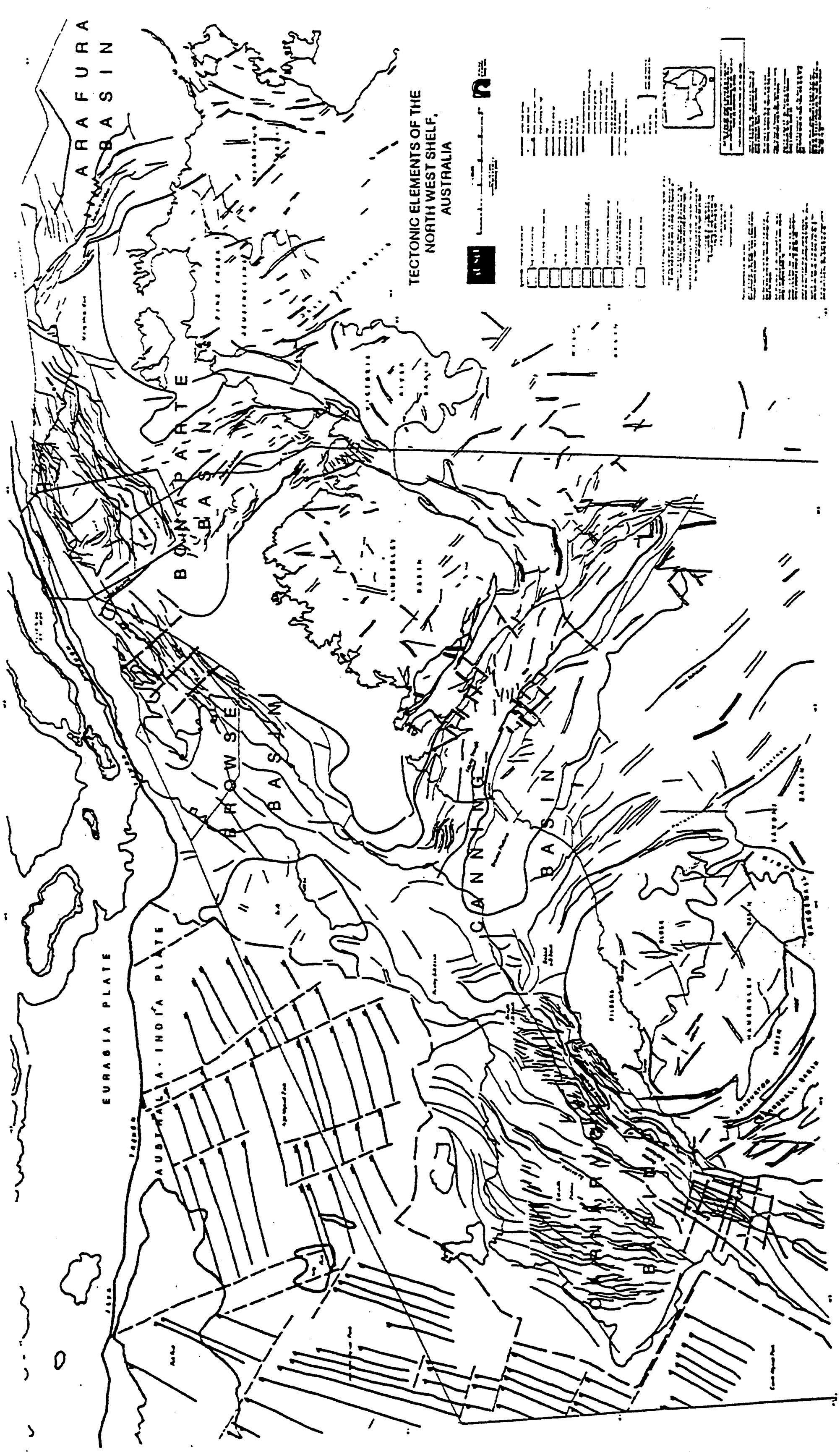


Figure 1: Regional geological setting of the North West Shelf (Stagg, 1993).

