Deep structure of the Browse Basin region, North West Shelf, Australia: Cruise proposal

by

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DEEP STRUCTURE OF THE BROWSE BASIN REGION, NORTH WEST SHELF, AUSTRALIA

CRUISE PROPOSAL

Project 121.28

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Australian Geological Survey Organisation

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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EXECUTIVE SUMMARY

The Browse Basin underlies the outer shelf and upper slope of the central part of Australia's North West Shelf, in water depths of 100-1000 m. Although the North West Shelf is generally considered to be one of Australia's most heavily explored offshore regions, there are significant portions of it, such as the offshore Canning and Browse Basins, that remain under-explored. Relatively little is known of the primary structural architecture of the basin systems of the North West Shelf, and the influence of that architecture on the occurrence of hydrocarbons. The Browse Basin study (AGSO Project 121.28 - Basin development and hydrocarbon potential of the Browse Basin and adjacent margin) is part of a major AGSO regional research program over the north western Australian margin, and has the following main objectives:

- Determine the regional structural framework of the Browse Basin and its relationship to adjacent features such as the Vulcan Sub-basin, Rowley Sub-basin, Scott Plateau and Kimberley Block;

- Define the broad deep-crustal structure of the region and develop a model explaining the tectonic, subsidence and thermal history of the basin in relation to the development of the continental margin and adjacent ocean basin (the Argo Abyssal Plain);

- Assess the effects of deep structure and reactivation on the development of known petroleum accumulations.

To address these objectives it is proposed that RV *Rig Seismic* be used to acquire about 3200 km (up to a maximum of 3600 km depending on contingencies) of deep seismic and other geophysical data along 11 lines tying 18 exploration wells in the Browse Basin/Scott Plateau region. The survey will also tie into the 1990 Vulcan Sub-basin survey (98) to the northeast, and the forthcoming survey over the offshore Canning Basin to the southwest.

In line with the Marine Geoscience and Petroleum Geology Program's (MGPGP's) most recent deep seismic surveys over the North West Shelf, the Browse Basin survey will use a 4800 m streamer, configured with 192 x 25 m active groups; data will be recorded with a 16 second record length, and a 2 millisecond sample interval; the seismic source will be dual airgun arrays with a total capacity of 49 litres, and will be fired every 50 metres to give 48-fold CDP coverage; and navigation will be by differential GPS. These parameters are the same as used on two surveys over the northern Carnarvon Basin (SNOWS-1 and SNOWS-2) and three surveys over the Bonaparte Basin - Timor Sea, and will also be used on the SNOWS-3 survey over the offshore Canning Basin, following the Browse survey. Using these parameters AGSO has consistently recorded reflections down to 8-12 seconds two-way time (12-20 km depth), as well as obtaining good resolution in the upper 6 seconds of data, which is normally the limit recorded by industry.

The proposed plan for the Browse Basin survey incorporates seven dip lines and four strike lines, and contains four main elements:

1. **Browse Basin dip lines:** 7 NW-SE oriented dip lines (BB-A to G) totalling 1711 km and tied to 18 wells. These lines extend from the Leveque Platform and Yampi Shelf in the

east, across the main Browse Basin (and what some consider to be the northern Rowley Sub-basin) depocentre to the Scott Plateau in the west.The lines cross all of the Browse Basin's main structural features - the Prudhoe Terrace, the Inner and Central Basin Arches, and the Barcoo, Scott Reef, Buffon and Seringapatam Trends.

2. **Browse Basin strike lines:** 4 NE-SW oriented strike lines (BB-H to K) totalling 1452 km and tied to 4 wells. One strike line(BB-H) will run adjacent to the Prudhoe Terrace and tie with another tie-line(to be collected on AGSO's current Malita Graben survey) running northeast into the Petrel Sub-basin; two lines (BB-I and J) will run along the main basin depocentre and tie into AGSO's Vulcan Sub-basin lines 98/005B and 98/009A; and an outer strike line (BB-K) will cross the inner part of the Scott Plateau (the Outer Browse Basin of Willis, 1988) adjacent to the Scott Reef Trend. The strike lines form an important component of the survey as they will image the change in style from the Vulcan Sub-basin in the north, to the Browse Basin in the south. They should also help define the major transfer/accommodation zones that appear to compartmentalise the basin, such as the NW-trending feature that separates the Leveque Platform and Yampi Shelf.

