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DEEP STRUCTURE OF THE SOUTHERN NORTH WEST SHELF: SNOWS-II CRUISE PROPOSAL

Project 121.17

H.M.J. Stagg

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EXECUTIVE SUMMARY

While the southern North West Shelf has been one of Australia's most heavily explored areas for hydrocarbons in the past three decades, relatively little is known of its deep structure and the controlling effect this deep structure has on the occurrence of hydrocarbons. BMR Project 121.17 (Regional Structural Framework of the Southern North West Shelf and Offshore Canning Basin) seeks to rectify this shortcoming and has the following aims:

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

* To determine the deep crustal structure of the region;

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

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

To address these points, a program of three cruises of the RV *Rig Seismic* has been developed, during which deep seismic data are to be recorded (SNOWS-I to SNOWS-III). The first cruise, SNOWS-I, completed in June 1991, acquired 1654 km of seismic data along 10 widely spaced lines tied to 20 exploration wells in the Barrow, Dampier, and Exmouth Sub-basins, and on the inner flank of the Exmouth Plateau. The data were processed by March 1992, and show basin structure down to a depth of at least 10 s TWT (>20 km); these are the first data recorded on the southern North West Shelf that show such deep structures.

SNOWS-II, proposed here, is intended to acquire up to 2765 km of deep seismic data tied to 21 exploration wells (of which 4 were also tied on SNOWS-I). As with SNOWS-I, the data recording parameters will include a 4800 m streamer (192 x 25 m groups), 49 litre sleeve gun arrays, 16 second records, and 48-fold coverage. Four elements in the SNOWS-II program are proposed, as follows:

1) **Beagle Sub-basin:** 1184 km along 7 lines tied to 8 wells designed to cross the principal structural trends. These lines extend northeast on to the Bedout High, southeast into the Bedout Sub-basin, south to the Lambert Shelf, and north to the inner Exmouth Plateau. The lines also tie into the SNOWS-I grid in the Dampier Sub-basin to the west.

2) **Outer Basin Strike Line:** 448 km along 1 line tied to 3 wells (of which 1 well is also tied on Stage 3) from offshore of the Beagle Sub-basin, outside the Dampier Sub-basin, to the Kangaroo Syncline.

3) **Barrow and Dampier Sub-basins and inner Exmouth Plateau:** 717 km along 4 lines tying 9 wells (of which 1 well is also tied on Stage 2) that provide fill-in dip line coverage in the Barrow and Dampier Sub-basins and on the inner flank of the Exmouth Plateau.

4) **Exmouth Plateau:** 414 km along 2 lines tying 2 wells that provide a short strike line along the axis of the Exmouth Plateau Arch, and complete the North West Shelf to Gascoyne Abyssal Plain transect that was commenced on SNOWS-I.

The program proposed here assumes a 30 day cruiss. While the total of 2765 km of seismic data programmed for SNOWS-II is quite high for regional deep crustal work, in the event of good weather conditions and high equipment reliability, it should be possible to finish the program in the time available. However, in the event of adverse weather or serious equipment problems, or delays due to extrenal operational problems, it should be possible to complete at least Stages 1 and 2, and the most important parts of Stage 3.

PROJECT BACKGROUND

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

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

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

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

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

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

3) Northern Carnarvon Basin (Exmouth-Barrow-Dampier-Beagle Sub-basins and Exmouth

Plateau; SNOWS-I) - 1654 km of deep seismic data - completed May-June, 1991 (Stagg & others, 1991; Appendix 1).

4) Northern Carnarvon Basin (Beagle-Dampier-Barrow Sub-basins; Exmouth Plateau); 2000+ km of deep seismic data scheduled for acquisition in mid-1992.

5) Timor Sea - 2000+ km of deep seismic data linking the two Bonaparte Basin surveys (1 and 2, above) with the planned deep seismic program in the Browse Basin (6, below).

6) Browse Basin - approximately 2000-2500 km of deep and conventional seismic data - scheduled for late 1992 / early 1993.

7) Offshore Canning Basin - 2000+ km of deep seismic data - tentatively scheduled for mid- to late-1993.

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

EXPLORATION HISTORY

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

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

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

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

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

By 1992, about 150000 km of conventional 2-D reflection seismic data have been recorded, and over 250 wells have been drilled on the southern North West Shelf (Fig. 4); the line-km of 3-D seismic data is increasing exponentially. Of these data, less than 2000 km is conventionally recorded deep seismic data (record lengths > 10 seconds). These deep data consist of 2 lines in the central Dampier Sub-basin, recorded by Geophysical Services International (GSI) in 1986, and the 10 lines recorded by BMR during SNOWS-I in mid-1991 (Fig. 5). In addition, a single two-ship wide aperture CDP seismic line was recorded in 1986 by BMR and the Lamont-Doherty Geological Observatory from the Dampier Sub-basin, west-northwestwards across the Exmouth Plateau, to the Gascoyne Abyssal Plain (Williamson & others, 1990). Conventional multichannel seismic lines were recorded by BMR across the western and northern margins of the Exmouth Plateau by Williamson & Falvey (1988), Exon & Williamson (1988), and Exon & ramsay (1990). These surveys were related to the drilling of six continuously cored Ocean Drilling Program Sites on the Exmouth Plateau (von Rad, Haq, & others, 1992).

STRUCTURE

The gross structure of the North West Shelf comprises a series of generally NE-SW trending rifted Mesozoic depocentres overlying Palaeozoic NW-SE trending basins that may have constituted failed arms of a previous rift valley (Veevers, 1988). Within the northern Carnarvon Basin, the four principal shelf and upper slope depocentres - the Exmouth, Barrow, Dampier, and Beagle Sub-basins (Fig. 6) - accumulated most of their sedimentary fill in the Triassic and Jurassic, before the rift system aborted with the separation of Australia from (?)Greater India along a parallel rift system along the northwest and northern margins of the Exmouth Plateau. Although the four sub-basins have frequently been treated as separate entities in the literature, this is largely due to the concentration of individual exploration companies in one or other of the sub-basins. In fact, the sub-basins are very closely related, particularly in the case of the Barrow and Dampier Sub-basins, and any analysis of the basin-forming mechanisms of the area should consider all of them together.

BOUNDARIES BETWEEN SUB-BASINS

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

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

INTERNAL SUB-BASIN STRUCTURES (Figs 7 & 8)

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

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

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

The seaward boundary of the Barrow-Dampier rift is formed by the structurally high Rankin Platform and its associated structures, the Kendrew Trough (or Kendrew Terrace) and positive Madeleine Trend. The Rankin Trend itself is the southeastern border zone of the Exmouth Plateau/Rankin Platform megacrustal block (Woodside, 1988). The Rankin Platform has the strongest gravity signature on the southern North West Shelf (Fig. 9) and is obviously a fundamental structure of the rift system, as well as being host to the largest hydrocarbon reservoirs. For much of its length, the Rankin Platform is strongly fault-segmented, consisting of a series of NNE-trending pivotal Triassic horsts and grabens, again in an *en echelon* arrangement, suggesting that the trend formed in response to strike-slip movements (Woodside, 1988). Woodside further suggest that the entire complex area lying between the Rankin Trend and the Madeleine Trend formed above a deep-seated wrench zone.

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

The southeast boundary of the Exmouth Sub-basin is formed by the Rough Range Fault, while the northwest boundary is ill-defined, due to the scarcity of seismic data northwest of

Northwest Cape. The deep structure of the Exmouth Sub-basin consists of a series of east-tilted fault blocks that are down-thrown to the west by as much as 3000 m in the pre-Cretaceous and show evidence of some reverse movement in the late Miocene (Parry & Smith, 1988).

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

AGE AND STYLE OF FAULTING

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

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

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

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

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

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

STRATIGRAPHY

While the work set out in this cruise proposal is primarily directed at solving structural problems on the southern North West Shelf, for completeness of background the following summary of general stratigraphy is given (Fig. 10). Given that the North West Shelf is well-explored by Australian standards, the stratigraphy is relatively well-documented, particularly in the Barrow and Dampier Sub-basins. This section is based upon the studies of Parry & Smith (1988) and Woodside (1988).

PALAEOZOIC

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

MESOZOIC-CAINOZOIC

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

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

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

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

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

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

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

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

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

HYDROCARBON ACCUMULATIONS

The hydrocarbon fields of the southern North West Shelf fall into two categories (Vincent & Tilbury, 1988) - those reservoired in the pre-'Main Unconformity' (pre-MU) section, and those reservoired in the post-MU section (Appendix 2).

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

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

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

GENERAL OBJECTIVES & SPECIFIC PROBLEMS

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

* To determine the regional structural framework of the northern Carnarvon Basin by examining the boundaries between major structural elements along key transects of the shelf.

* To determine the deep crustal structure of the sub-basins of the northern Carnarvon Basin and their relationship to the development of the continental margin adjacent to the southeastern Argo Abyssal Plain.

* To assess the effect of deep structure on the development of the major fields and petroleum plays in the region, and in particular the structural and depositional effects resulting from Tertiary reactivation of these deep structures.

* To provide modern regional seismic well-tie data to allow basin-wide seismic correlations.

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

1) Detachment Models: Recent models of the formation of passive continental margins propose that the formation of sedimentary basins takes place by extension above and

below sub-horizontal detachment faults in the crust (Lister & others, 1986). Assuming such detachment models provide a plausible explanation for basin formation, where are the major detachment faults beneath the northern Carnarvon Basin and the Exmouth Plateau and how can detachment models be applied to the area?

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

3) Strike-Slip Movements: The *en echelon* character of the major fault system and the Rankin Trend fault blocks, and the existence of major anticlines (Barrow Island Anticline) and sedimentary deeps (eg Lewis Trough), has led to the obvious conclusion that strike-slip movement has been a major factor in the genesis of the northern Carnarvon Basin. What was the age, extent, and azimuth of these ?multiple phases of movement, and what is their relationship to any phases of simple basin-forming extension?

4) Transfer Faults: Major transfer faults in the Barrow-Dampier Sub-basins can be broadly identified or inferred and their reactivation effects may be visible in the bathymetry (Fig. 11); however, they have not been delineated seismically. These transfer zones probably have significant effects on the distribution of reservoir and source rocks, on migration paths, and as trapping mechanisms. Is it possible to image these transfer zones in deep seismic data, such that, at a later stage of study, they can be mapped more accurately and related to the known hydrocarbon fields?

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

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

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

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

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

SNOWS-I - PRELIMINARY RESULTS

During the SNOWS-I (Survey 101) cruise, a total of 1654 km of high-quality deep seismic data were recorded along 6 dip and 4 strike lines in the Dampier, Barrow, and Exmouth Sub-basins, and on the inner flank of the Exmouth Plateau. These lines were tied to 20 exploration wells throughout the region (Appendix 3).

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

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

LINE 10

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

Comments: A strong band of reflectors at the southeast end of the line, beneath the shallow basement of the Lambert Shelf, at a depth of 9.5-11.3 s (~25 km) are probably from laminated lower crust. It is noted that this type of reflection is observed beneath shallow basement in the region, but never when there is a thick sedimentary section. The Lewis Trough contains sediment down to at least 6.5 s and unlike other crossings of the feature, sediments are quite flat-lying down to at least 4 s and extensively faulted on the southeastern flank, adjacent to the

Legendre Trend. The Rankin Platform is poorly defined, probably due to extensive faulting, in contrast to the Victoria Syncline and Brigadier Trend which are well-imaged down to at least 9 s. A moderately strong, though discontinuous reflector at about 9 s (referred to in this report as Horizon B) appears to mark the lower limit of well-layered probable sedimentary rocks.

LINE 9

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

Comments: Banded lower crustal reflectors are again visible at the SE end of the line beneath the Lambert Shelf and Enderby Terrace, down to 13 s (~30 km). Shallow crustal reflectors beneath the Enderby Terrace (better imaged on the GSI deep seismic lines to the northeast) appear to be detachment surfaces on which the Enderby Terrace faults sole out. The Lewis Trough is strongly synclinal (cf line 10) and sedimentary rocks can be seen down to >6.5 s. Imaging of the Goodwyn Block is excellent (Fig. 12), with the landward fault dipping SE beneath the Lewis Trough, probably soling out in the lower crust beneath the Enderby Terrace. In contrast, the seaward-bounding fault of the Goodwyn Block is high angle. Sedimentary rocks within the Goodwyn Block have a synclinal form and can be clearly distinguished down to about 8.5 s, where they overlie a strong (?basement) reflector (Horizon B). This reflector shows good continuity for a deep event, and can be traced beneath much of the outer shelf.