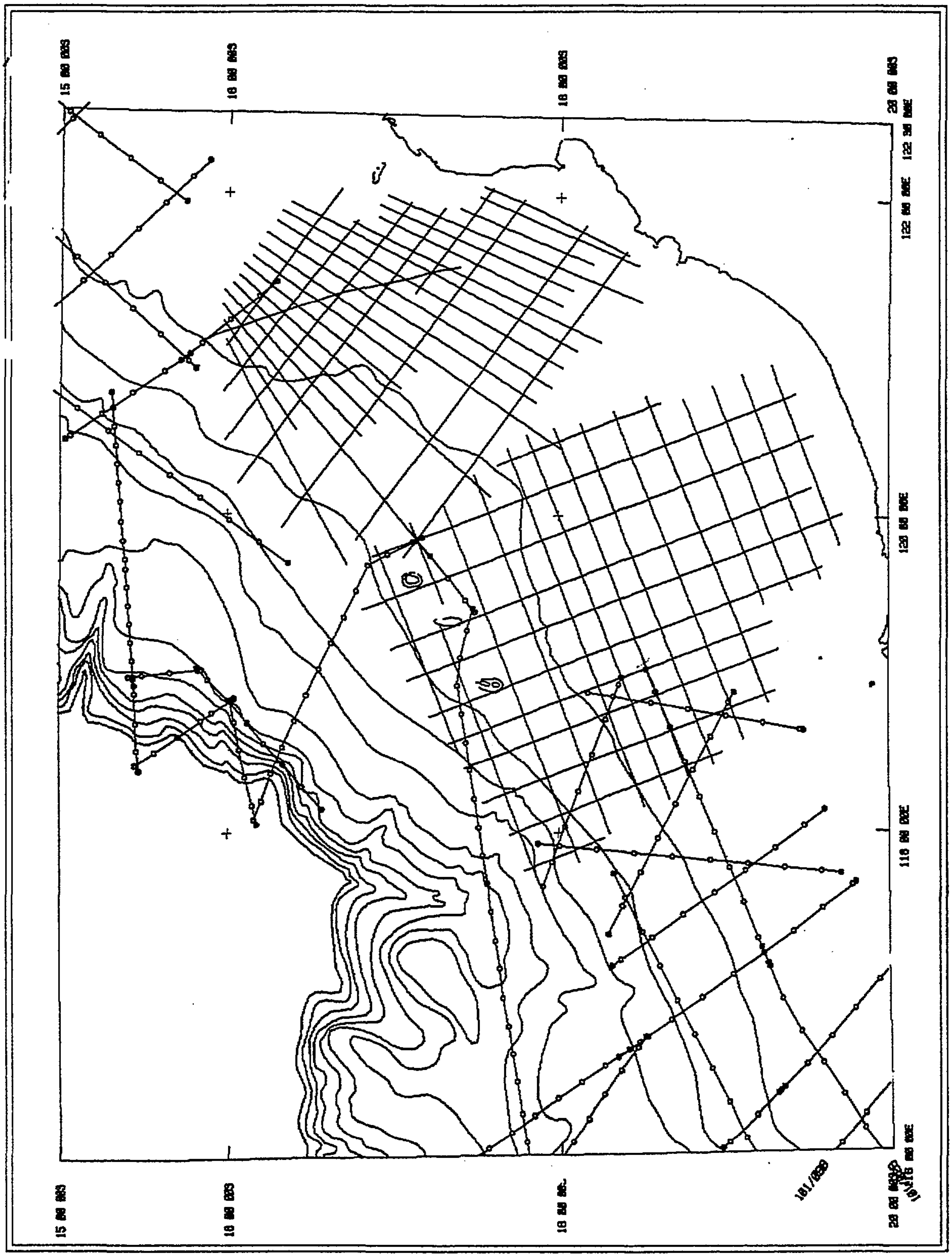


Figure 2: Regional seismic lines in the offshore Canning Basin. Lines shown with shot-point symbols in the southwest are AGSO Survey 110 (SNOWS-2); lines with shot-point symbols north of 18^{o} S are AGSO Survey 95 ('Triassic Reefs' project); remaining lines (no shot-point symbols) are Japan National Oil Corporation 1987 and 1988 surveys.