3. **Margin transects:** Northwest extensions of two dip lines (BB-E and G) totalling an extra 487 km, will create two deep crustal transects across the full width of the margin from unrifted cratonic basement near the coast, across the Browse Basin and adjacent Scott Plateau, and onto the Late Jurassic oceanic crust of the north-eastern Argo Abyssal Plain. These transects are critical to understanding the development of the Browse Basin within the context of the evolution of the whole north-western Australian continental margin.

4. **Crustal refraction line:** During this survey it is planned to obtain deep velocity data by placing seismic recording stations on Browse Island and on the Kimberley coast to obtain refraction and wide-angle reflection data during the shooting of line BB-C, in particular, and other lines in the area. These data will aid the identification of deep crustal boundaries and the crust-mantle boundary, and will test the feasibility of using ocean-bottom seismometers (OBS's) on future North West Shelf surveys.

The program proposed here assumes a 30 day cruise. While the 3200-3600 km of seismic data acquisition planned for this survey is very high, recent experience with similar surveys has shown that given reasonable weather conditions and high equipment reliability, 3200 km of seismic data is certainly possible. The seismic lines have been prioritised and all high priority lines will be shot on this survey. Any data not acquired as a result of adverse weather or serious equipment problems, or delays caused by external operational considerations, will be re-scheduled for acquisition during the Timor Sea/Browse Basin infill survey (late 1993), or a northern Scott Plateau survey (1994).

INTRODUCTION

In 1990 AGSO's Marine Geoscience and Petroleum Geology Program (MGPGP) commenced a program of deep seismic acquisition (up to 16 second records) over the north-western margin of Australia, with the objective of obtaining a full regional data set from the North West Cape in the south, to the western Arafura Sea in the north (Fig. 1). This region was seen to be the most prospective part of Australia's margin outside of the Bass Strait basin system, and likely to be the major source of Australia's future petroleum supplies as production from Bass Strait decreases. While portions of the North West Shelf have been quite intensively explored since the 1960's, there has been very little recent analysis of its regional structural framework incorporating modern extensional tectonic concepts for the formation of margins and their basins (e.g. Etheridge & others, 1988; Lister & others, 1991), collisional tectonic concepts (e.g. Beaumont, 1980; Allen and Homewood, 1986), and the significant contribution of intraplate stress to reactivation of the primary basin-forming structures (e.g. Etheridge & others, 1991).

The MGPGP program over the north-western Australian margin is designed to establish the gross architecture of the North West Shelf region by imaging the primary margin and basin-forming structures. This approach will improve understanding of the relationship between plate tectonic setting, basin formation and reactivation, and may highlight critical regional factors controlling the petroleum system within each basin element. It will also provide new insights into the linkages between the major structural elements and allow revision of the gross structure of the region. Such information is vital to the development of new exploration strategies for the North West Shelf, and will aid future basin framework and resource studies.

The main objectives of the program are to:

- determine the broad regional structural framework by examining the relationships between the major structural elements;
- determine the deep crustal structure;
- assess the influence of deep structure on the development of the major hydrocarbon fields and plays in this relatively well-explored area, 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 exploration wells throughout the region to allow regional seismic correlations.

To address these objectives, MGPGP devised a margin-wide program of deep-seismic acquisition. It is expected that, by mid-1994, there will be a regional grid of up to 30 000 km of deep-seismic data extending from North West Cape to the eastern Timor Sea. An important aspect of this program is the acquisition of a series of full-margin 'dip' transects (at least one in each major basinal element), extending, where possible, from unrifted cratonic basement near the coast across the margin to beyond the continent-ocean or plate boundary, and at least two 'strike' transects that will extend along the full length of the shelf. These transects should provide a new understanding of the development of the North West Shelf basin system, within the context of the development of the whole continental margin province.

Recent interpretation of AGSO's deep seismic data in the Bass Strait - Gippsland Basin region, where refraction data are also available, has shown that deep seismic events can be