LINE 8

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

Comments: This line is near the junction (and change in trend) of the Dampier and Barrow Sub-basins, which may account for the rather confused structuring. Basement at the SE end of the line is down-faulted northwestwards and Permian and older sediments (dated at Arabella-1) are strongly rotated, indicating a major episode of extension in the Palaeozoic (Fig. 13). Banded reflectors are again visible in the lower crust down to >12 s. The Lewis Trough is poorly defined on this line, and it may be that the movement that produced the large 'hole' into which Jurassic clastic sediments were dumped, has transferred into the Barrow depocentre, to the west. The sedimentary section beneath the outer shelf is again underlain by Horizon B at depths of 7-10 s.

LINE 7

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

Comments: Due to rapidly decreasing water depths, this line (and lines 6 & 5) had to be terminated at the Barrow depocentre. This depocentre is seen as a structural inversion with about 1s (~1.5 km) of positive relief at the Early Cretaceous level and about 1 s (~2 km) of negative relief at the base of the visible sedimentary section; most of this 'pod' of sediments is interpreted to be of Jurassic to Early Cretaceous age. Deep structural details of Gorgon Block are not immediately obvious; however, its development appears to be tied in with a major ?adjacent wrench-related anticline beneath the continental slope (Fig. 14). This anticline has its roots in dislocations in the underlying Horizon B and has been strongly eroded, probably in the Late Triassic or Early Jurassic. Horizon B can be traced through much of the Kangaroo Syncline and there are indications of its presence beneath the Exmouth Plateau Arch. If Horizon B marks the base of the sedimentary section, then there is more than 8 s of sediment underlying the Kangaroo Syncline; of this thickness, at least 6 s is Triassic and older.

LINE 6

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

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

LINE 16

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

Comments: The principal features of interest on this line are two prominent mid-crustal reflectors that extend along most of the line, deepening from southwest to northeast. The upper reflector. at 7-9 s depth, is a detachment upon which faulting in the ?Palaeozoic to Triassic section soles out. The deeper reflector, at 9-10 s (Fig. 15), possible corresponds to the Horizon B, seen beneath the outer shelf and inner Exmouth Plateau.

LINE 5

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

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

LINES 4-2

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

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

PROPOSED PROGRAM

The proposed lines for SNOWS-II are shown in Figures 16-19. These lines total 2765 km and tie 21 exploration wells (Appendix 4), including 4 wells that were also tied on SNOWS-I. For planning and operational purposes, these lines can be considered in four stages, in approximate priority order. Stage 1 is concentrated in the Beagle Sub-basin (Fig. 17) and is the highest priority (7 lines). This work extends the coverage of SNOWS-I to the northeast and will link in with the proposed deep seismic cruise in the offshore Canning Basin (SNOWS-III), scheduled for 1993. The Stage 1 lines are designed, where possible, to be orthogonal to the principal trends of the sub-basin. Stage 2 consists of a single strike line linking the outer parts of the northern Carnarvon Basin (Figs 17,18). While this line is of lower priority than Stage 3, the vessel will in any case have to transit to the Barrow-Dampier area, so the opportunity will be taken to record the data. Stage 3 consists of several lines in the Barrow and Dampier Sub-basins and on the inner flank of the Exmouth Plateau that will fill in some of the gaps left after SNOWS-I. Stage 4 is concentrated on the central and outer Exmouth Plateau (Fig. 19) and is principally designed to complete the North West Shelf to

Gascoyne Abyssal Plain transect that was commenced on SNOWS-I.

While the total of 2765 km of seismic data programmed for SNOWS-II is quite high for regional deep crustal work, in the event of good weather conditions and high equipment reliability, it should be possibility to finish the program in the 30 days available for the survey. However, even in the event of adverse weather or serious equipment problems, it should be possible to complete at least Stages 1 and 2, and the more important parts of Stage 3.

A summary of each line follows; way points for each line are included in Appendix 5:

STAGE 1: BEAGLE SUB-BASIN (1184 km; 8 wells; Fig. 17)

LINE 1 (196 km)
Southern flank of the Bedout High, through the northwest corner of the Bedout Sub-basin, across the North Turtle Hinge, and along the axis of the Cossigny Trough, tying to line 101/2 of SNOWS-I. Ties to Lines 2, 3, 4, 6, and 7, and to Phoenix-1 and North Turtle-1.

LINE 2 (188 km)
Dip line across the southwest Beagle Sub-basin, from the Lambert Shelf, across the southwest end of the Cossigny Trough and the Picard Trend, to the inner flank of the Exmouth Plateau. Ties to Lines 1 and 8, and to Cossigny-1, Ronsard-1, and Delambre-1.

LINE 3 (170 km)
Dip line across the southwest Beagle Sub-basin, from the Lambert Shelf, across the central Cossigny Trough and northeast Picard Trend, to the inner flank of the Exmouth Plateau. Ties to Lines 1, 4, and 8, and to Bruce-1 and Picard-1.

LINE 4 (168 km)
?Dip line from the Lambert Shelf, across the northeast end of the Cossigny Trough, and along the axis of the Thouin Graben to the inner flank of the Exmouth Plateau. Ties to Lines 1, 3, 4, and 7. No well ties.

LINE 5 (144 km)
Extends from the Bedout High, across the North Turtle Hinge and the northern end of the Thouin Graben, to the inner flank of the Exmouth Plateau. Ties to Lines 4 and 6, and to Minilya-1.

LINE 6 (136 km)
Dip line from the Bedout High, across the western end of the Bedout Sub-basin, to the Lambert Shelf. Ties to Lines 1, 5, and 7, and to Phoenix-1.

LINE 7 (182 km)
Northwest end of the Bedout Sub-basin, across the North Turtle Hinge and southern Thouin

Graben to the inner flank of the Exmouth Plateau. Ties to Lines 1, 4, 6, and 8. No well ties.

STAGE 2: OUTER BASIN STRIKE LINE (448 km; 3 wells; Figs 17, 18)

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

LINE 8 (448 km)
Strike line along the inner flank of the Exmouth Plateau from offshore of the Beagle Sub-basin, outside the Dampier Sub-basin, to the Kangaroo Syncline. Ties to Lines 2, 3, 7, 9, 101/8, 101/9, 101/10, 101/7, 101/6, and 101/16, and to Brigadier-1, Gandara-1, and Saturn-1.

STAGE 3: BARROW-DAMPIER-EXMOUTH IN-FILL (717 km; 9 wells; Fig. 18)

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

LINE 9 (216 km)
Dip line from the junction of the Scholl Island and Rosemary Fault Systems, across the northern end of the Barrow Island Anticline and the Rankin Platform, to the Kangaroo Syncline. Ties to Line 8 and to Campbell-2, Sultan-1, and Saturn-1.

LINE 10 (29 km)
Dip line extending line 101/8 across the southeast boundary of the Dampier Sub-basin. Ties to Arabella-1.

LINE 11 (144 km)
Dip line from the southern Barrow Sub-basin to the southwest Exmouth Plateau. Ties to lines 101/4 and 101/16, and to Outtrim-1, Novara-1, and Zeewulf-1.

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

STAGE 4: OUTER EXMOUTH PLATEAU (414 km; 2 wells; Fig. 19)

LINE 13 (125 km)
Strike line along the Exmouth Plateau Arch through the Scarborough gas field. Ties to Lines 12, 14, and 101/7, and to Scarborough-1 and Jupiter-1.

LINE 14 (289 km)
Strike line from the Exmouth Plateau Arch across the northwest flank of the Exmouth Plateau, to the oceanic crust of the Gascoyne Abyssal Plain, thus completing the North West Shelf - Gascoyne crustal transect. Ties to Lines 13 and 101/7, and to Jupiter-1.

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

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

Notes

[1] Trap types as follows -

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

[2] Units for reserves

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

APPENDIX 3
WELLS TIED ON SNOWS-I

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

APPENDIX 4
WELLS TO BE TIED ON SNOWS-II

Well	Operator	Date	TD	Oldest sequence
*Arabella-1	Aust. Occidental	1983	2209	Early Permian
*Brigadier-1	Woodside	1978	4292	Triassic
Bruce-1	Stirling	1979	2168	Middle Triassic
Campbell-2	Bond	1986	2796	Jurassic
Cossigny-1	Woodside/Burmah	1972	3203	Middle Triassic
Delambre-1	Woodside	1980	5495	Late Triassic
Eendracht-1	Esso	1980	3410	Late Triassic
Gandara-1	Hudbay	1979	4361	Late Triassic
Investigator-1	Esso	1979	3745	Late Triassic
*Jupiter-1	Phillips	1979	4946	Late Triassic
Minilya-1	Woodside/Burmah	1974	2400	Jurassic
North Turtle-1	BP	1982	4420	Jurassic
Novara-1	Esso	1982	2753	Neocomian
Outtrim-1	Esso	1984	1725	Late Jurassic
Phoenix-1	BP	1980	4880	Middle Triassic
Picard-1	Woodside/Burmah	1972	4216	Middle Jurassic
Ronsard-1	Woodside/Burmah	1973	2848	Early Jurassic
Saturn-1	Phillips	1980	4000	Late Triassic
Scarborough-1	Esso	1979	2360	Berriasian
Sultan-1	Wapet	1979	3620	Late Triassic
*Zeewulf-1	Esso	1979	3500	Late Triassic

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

APPENDIX 5
WAY POINTS FOR SNOWS-II

Line	Way pt	latitude	Longitude	Comments
1	1	18 36 03.2	118 53 46.4	SOL
1	2	18 38 07.1	118 47 07.4	Phoenix-1
1	3	18 54 35.3	118 05 16.0	North Turtle-1
1	4	19 16 06.4	117 10 06.3	EOL
2	1	19 47 21.3	117 39 25.7	SOL
2	2	19 19 53.3	117 17 26.0	Cossigny-1
2	3	19 08 30.6	117 09 38.7	Ronsard-1
2	4	18 31 05.0	116 41 48.0	Delambre-1
2	5	18 24 19.5	116 37 42.9	EOL
3	1	18 21 31.5	117 10 08.5	SOL
3	2	18 57 59.7	117 37 20.4	Picard-1
3	3	19 22 31.5	117 55 41.7	Bruce-1
3	4	19 36 03.2	118 06 45.6	EOL
4	1	19 25 49.8	117 45 29.9	SOL
4	2	17 55 10.7	117 54 54.3	EOL
5	1	17 55 40.5	117 39 43.1	SOL
5	2	18 19 28.7	118 43 56.7	Minilya-1
5	3	18 23 55.1	118 55 54.9	EOL
6	1	19 27 58.9	118 37 44.8	SOL
6	2	18 38 07.1	118 47 07.4	Phoenix-1
6	3	18 15 04.0	118 50 56.6	EOL
7	1	19 05 22.9	118 54 38.9	SOL
7	2	18 19 49.3	117 22 32.1	EOL
8	1	18 22 03.8	117 41 46.1	SOL
8	2	19 05 48.8	116 08 09.5	Brigadier-1
8	3	19 16 30.9	115 49 15.1	Gandara-1
8	4	19 54 35.6	114 56 40.8	Saturn-1
8	5	20 28 21.8	114 04 02.3	EOL

Line	Way pt	latitude	Longitude	Comments
9	1	19 37 17.8	114 26 59.1	SOL
9	2	19 54 35.6	114 56 40.8	Saturn-1
9	3	20 02 38.5	115 11 21.2	Sultan-1
9	4	20 24 55.5	115 43 44.1	Campbell-2
9	5	20 42 00.0	116 10 00.0	EOL
10	1	20 40 30.0	116 12 00.0	SOL
10	2	20 28 12.0	116 01 52.0	Arabella-1 (EOL)
11	1	20 56 15.0	113 19 02.3	SOL
11	2	21 06 32.5	113 37 13.2	Zeewulf-1
11	3	21 21 26.0	114 04 30.2	Novara-1
11	4	21 31 52.7	114 27 02.7	Outtrim-1
11	5	21 33 48.0	114 31 42.0	EOL
12	1	21 26 00.0	114 48 00.0	SOL
12	2	20 21 06.6	112 58 01.5	Investigator-1
12	3	19 54 28.9	112 14 35.2	Eendracht-1
12	4	19 50 43.6	112 08 34.1	EOL
13	1	20 15 00.0	112 40 45.9	SOL
13	2	19 53 06.6	113 08 44.5	Scarborough-1
13	3	19 34 53.0	113 31 58.0	Jupiter-1
13	4	19 31 22.6	113 35 11.5	EOL
14	1	19 34 53.0	113 31 58.0	Jupiter-1 (SOL)
14	2	18 13 20.0	111 11 25.7	EOL