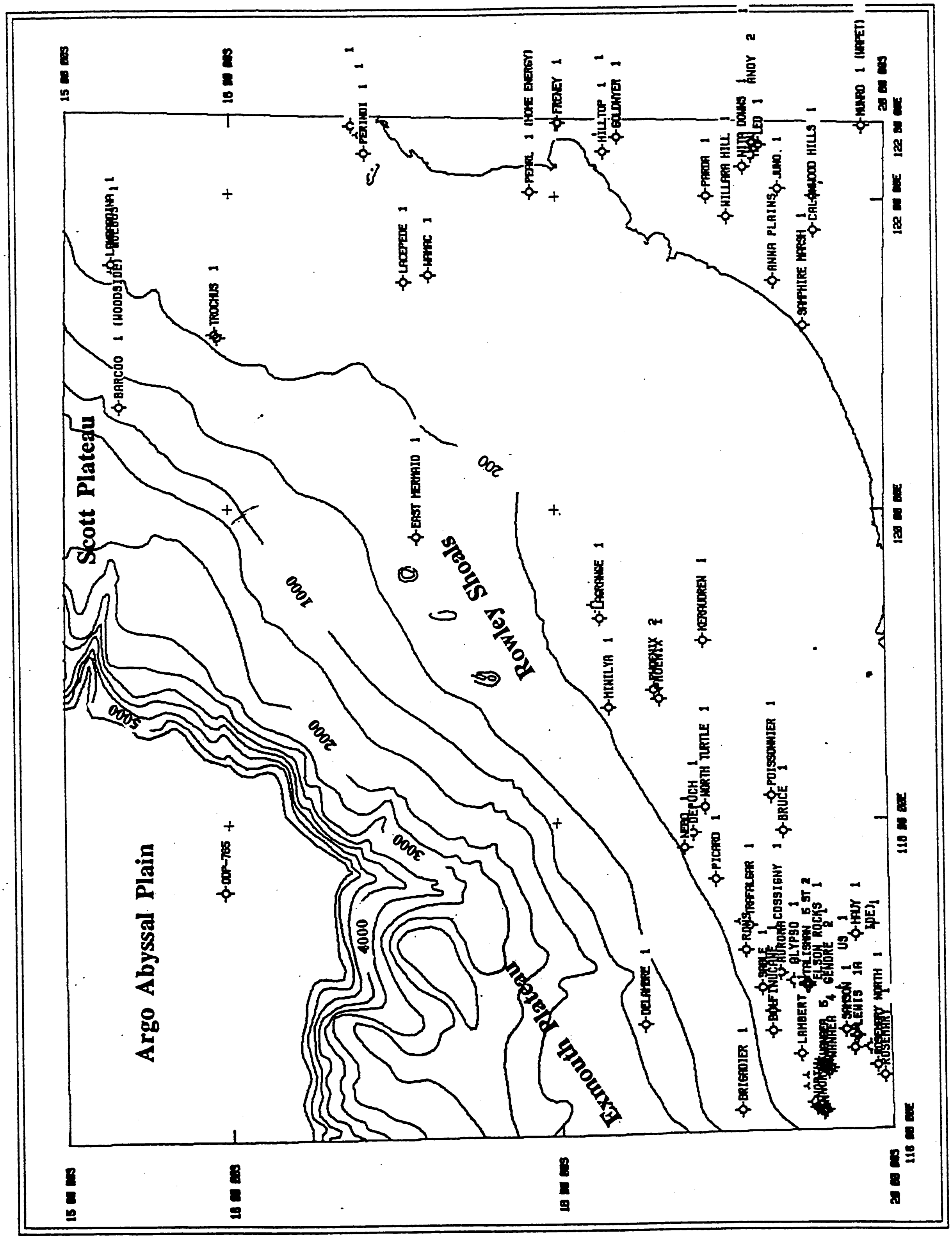


Figure 3: Bathymetry and wells in the offshore Canning Basin. Shallowest bathymetric contour is 200 m; remaining bathymetric contours at a 500 m interval.