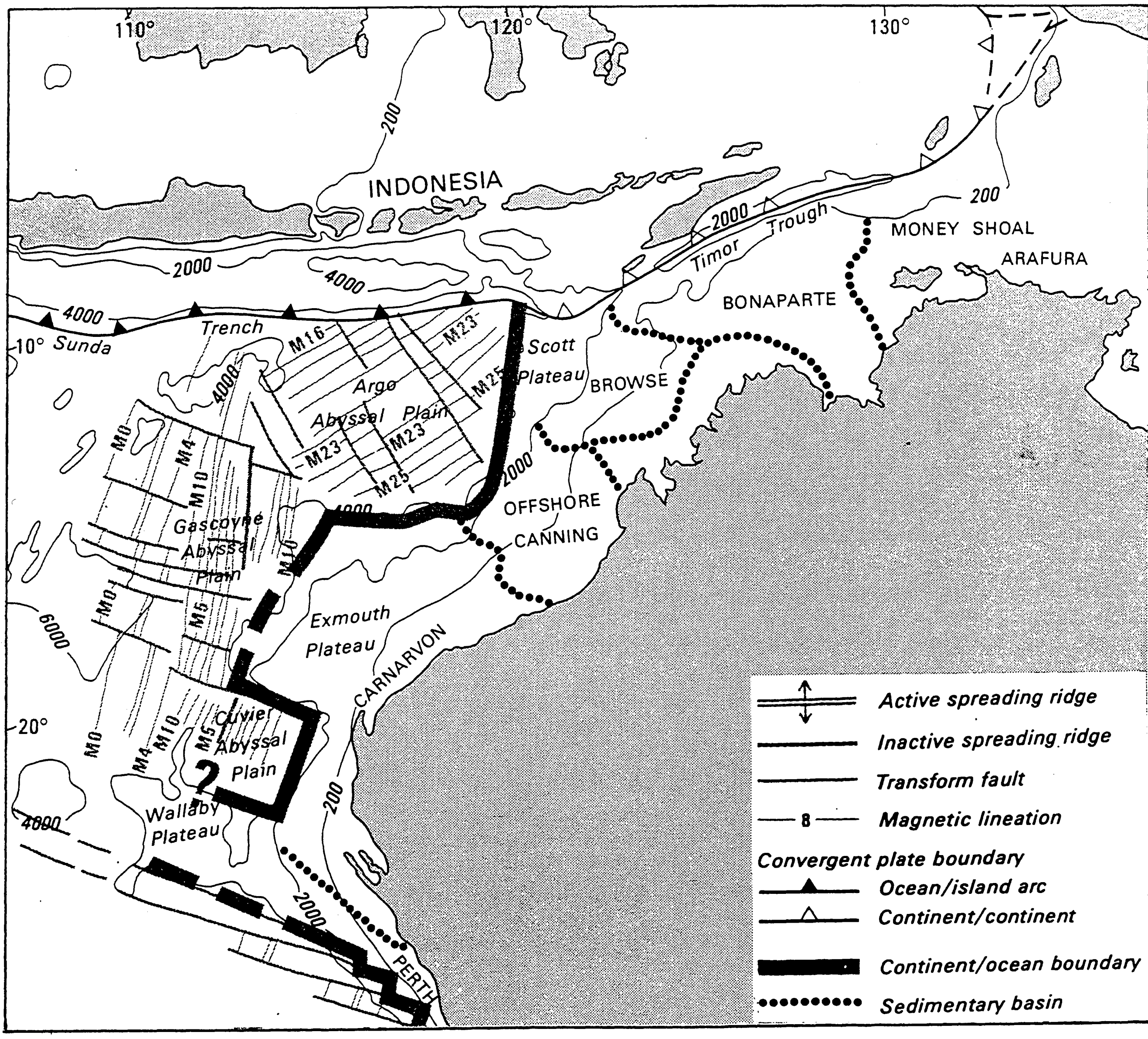

Figure 1. Regional tectonic and basin setting off northwestern Australia.

unequivocally linked to major discontinuities in the crust (Willcox & others, 1992). The value of such data sets to hydrocarbon exploration is becoming more widely acknowledged as it is seen that data can be recorded which have 'industry-standard' resolution in the top part of the section, while also clearly imaging the deep basin-forming structures that underpin the targets of interest to the exploration industry. The deep seismic data is leading to revision of many pre-existing ideas on basin formation and development around Australia. For example:

- many of the basin-forming episodes are much older than has generally been accepted, and the structures seen on conventional data are, for the most part, reactivation effects controlled by deeper structures;
- strike-slip movement and wrenching have been important throughout the development of many of the basin systems;
- many of Australia's oil and gas fields are reservoired in structures that result from reactivation of a pre-existing (primary) structure; and
- there are fundamental linkages between elements along entire margins, resulting from development under the influence of common stress fields.

In particular, on the North West Shelf, probably the single most significant observation to come out of the deep seismic data to date is that the initial basin-forming extension occurred in the Early Palaeozoic, and was probably the only 'simple' extensional episode in the development of the region. Also, it appears that many of the structures that have been interpreted as primary features in conventional seismic data are really reactivation features (as has been suggested by Etheridge & others, 1991) that have been localised along the original basin-forming dislocations.