APPENDIX 6
SEISMIC ACQUISITION PARAMETERS

Seismic Cable Configuration

Standard	length -	4800 m
	group length -	25 m
	no. channels -	192

Seismic Source

Airgun capacity	50 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 7
EQUIPMENT TO BE UTILISED ON SNOWS-II

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

Syntron RCL-3 cable levelers; individual remote control and depth readout

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

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

Digital seismic acquisition system designed and built by BMR: 16-bit floating point, SEG-Y output on cartridge tape

Raytheon echo-sounders: 3.5KHz (2 kW) 16-transducer sub-bottom profiler, and 12 KHz (2 kW) precision echo-sounder

Geometrics G801/803 magnetometer/gradiometer

Bodenseewerk Geosystem KSS-31 marine gravity meter

Racal 'Skyfix' differential GPS

Magnavox T-Set stand-alone GPS receiver

Magnavox MX 1107RS and MX 1142 transit satellite receivers

Magnavox MX 610D and Raytheon DSN 450 dual axis sonar dopplers; Ben paddle log

Sperry, Arma-Brown, and Robertson gyro-compasses

APPENDIX 8
COMPANIES CONSULTED DURING PROPOSAL PREPARATION

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

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

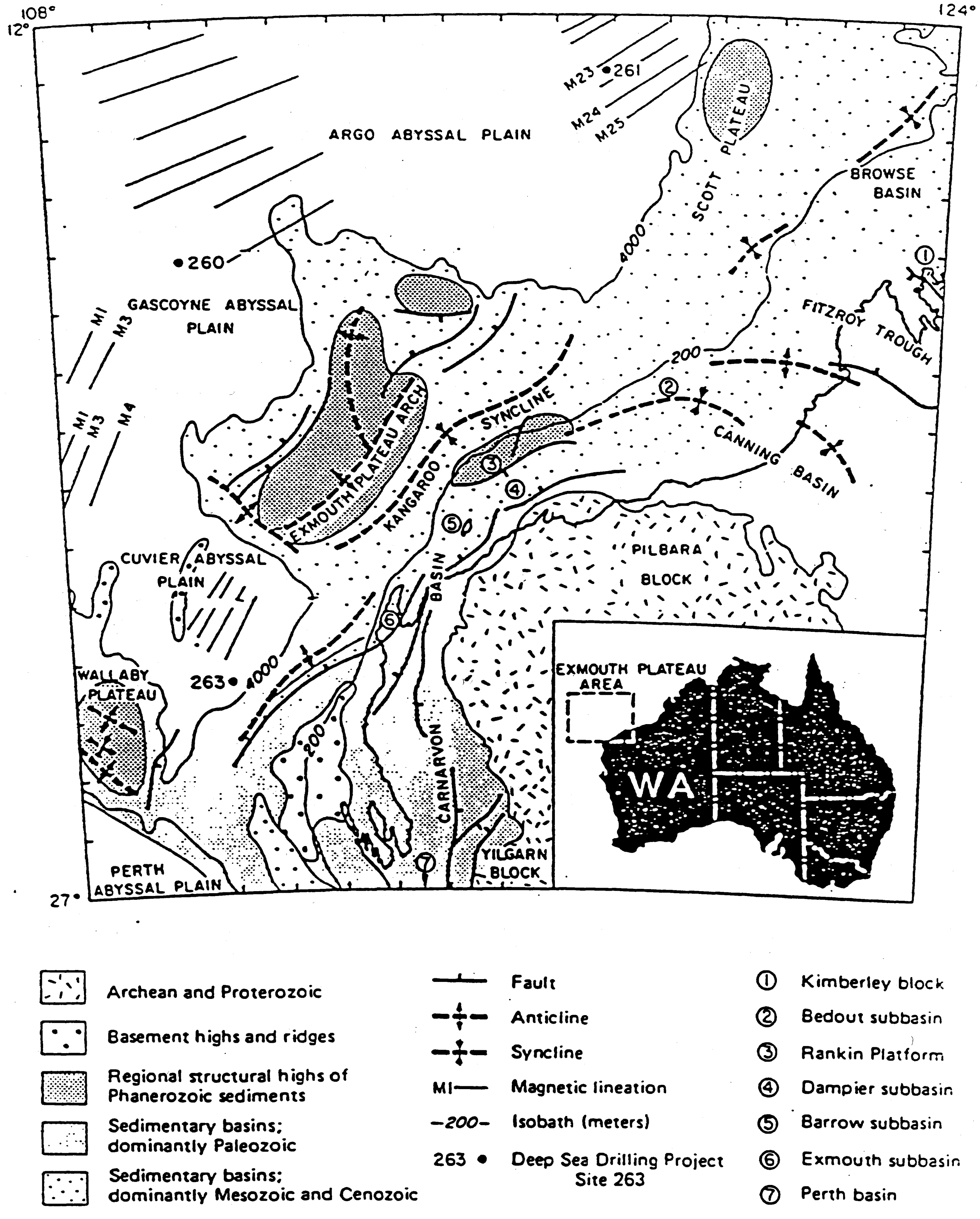

Figure 1: Regional setting of the North West Shelf (after Exon & Willcox, 1980).

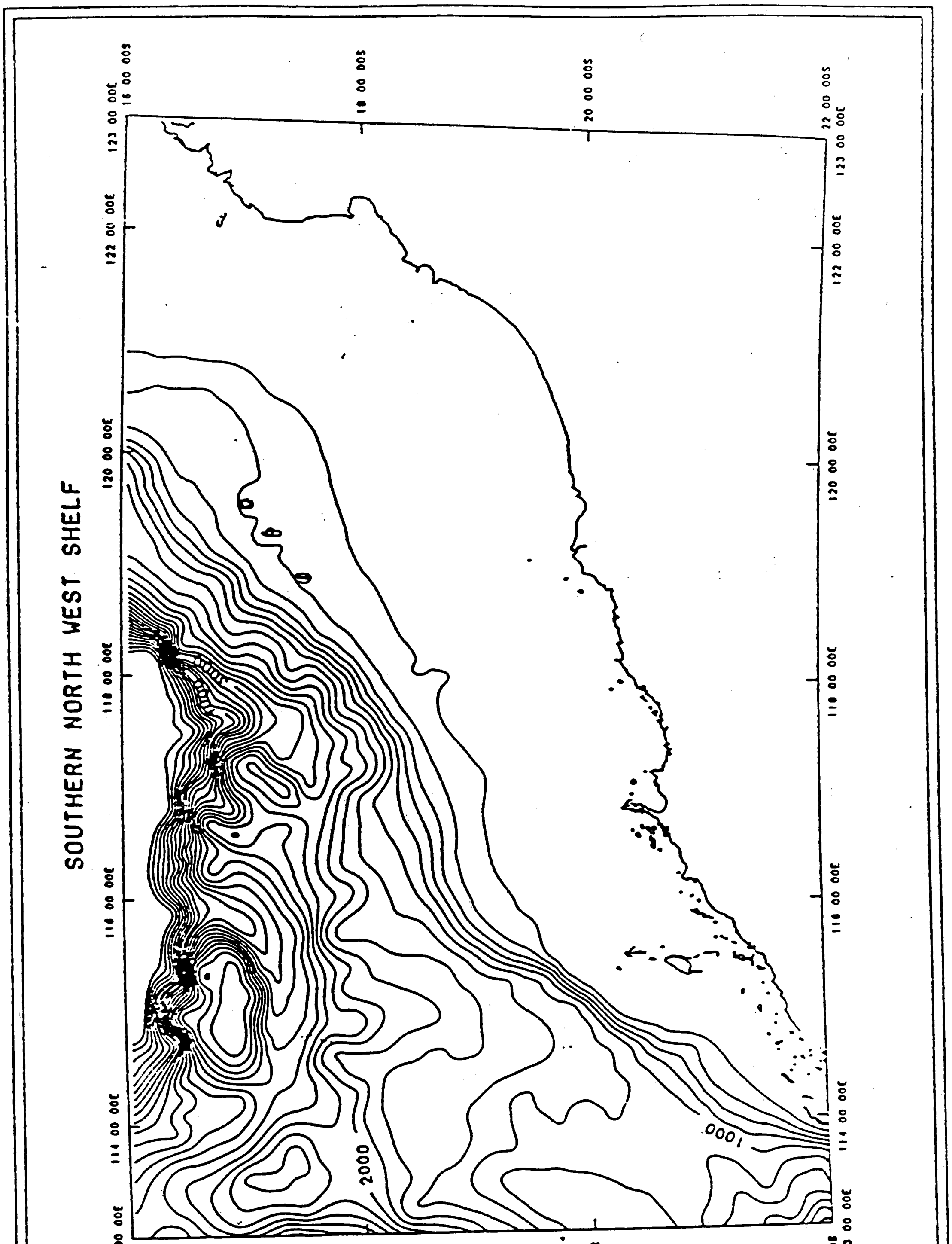

Figure 2: Bathymetry of the southern North West Shelf and Exmouth Plateau; contour interval 200 metres.

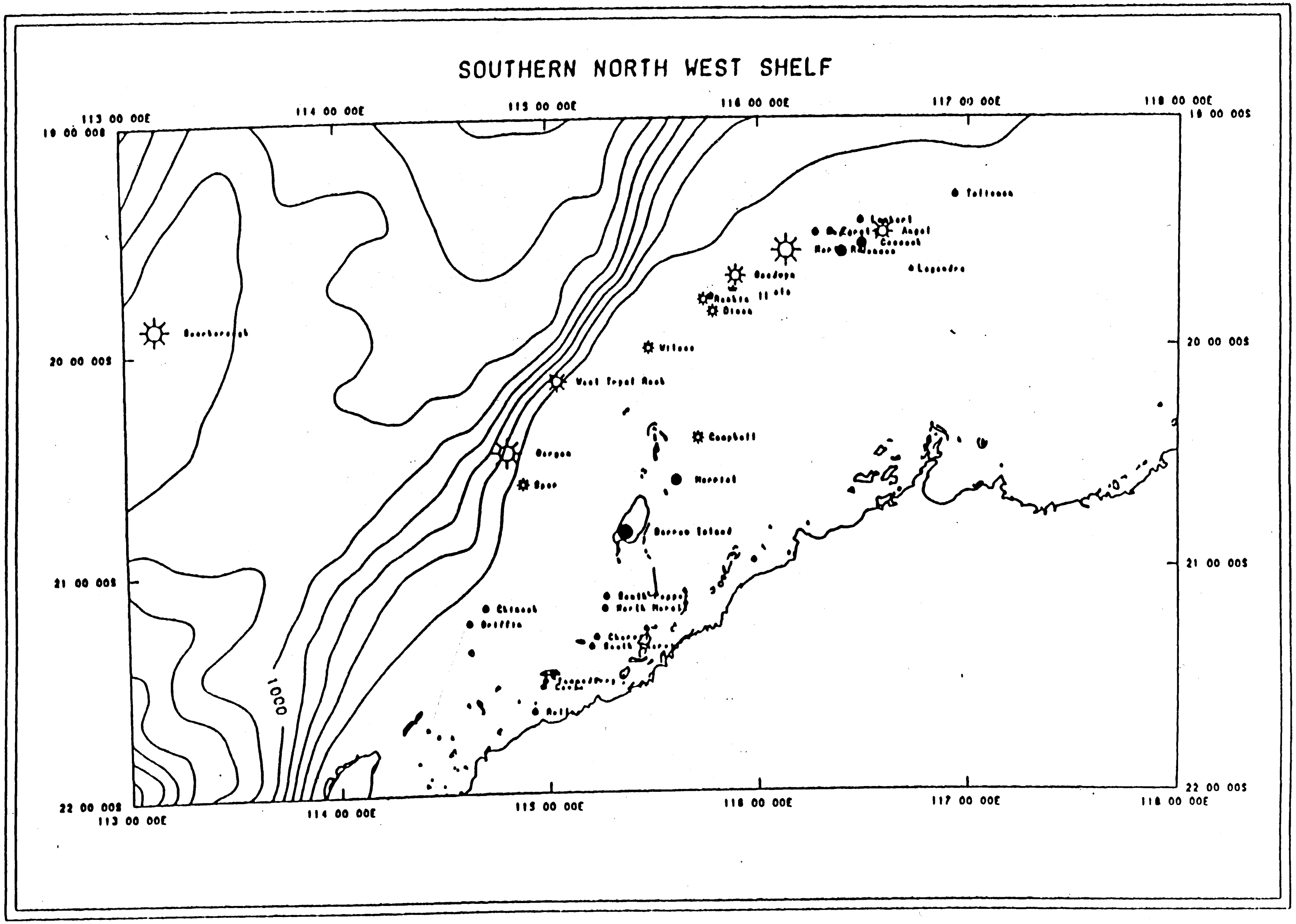

Figure 3: Locations of oil and gas fields on the southern North West Shelf. Bathymetry contour interval 500 metres.