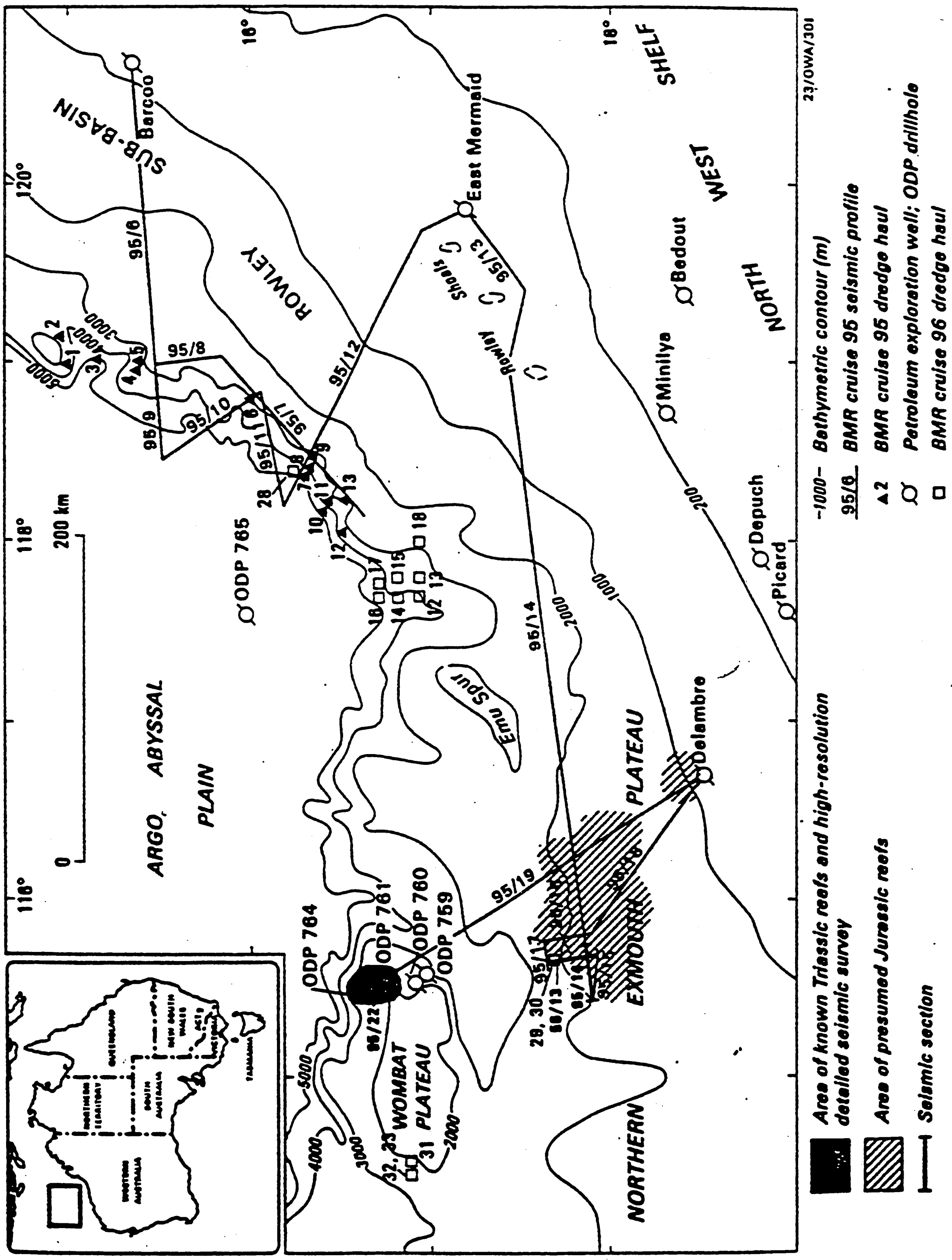


Figure 4: Dredge and ODP sites on the northern Exmouth Plateau and outer margin of the Rowley Sub-basin (Exon & others, 1991).