So far MGPGP has completed five deep seismic surveys in the North West Shelf region (Appendix 1), and a survey of the Malita Graben area is currently underway (May 1993). The final stage of this deep seismic program, which is considered to be only a "first pass" examination of the region, is scheduled to commence in June 1993 with surveys over the Browse Basin (this proposal), and then the offshore Canning Basin (SNOWS-3 ; Stagg, in prep), with the possibility of two further infill surveys to obtain additional information in critical areas. Other complementary surveys are also planned for the Roti Basin area and parts of the Timor Trough.

EXPLORATION HISTORY

A detailed review of the history of petroleum exploration in the Browse Basin is given in Willis (1988) and Cadman & others (1991).

Exploration commenced in 1963 when an aeromagnetic survey of the area by Woodside (Lakes Entrance) Oil Company N.L. revealed the presence of a sedimentary basin seaward of the Kimberley Block. Between 1964 and 1968, 4100 km of seismic data were collected in the area, mainly during reconnaissance surveys, with some semi-detailed coverage in the Scott Reef area. Additional regional coverage was provided by a Bureau of Mineral Resources (BMR) gravity, magnetic and sparker survey (Whitworth, 1969). In 1969, existing exploration tenements in the Browse Basin were converted into several new permits, and the pace of exploration accelerated. During the next five years about 22,000 km of seismic data were acquired, mainly at 24 fold coverage using airguns. Most of the 1964 to 1978 surveys were carried out with BOC of Australia Ltd and Woodside as operators. However, after 1978 several other companies conducted seismic surveys in the area. In 1985, Geophysical Service Inc. (GSI) carried out a 2700 km non-exclusive seismic survey that tied many of the wells in the Leveque Shelf area, and these data proved useful for regional evaluation. In 1988, Bridge Oil carried out the first 3D seismic survey in the basin in the area around Lyhner-1 well.

Major advances in data acquisition and processing technology since the start of exploration in the Browse Basin have produced a significant improvement in seismic data quality. In particular, many of the difficulties caused by poor seismic transmission and severe multiples related to the thick, high velocity Tertiary carbonates that occur over much of the Browse Basin, were overcome by the f-k domain multiple attenuation program introduced in 1978, and the use of long streamers. However, although the post-1978 data was superior to earlier data, it was generally more restricted in areal coverage as many of the surveys were of a semi-detailed to detailed nature.

The first well in the area, Ashmore Reef-1, was drilled on the northern margin of the Browse Basin in 1967. The first well drilled in the Browse Basin proper was Leveque-1, which was drilled in 1970 as a stratigraphic test on the south-eastern margin of the basin. During the episode of accelerated exploration activity from 1970-1975 ten wells were drilled in the basin including the major gas and condensate discovery at Scott Reef-1 in 1971. In the following years a series of major gas and condensate discoveries, and minor oil shows were made throughout the basin. Arquebus-1 (Haston & Farrelly, 1993), drilled in 1992, is the most recently completed well in the Browse Basin. Scheherezade-1 is currently being drilled about 20 km southwest of Arquebus-1.

To date some 34 wells have been drilled within and immediately adjacent to the Browse Basin - a summary of most of these is given in Appendix 2, and there locations are shown in Figure 2. The discovery of significant gas and condensate accumulations, minor oil and a variety of hydrocarbon shows indicates that viable source rocks are present within the basin.

By 1989 exploration had waned in the Browse Basin and permits were generally confined to the western half of the basin. Gazettal of acreage in 1991 led to renewed interest in the Browse Basin, and today much of the basin is under lease.

Only regional reconnaissance seismic data has been collected over the Scott Plateau, to the west of the Browse Basin, mainly by government organisations such as BMR, research institutes such as Lamont-Doherty Geological Observatory, and by the new ventures groups of oil companies such as Shell International Petroleum. The first survey was carried out in 1967 by BMR, and the most recent survey was in 1977 by the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR, Germany). A summary of all of the seismic surveys over the Scott Plateau is given in Appendix 3. Some dredging and coring has been conducted over the margins of the Scott Plateau during the 1977 BGR **Valdivia** survey (Hinz & others, 1978), and by BMR using **Rig Seismic** in 1990 (Colwell, Graham & others, 1990). A synthesis of much of this data is contained in Stagg & Exon (1981).