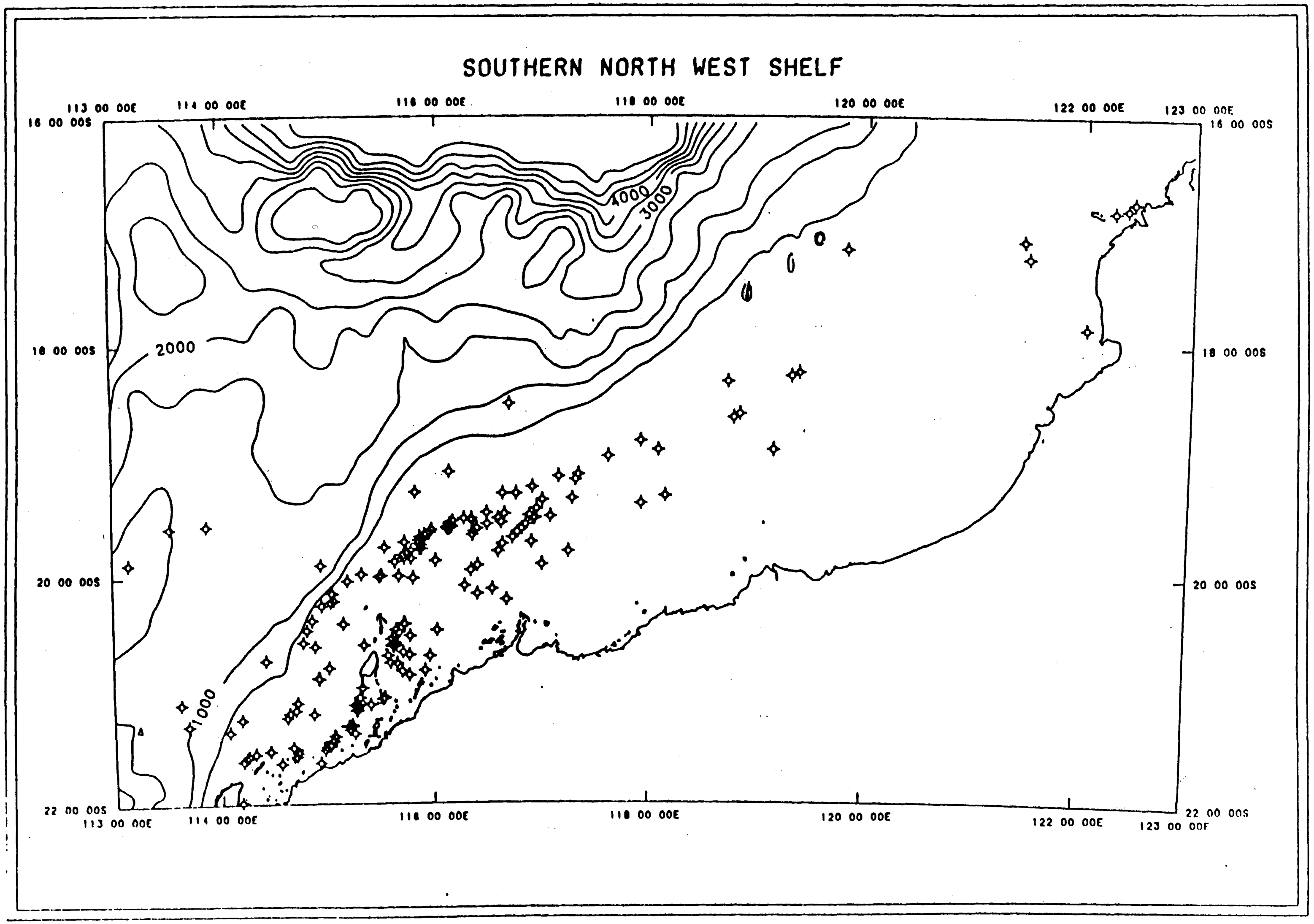

Figure 4: Locations of exploration wells on the southern North West Shelf. Bathymetry contour interval 500 metres.

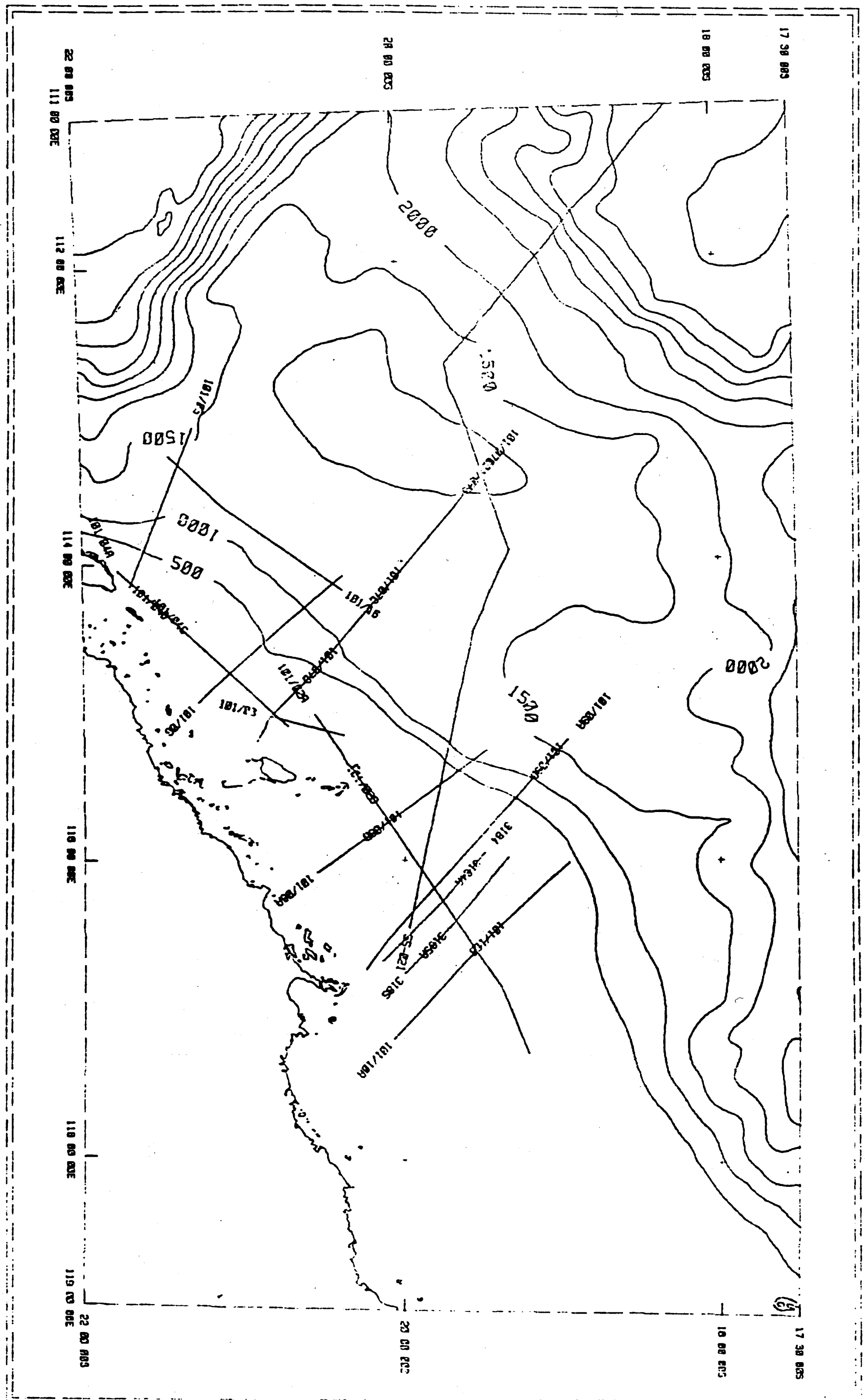

Figure 5: Locations of deep seismic profiles on the southern North West Shelf and Exmouth Plateau; data from 1986 BMR/Lamont-Doherty survey (line S55-021)

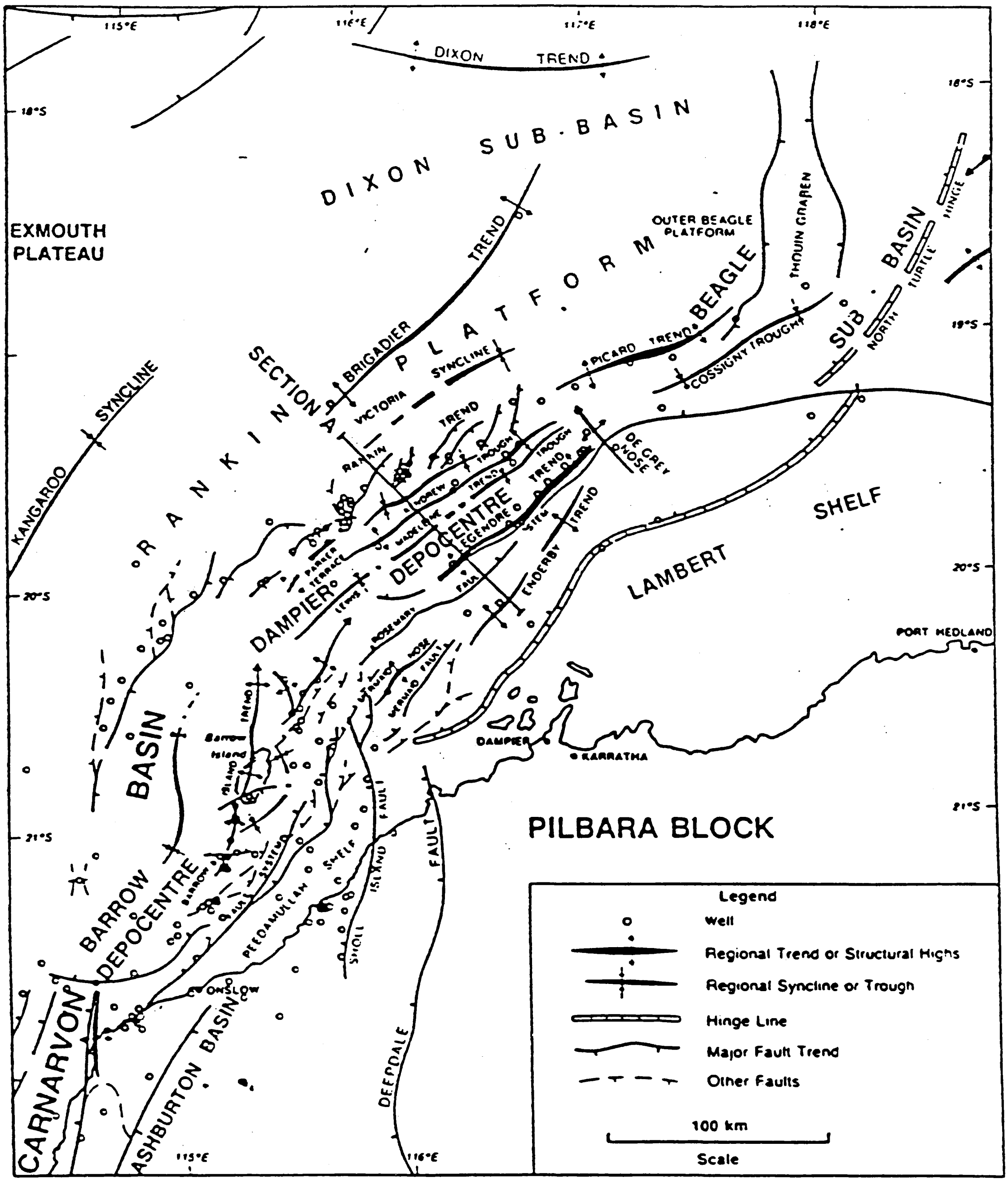

Figure 6: Tectonic elements of the southern North West Shelf (after Woodside, 1988).