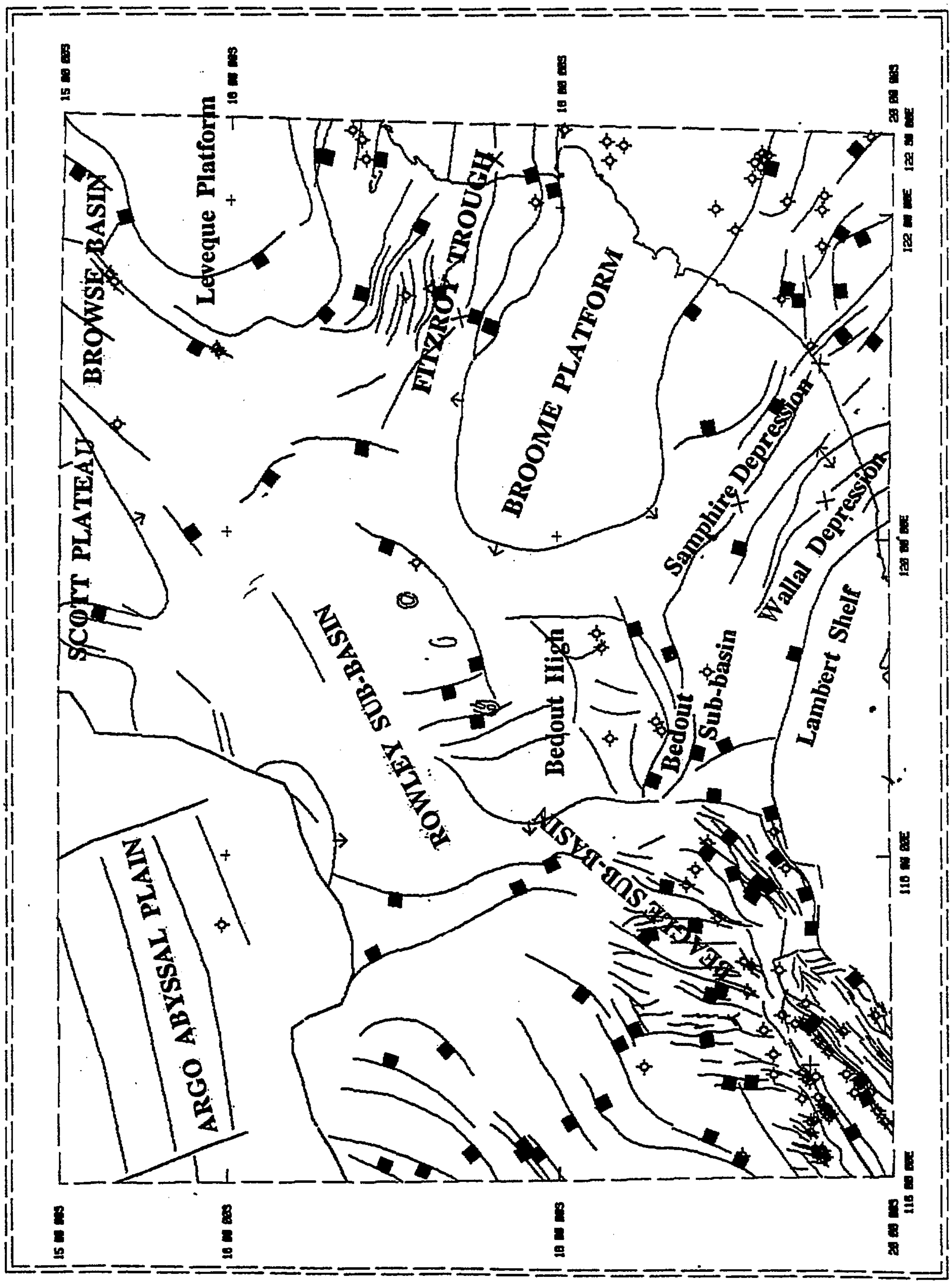
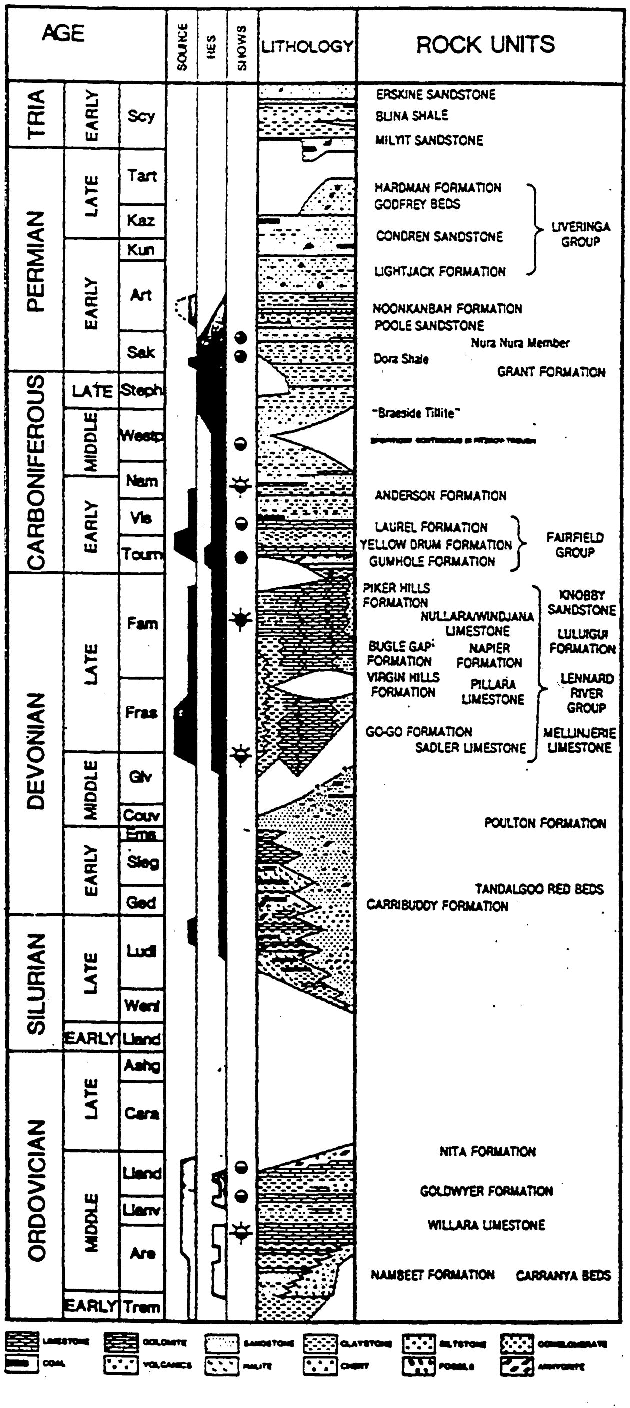