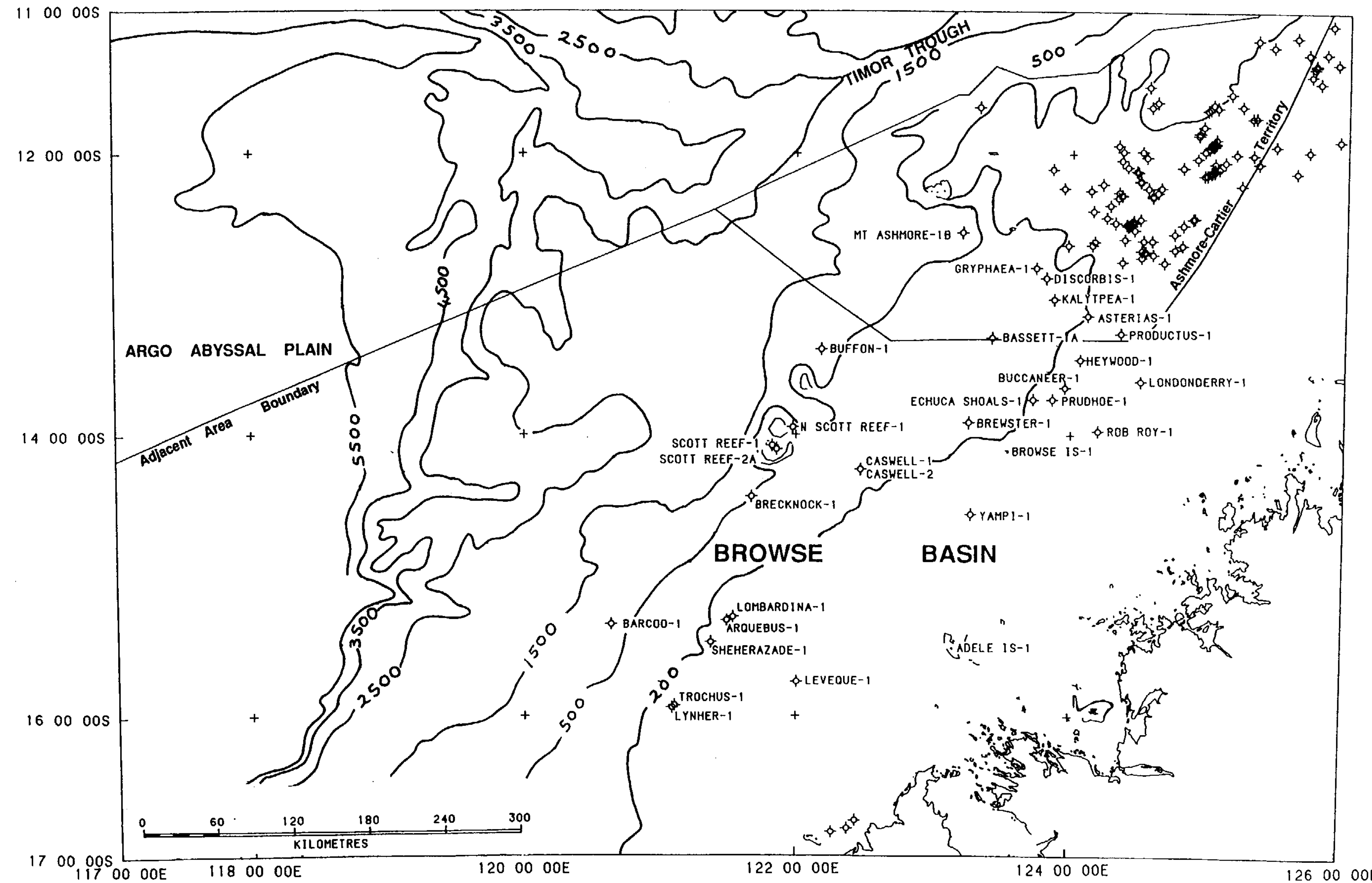

Figure 2. Location of the Browse Basin showing well locations.

REGIONAL GEOLOGY

Much of the following discussion on the geology of the Browse Basin area is summarised from Willis (1988), Elliott (1990), Cadman & others (1991) and Wilmot & others (1993), and for the Scott Plateau area from Stagg (1978) and Stagg & Exon (1981). Some of these studies draw on earlier work and syntheses of aspects of the geology of the region by Halse & Hayes (1971), Crostella (1976), Powell (1976), Allen & others (1978, 1979), Apthorpe (1979), Passmore (1980), and Barter & others, (1982), as well as on studies of the whole North West Shelf province such as Forrest & Horstman (1986), Bradshaw & others (1988) and Cockbain (1989).

BASIN SETTING

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. The principal sedimentary basins include, from south to north, the northern Carnarvon, offshore Canning, Browse, and Bonaparte Basins (Fig. 1). While the majority of the sedimentary fill in most of these basins is of Mesozoic age, all of the basins are now known to have begun forming in the Palaeozoic.