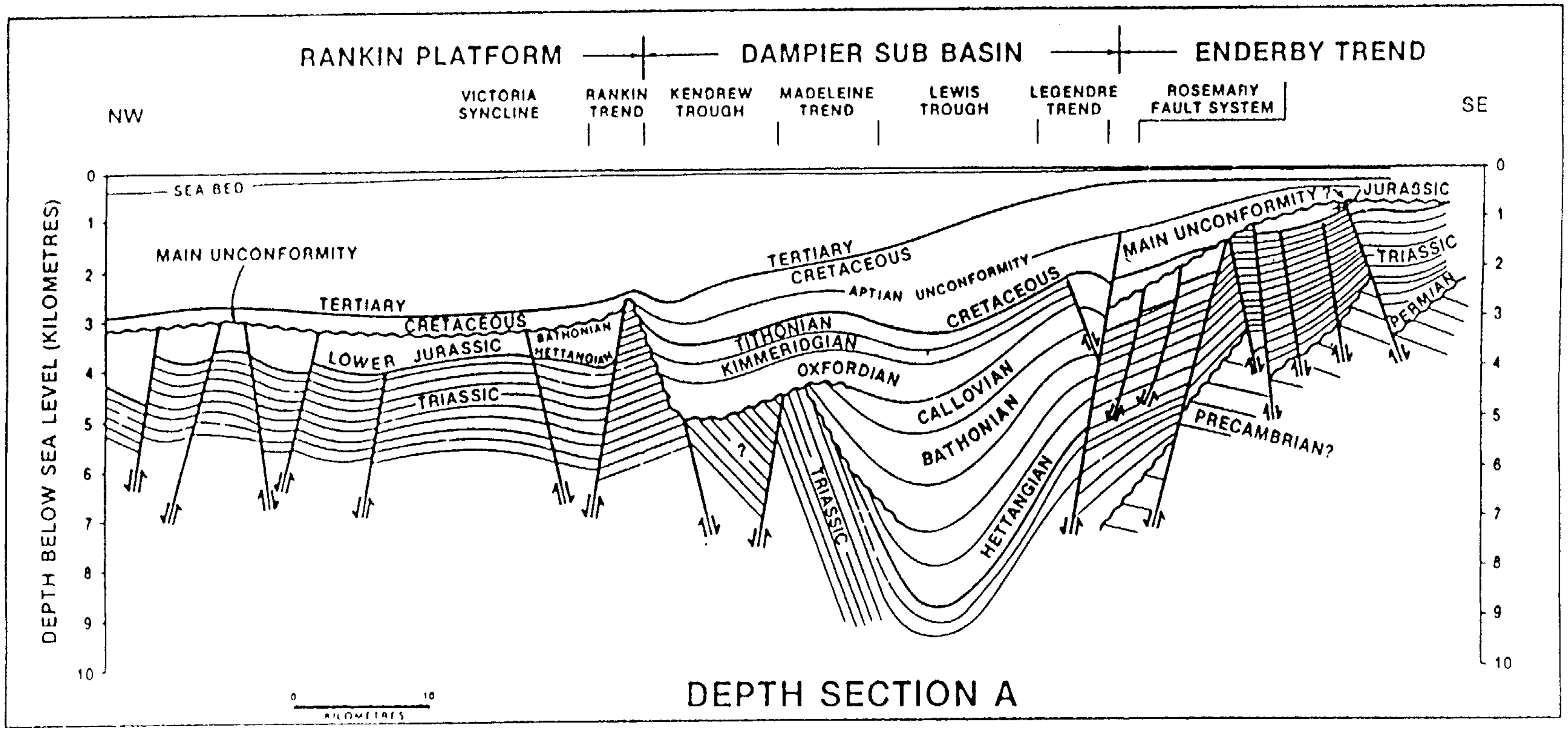

Figure 7: Depth profile across the Dampier Sub-basin (after Woodside, 1988).

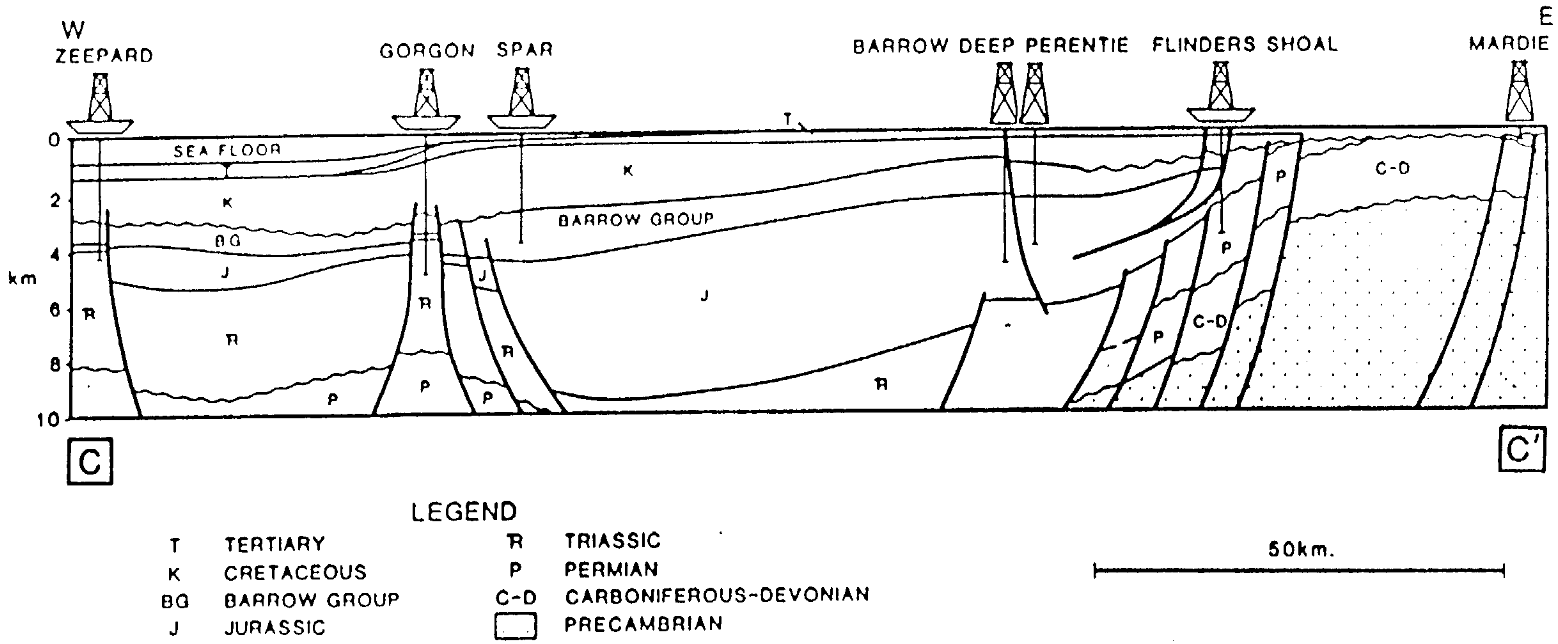

Figure 8: Depth profile across the Barrow Sub-basin (after Parry & Smith, 1988).

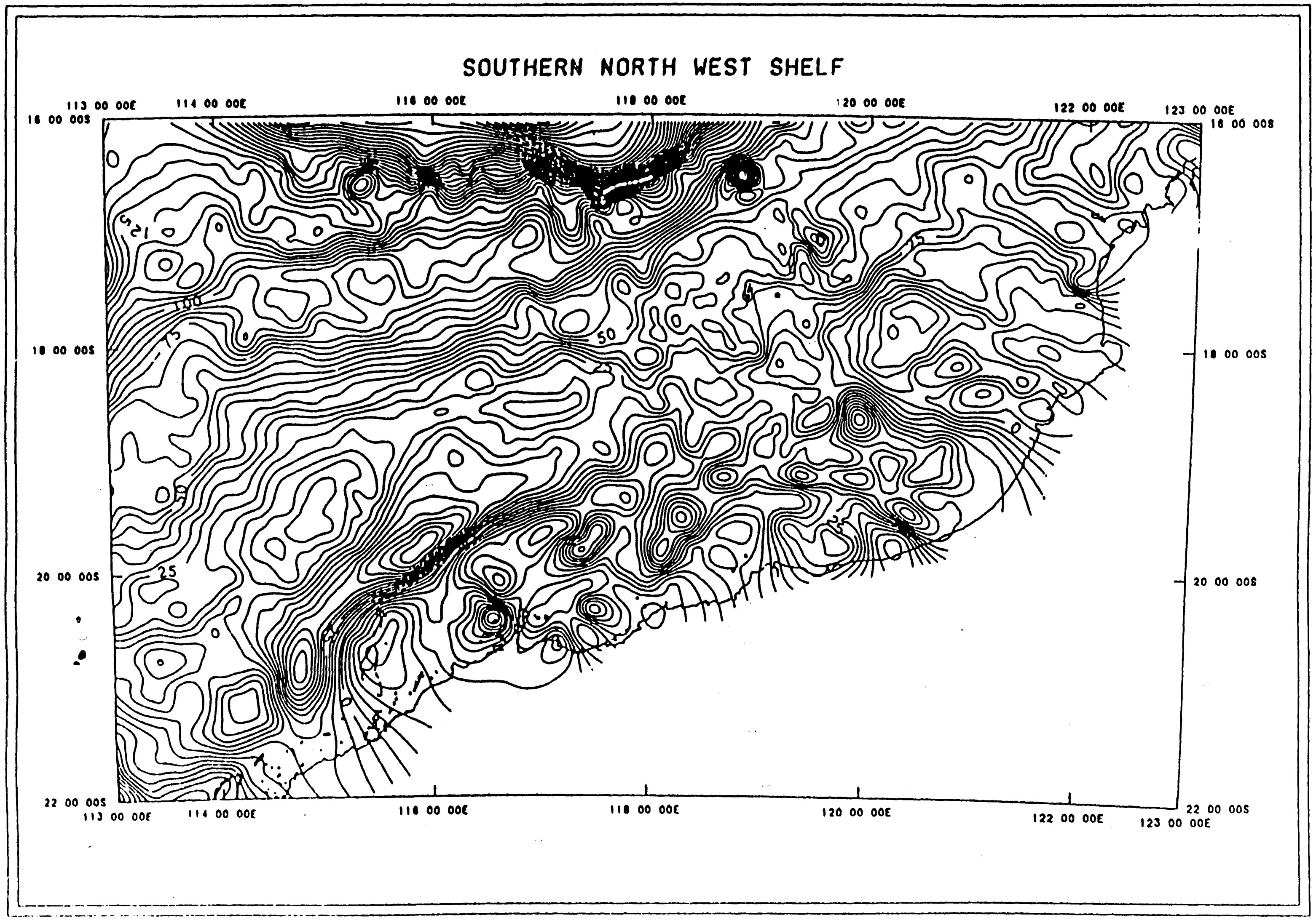

Figure 9: Bouguer gravity anomalies on the southern North West Shelf. Contour interval 5 mgal.