Figure 5: Tectonic elements of the offshore Canning Basin



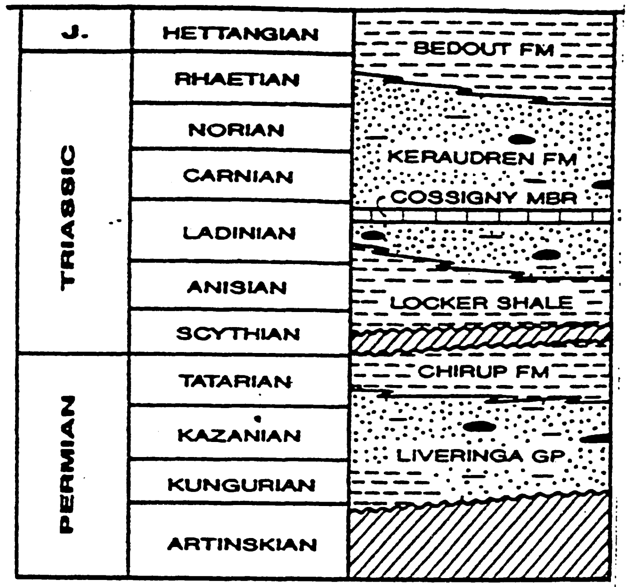


Figure 6: Stratigraphic table for the onshore Canning Basin (left; after Poll, 1983) and Bedout Sub-basin (right; after Lipski & Beattie, 1992).