To date, the principal hydrocarbon discoveries in the region 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).

BASIN DEFINITION

The Browse Basin is a northeast-southwest trending offshore sedimentary basin underlying approximately 140 000 km^2 of Australia's north-western continental shelf and slope between latitudes 13°S and 16°S, and longitudes 120°30'E and 124°30'E (Fig. 1). Most of the basin lies in more than 200 m of water, with water depths increasing uniformly from 100 m near its eastern margin to about 500 m on the eastern margin of the Barcoo-Scott Reef trend, and deepening rapidly to more than 1000 m just west of this trend. The Browse Basin is bounded in the east by the Kimberley Block, which extends offshore as the Yampi Shelf and Leveque Platform, and in the west by the 2000-2500 m deep Scott Plateau (Fig. 3). The Ashmore Platform forms much of the northern boundary of the basin, and further east a complex saddle, which is a structural extension of the Londonderry High, separates it from the Vulcan Sub-basin. Its southern boundary is poorly defined, but in the west it extends at least as far south as Lynher-1 well, where it starts to grade into the Rowley Sub-basin of the Canning Basin.

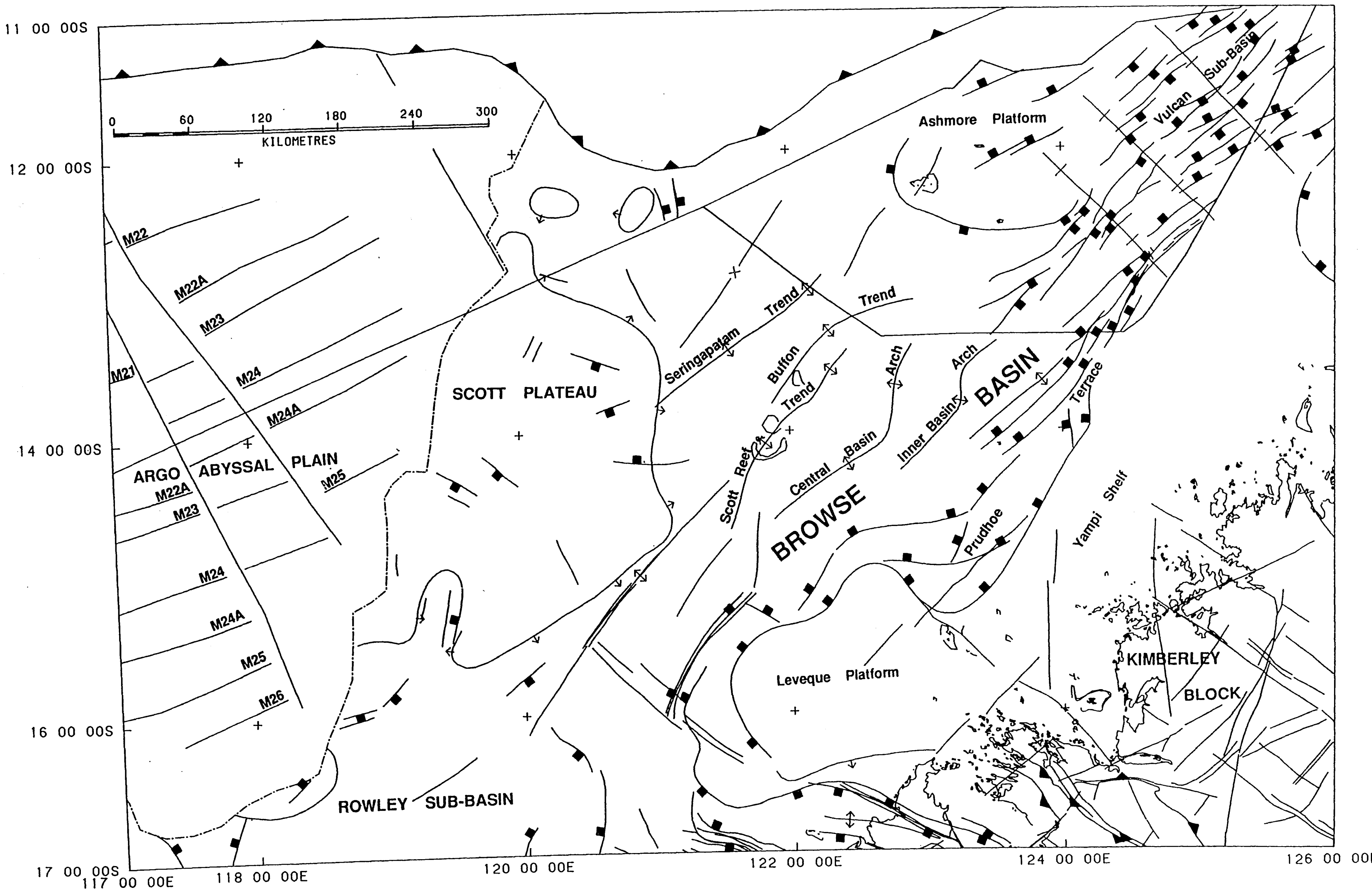

Figure 3. Stuctural elements map of the Browse Basin region (based on Stagg, 1993).

Further east the southern margin of the Browse Basin is defined by the Leveque Platform and its extensions.

STRUCTURAL ELEMENTS

The major structural elements of the Browse Basin region are shown on the map in Figure 3, in section in Figure 4, and are briefly described in the following summary based on Cadman & others (1991).

The Kimberley Block is a stable shield area consisting of Archaean and Proterozoic plutonics and metamorphics overlain by locally deformed sediments and minor volcanics, and forms the eastern boundary to the Browse Basin. The Kimberley Block, which has been down-faulted to the west in a series of terraces and plunges beneath the Phanerozoic Browse Basin sediments, represents regional economic basement and is considered to have been a major source for Browse Basin sediments (Allen & others, 1978).