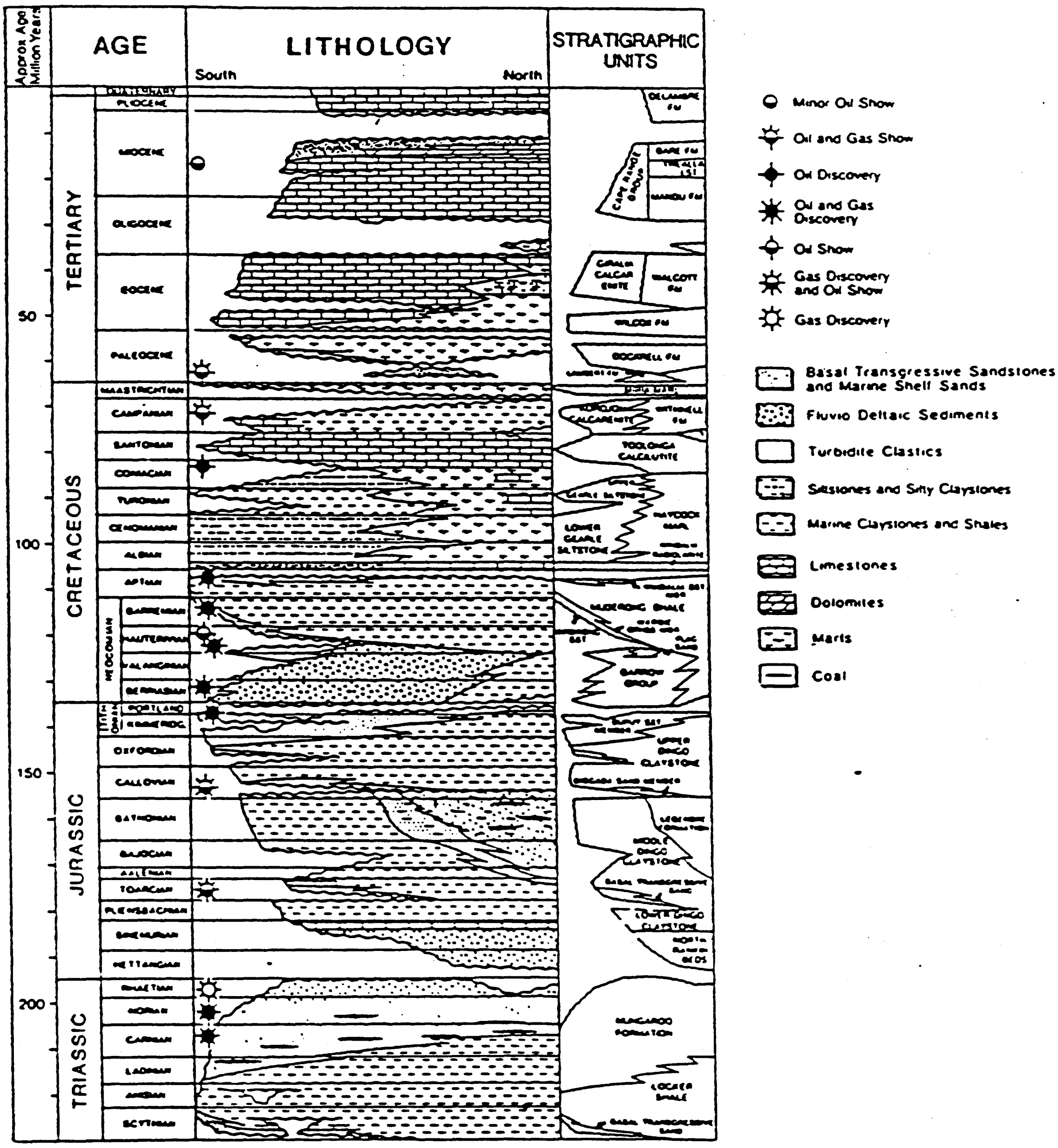

Figure 10: Stratigraphy of the southern North West Shelf (after Woodside, 1988).

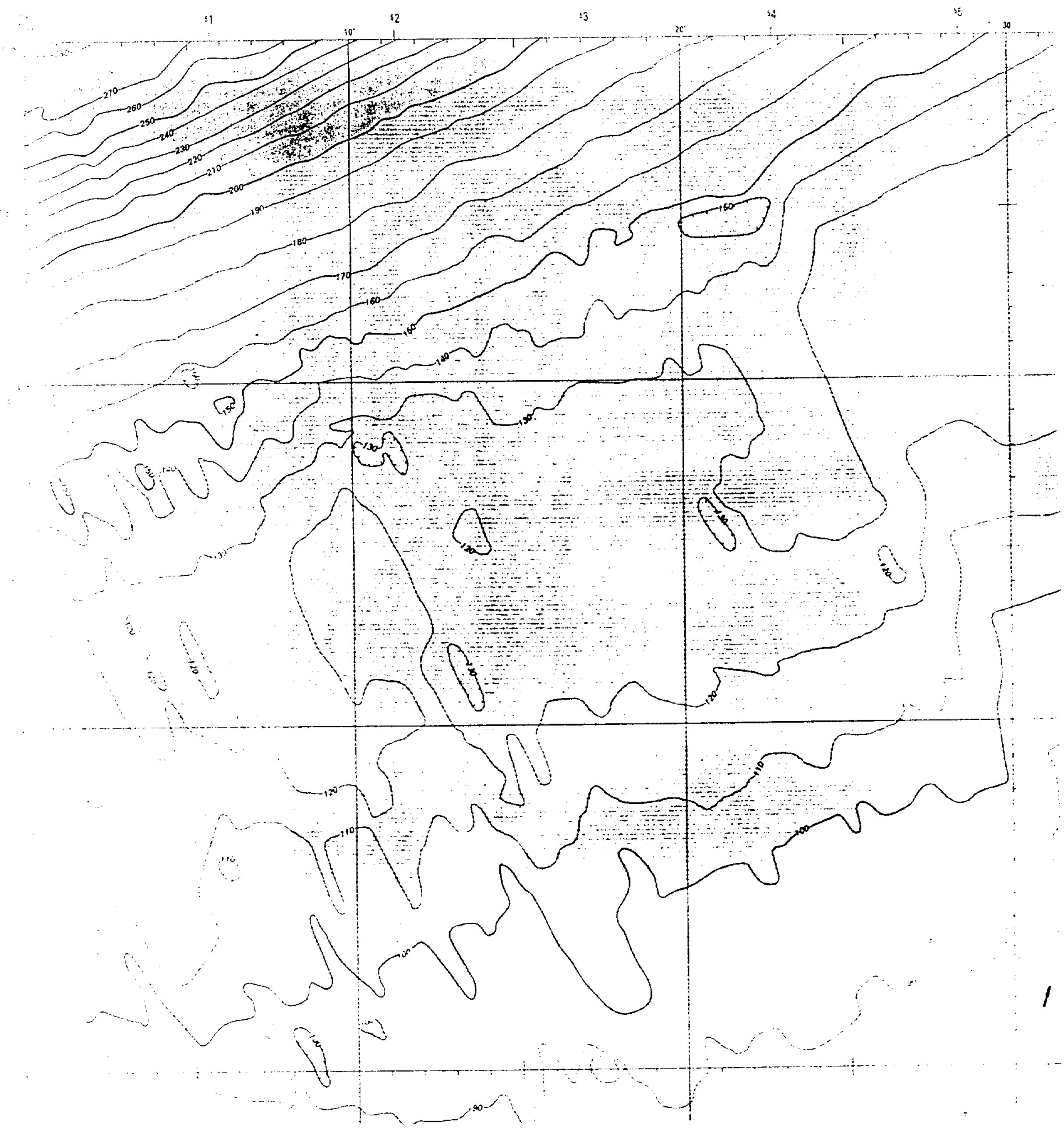

Figure 11: Portion of Sheet SE 50-15 of the National Bathymetric Map Series showing strong NNW-SSE lineaments in the seabed morphology, possibly the result of reactivation of deep-seated faults.

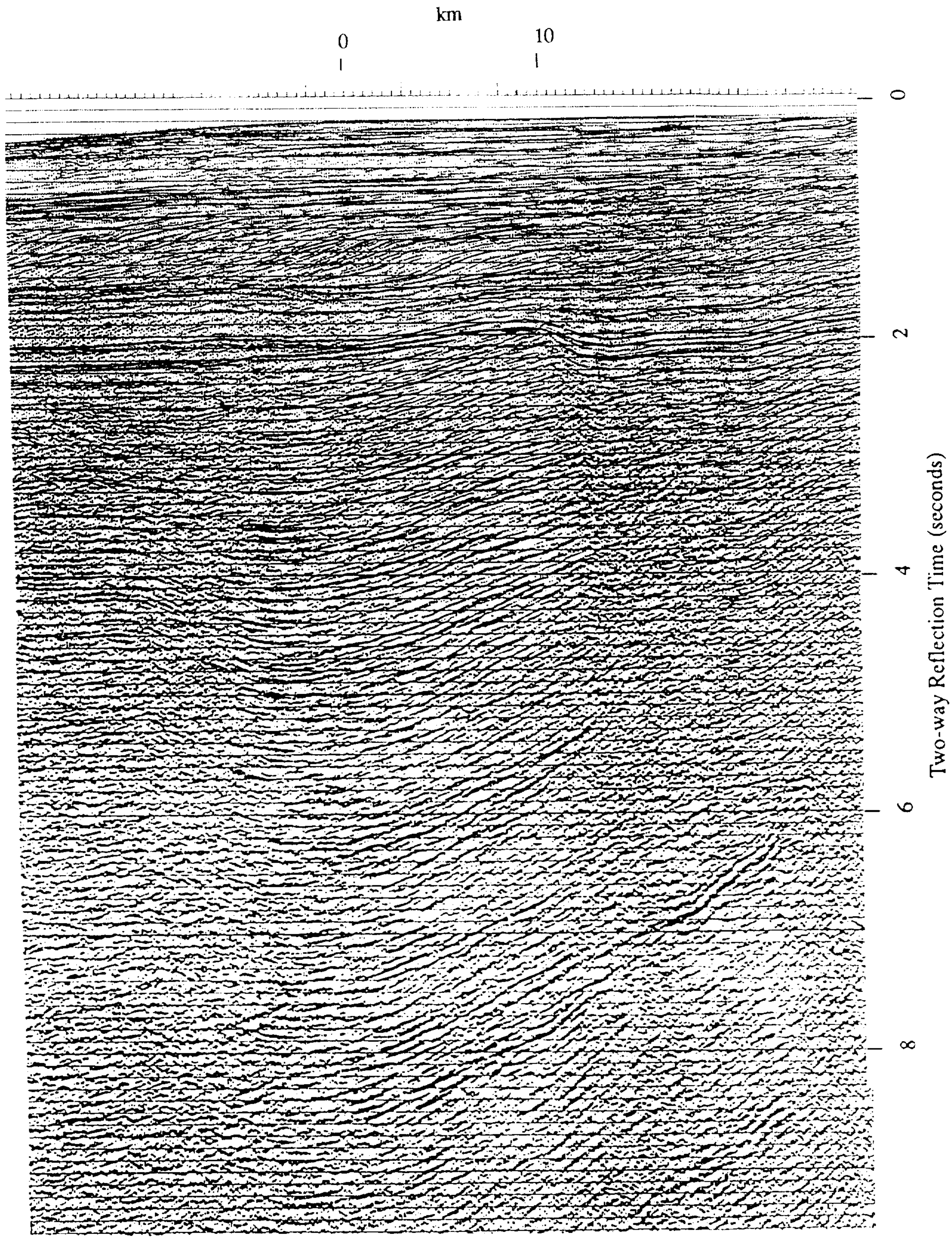

Figure 12: Portion of seismic section along SNOWS-I line 101/9, showing the Goodwyn Block.

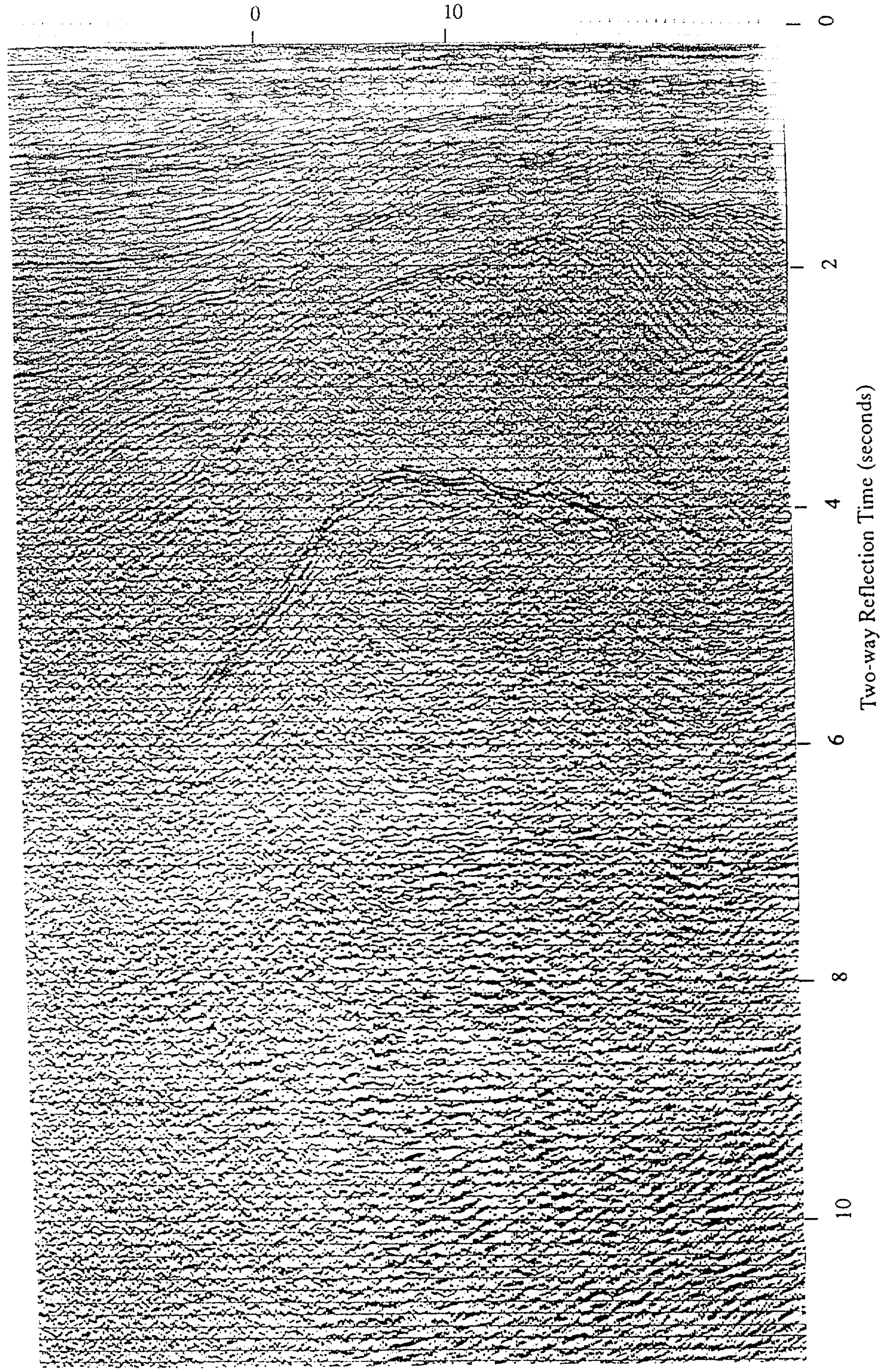

Figure 13: Portion of seismic section along SNOWS-I line 101/8, showing rotated Palaeozoic sediments above faulted basement at Arabella-1. Note the banded reflectors in the crust below 7 s.