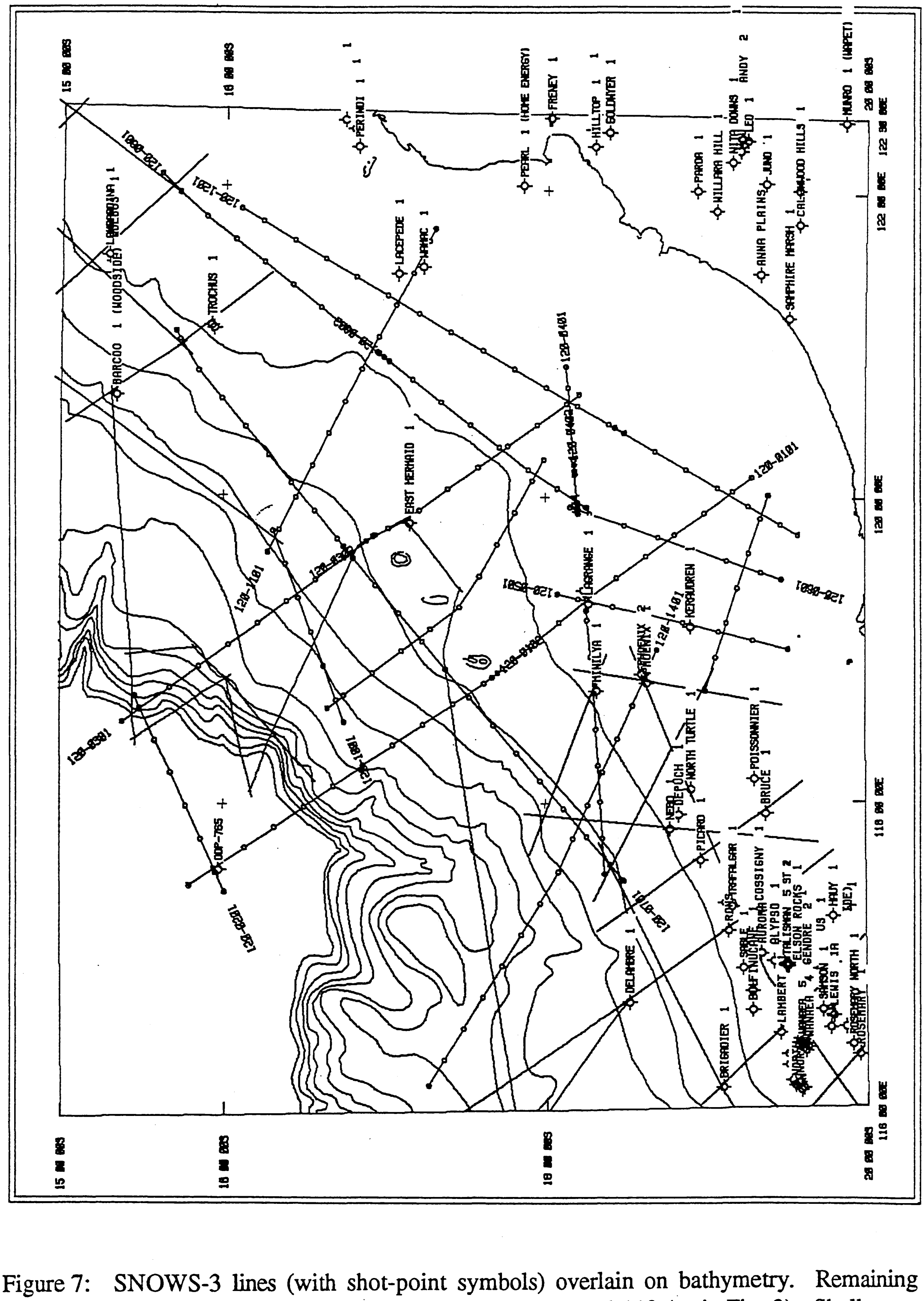


Figure 7: SNOWS-3 lines (with shot-point symbols) overlain on bathymetry. Remaining lines (no shot-point symbols) are AGSO surveys 95, 110, and 119 (as in Fig. 2). Shallowest bathymetric contour is 200 m; remaining bathymetric contours at a 500 m interval.