The Yampi Shelf forms the eastern flank of much of the Browse Basin, and consists of a seaward thickening wedge of Permian, Late Jurassic-Cretaceous and Tertiary sediments directly overlying basement. The Yampi Shelf is contiguous with the Londonderry Arch (High) to the north and the Leveque Shelf to the south. Small offsets in the NE-trend of the western margin of the Yampi Shelf appear to occur between Rob Roy-1 and Londonderry-1 wells.

The Leveque Platform is generally considered to be the southern extension of the Yampi Shelf and the Prudhoe Terrace. Basement beneath the Platform is overlain by Late Jurassic and Cretaceous sediments. The southern boundary of the Leveque Platform is controlled by the seaward extension of the WNW-ESE fault system that defines the northern margin of the Canning Basin, and the western edge of the Platform is defined by major NE-SW down-to-basin normal faults. Significant offsets in the overall NE-trend of the outer edge of the Leveque Platform, the major NW-trending offset of the margins of the Leveque Platform and Yampi Shelf, and more subtle offsets and changes in character of the outer edge of the Yampi Shelf, as mentioned above, may correspond with NW-trending transfer or accommodation zones. These zones may compartmentalise the Browse Basin in a similar manner to NW-trending features described in the Vulcan Sub-basin to the north (O'Brien & others, 1993). Both the Leveque Platform and Yampi Shelf exhibit little faulting or structural relief.

The Prudhoe Terrace is separated from the Yampi Shelf to the east by a NE-trending hinge zone, and the central part of the Browse Basin to the west by a series of major NE/ENE-trending down-to-basin normal faults. The Terrace is underlain by steeply dipping basement onlapped by a wedge of block faulted Permian sediments. These late Palaeozoic horst blocks are in turn onlapped by Late Jurassic sandstones, siltstones and claystones (Prudhoe-1). Up to 3500 m of Mesozoic section may be present on the Prudhoe Terrace.

The Central Browse Basin is bounded to the east by the Prudhoe Terrace, and to the west by the Outer Browse Basin of Willis (1988) and the Scott Plateau. Up to 11 000 m of late Palaeozoic and younger clastic, volcanic and carbonate sediments may have accumulated in