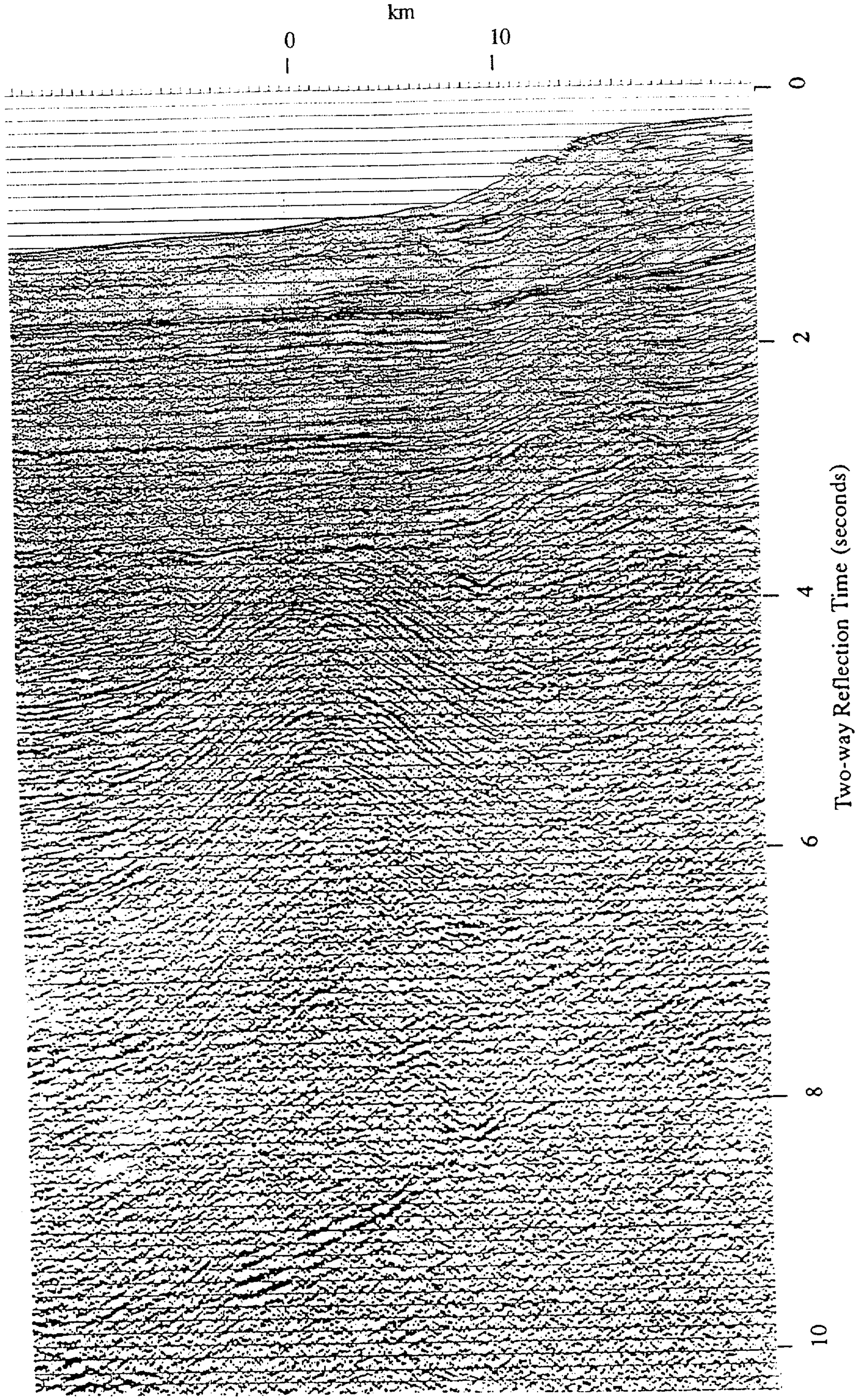

Figure 14: Portion of seismic section along SNOWS-I line 101/7, showing the Gorgon structure on the right of the section and the adjacent wrench anticline beneath the upper slope. The strong reflector at about 9 s is Horizon B.

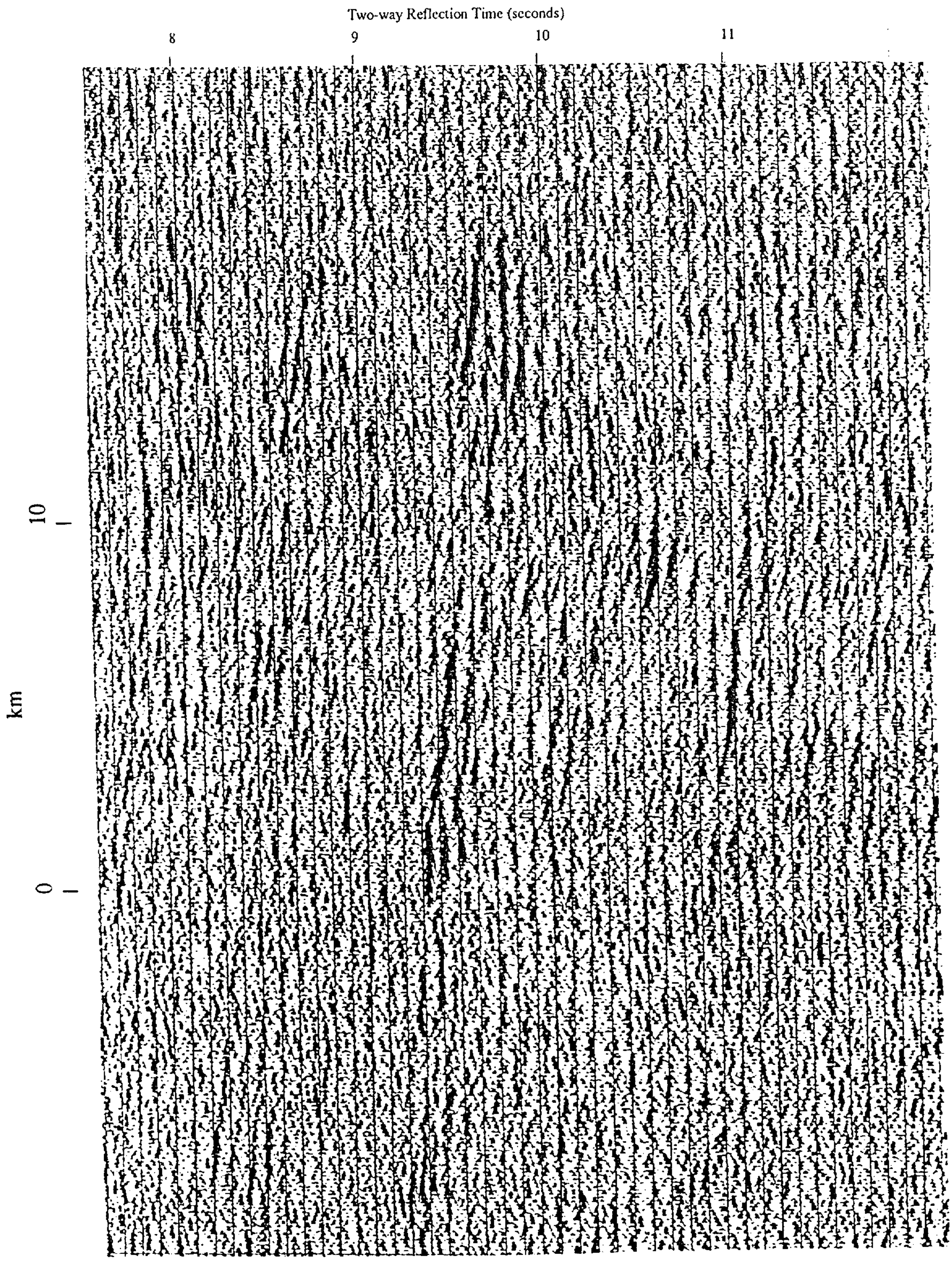

Figure 15: Portion of seismic section along SNOWS-I line 101/16, showing crustal reflectors at 8.4 s and 9.4 s, beneath the Kangaroo Syncline.

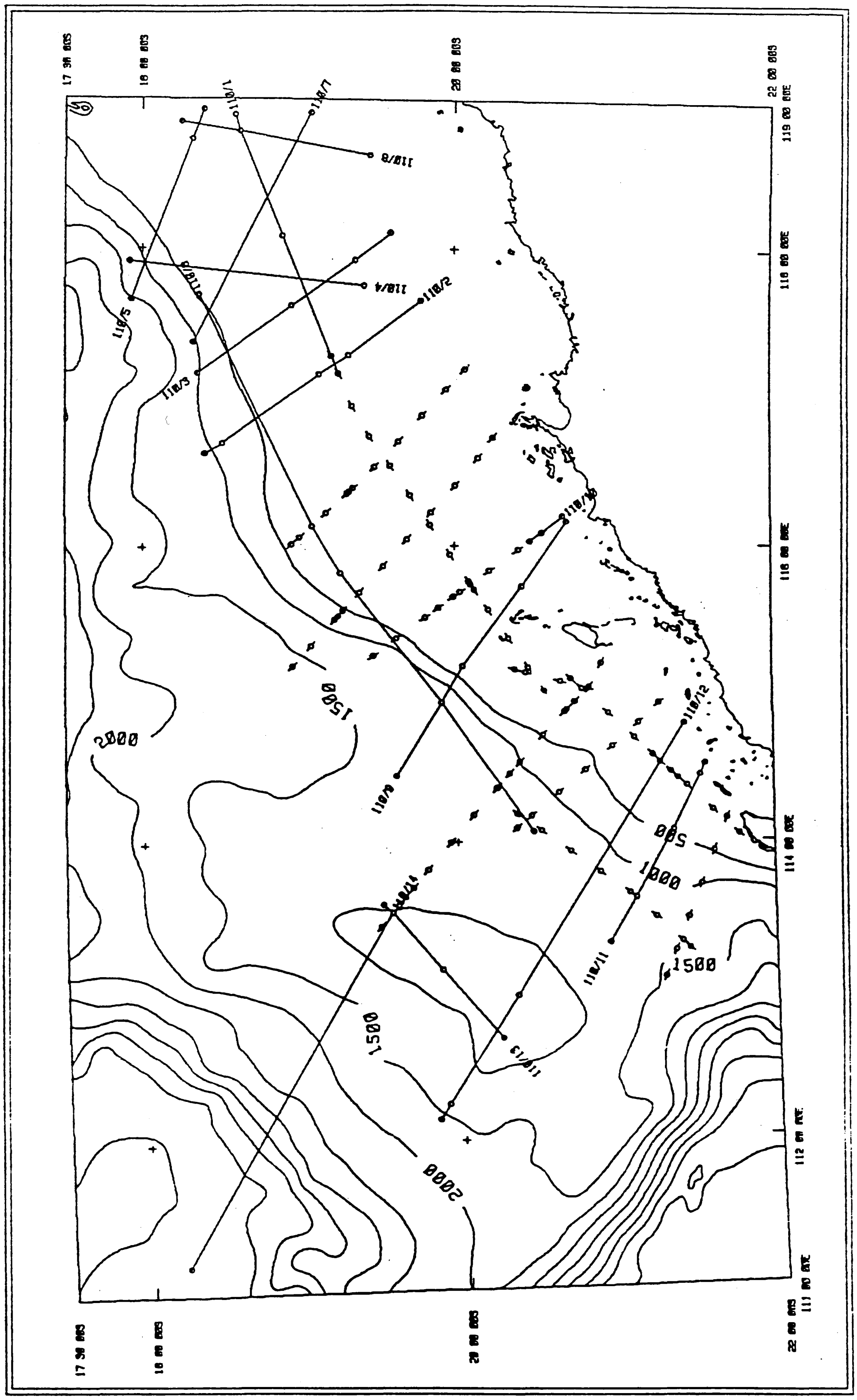

Figure 16: Proposed lines for SNOWS-II (solid lines) on the southern North West Shelf. SNOWS-I lines are shown with shot-point symbols.