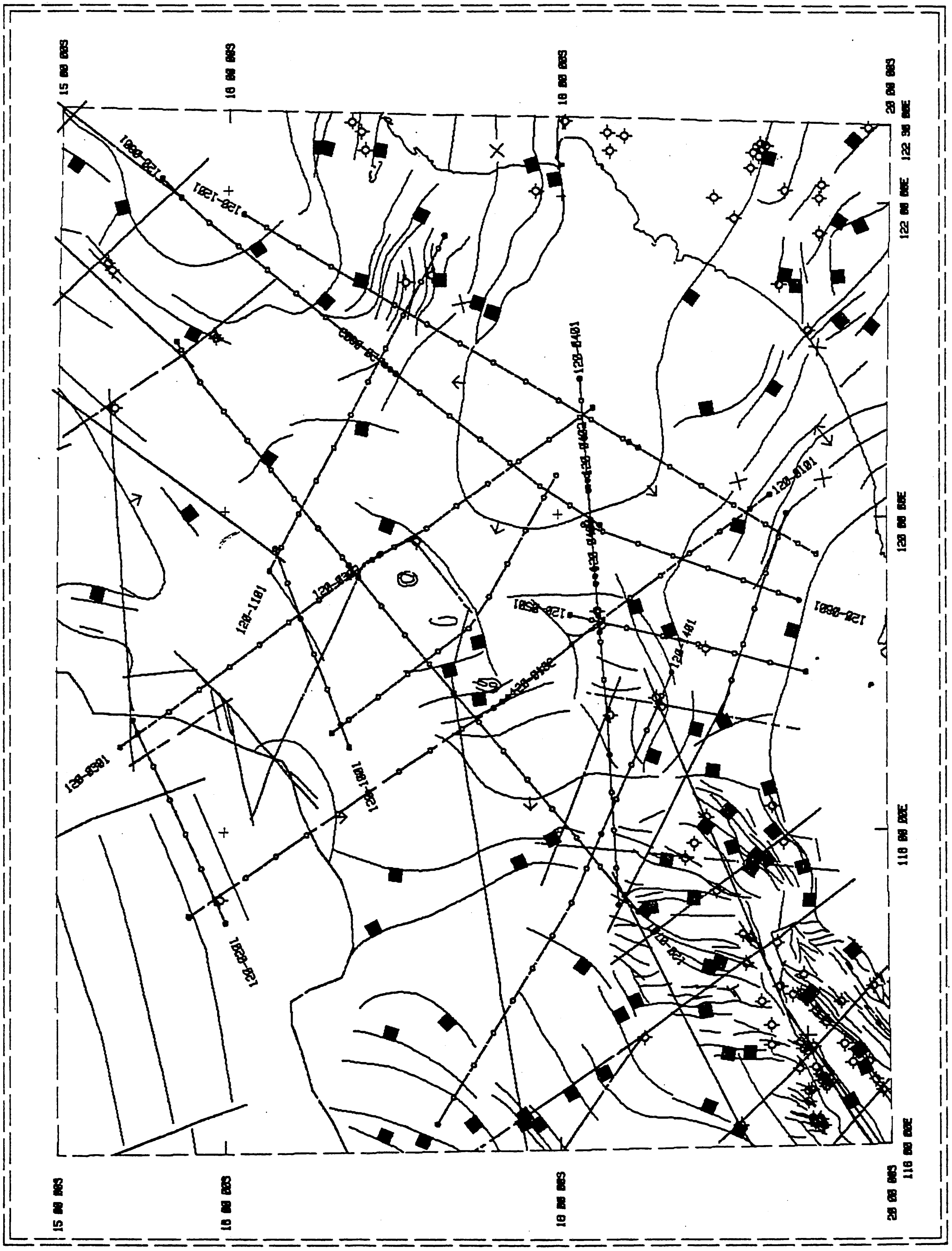


Figure 8: SNOWS-3 lines (with shot-point symbols) overlain on tectonic elements. Remaining lines (no shot-point symbols) are AGSO surveys 95, 110, and 119 (as in Fig. 2). Shallowest bathymetric contour is 200 m; remaining bathymetric contours at a 500 m interval.