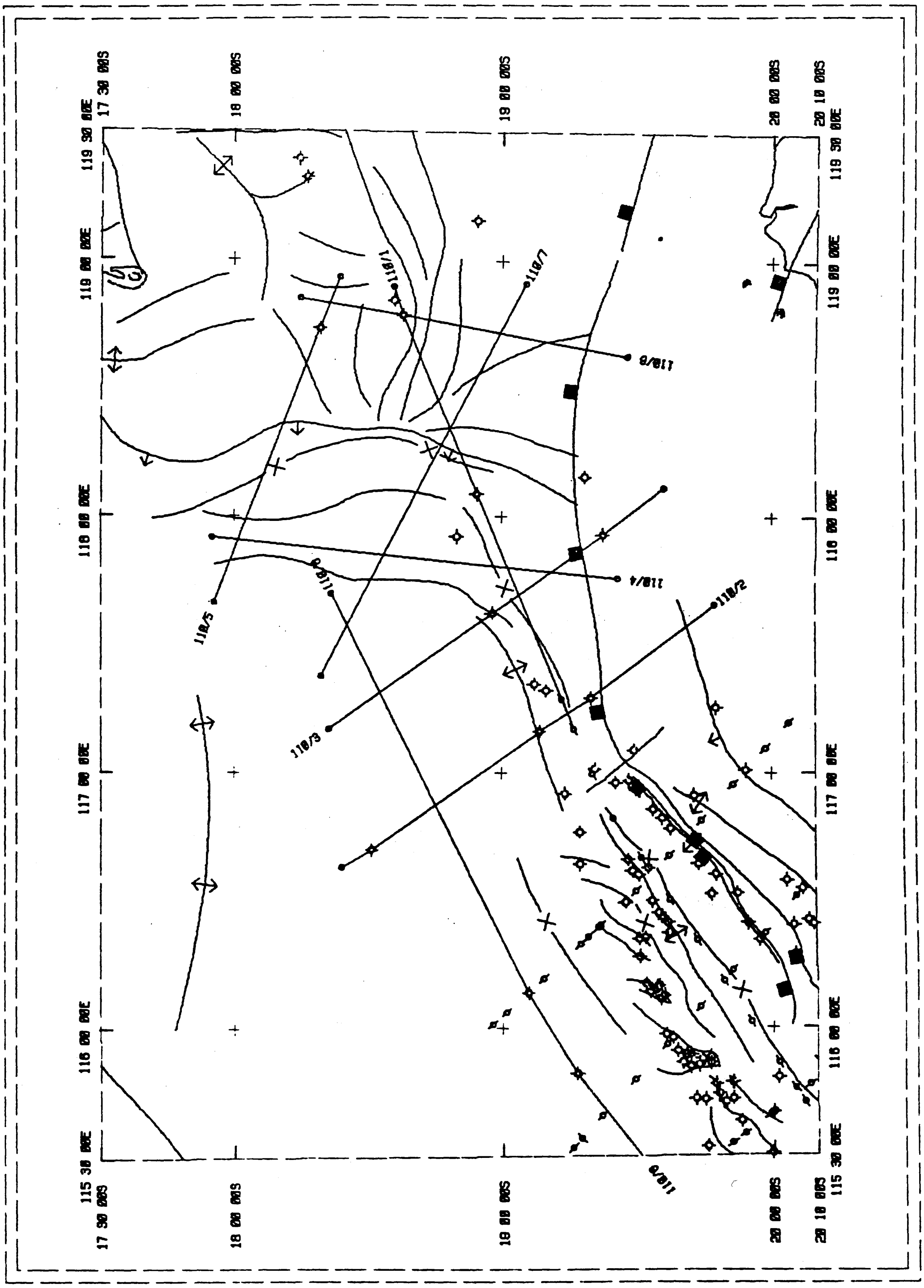

Figure 17: Proposed lines for SNOWS-II (solid lines) in the Beagle Sub-basin and inner flank of the Exmouth Plateau. SNOWS-I lines are shown with shot-point symbols.

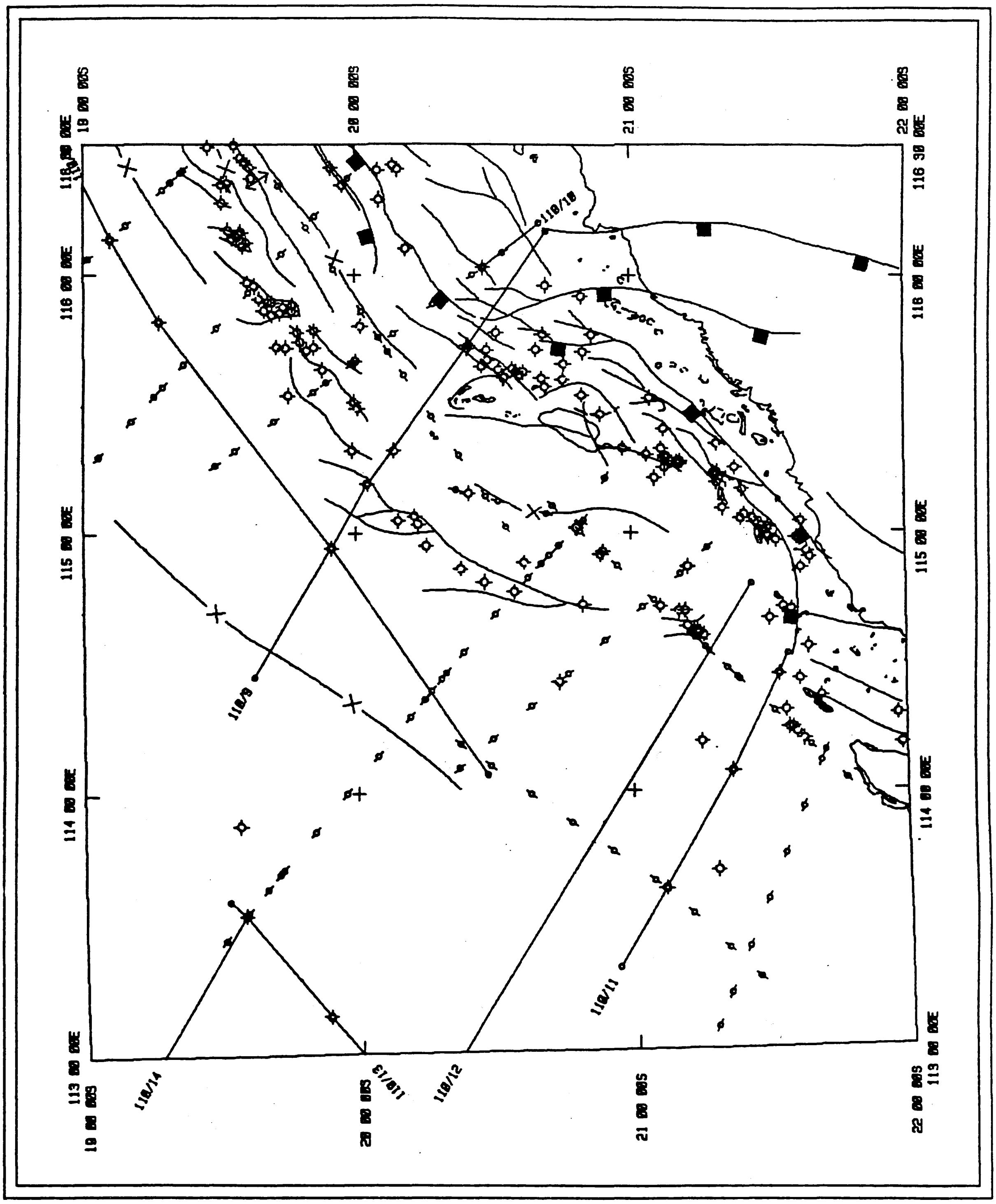

Figure 18: Proposed lines for SNOWS-II (solid lines) in the Barrow and Dampier Sub-basins and inner flank of the Exmouth Plateau. SNOWS-I lines are shown with shot-point symbols.

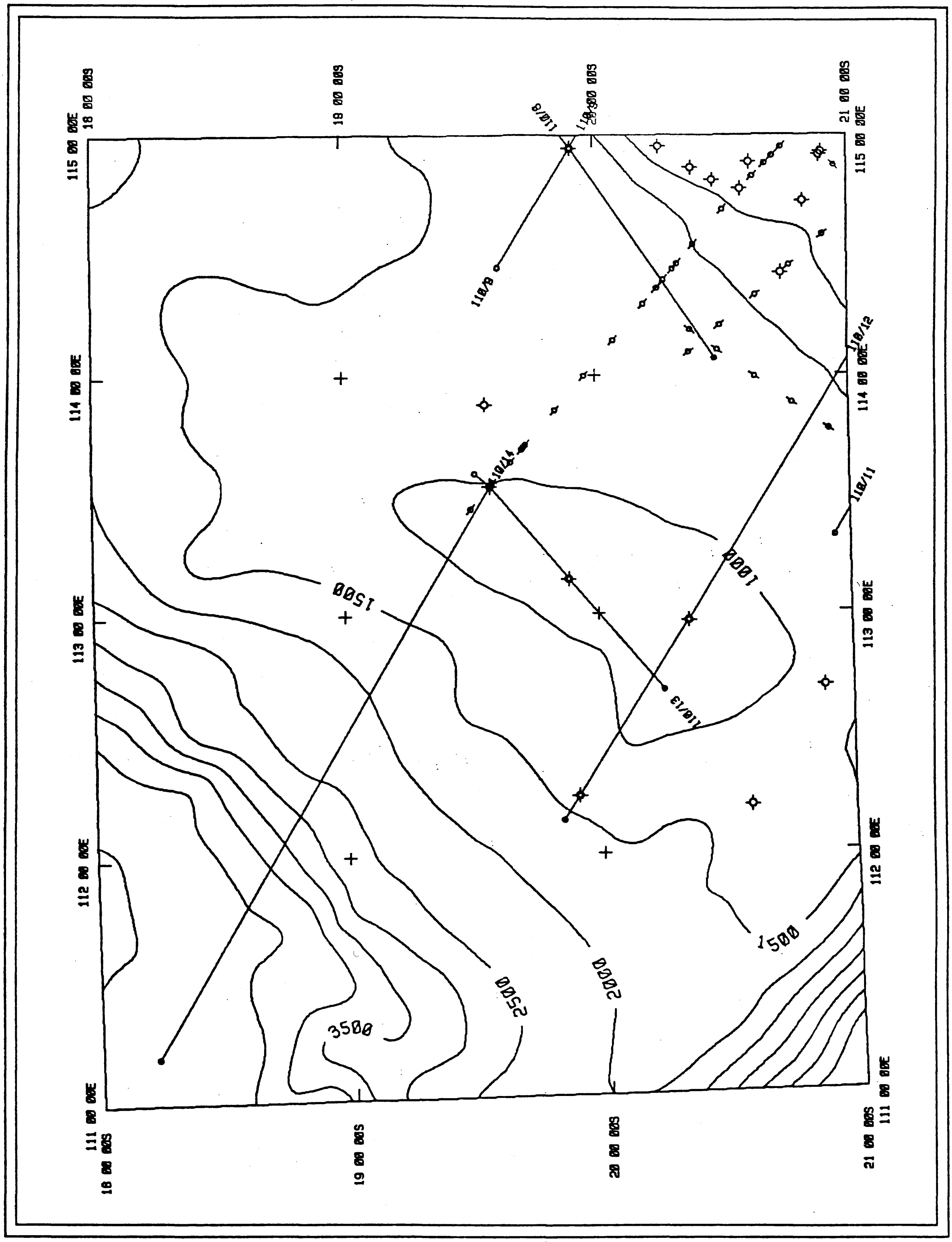

Figure 19: Proposed lines for SNOWS-II on the central and outer Exmouth Plateau. SNOWS-I lines are shown with shot-point symbols.