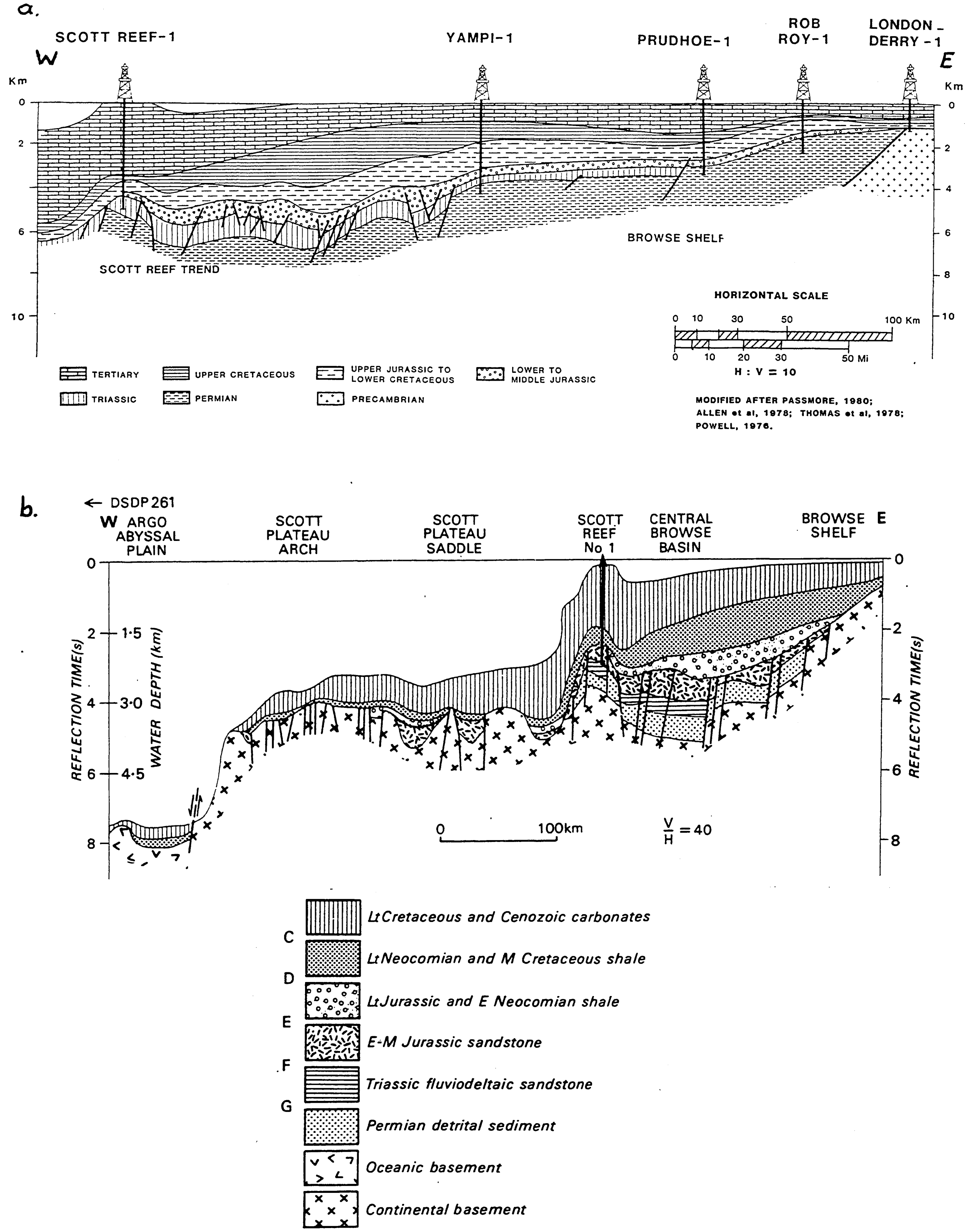

Figure 4. Schematic structural sections across (a) the Browse Basin (after Forrest & Horstman, 1986), and (b) the Browse Basin/Scott Plateau margin (after von Rad & Exon, 1983).

this part of the basin (Allen & others, 1978; Elliott, 1990). Faulting is generally sub-parallel to the overall NE-SW structural grain of the basin, and appears to have been active until at least the Early Cretaceous (Allen & others, 1978). The main structural features of the central Browse Basin are the Inner and Central Basin Arches, and the Scott Reef Trend, which forms the western margin of the central basin. Although all these features exhibit the typical northeast regional trend, they appear to be relatively complex features, perhaps affected by a cross-cutting NW-trend.

The Outer Browse Basin lies between the northern Scott Plateau in the west, and the Scott Reef Trend in the east (Willis, 1988). The main structural features within this relatively poorly known part of the Browse Basin are the NE/ENE-trending Seringapatam and Buffon Trends.

The Scott Plateau, which lies at an average water depth of about 2500 m, forms a subsided oceanward margin to the Browse Basin. Regional seismic data suggests that the plateau proper is underlain by relatively shallow Palaeozoic and basement rocks overlain by an average of 1000 m of Late Cretaceous and Cainozoic carbonates. Permian to Jurassic Browse Basin sediments appear to pinch out on the eastern flank of the Scott Plateau, although fault controlled lows could contain Triassic and Jurassic section (Powell, 1976), particularly just west of the Scott Reef Trend beneath the Scott Plateau Saddle (Stagg & Exon, 1981). Throughout much of the period from the Carboniferous to Late Jurassic, when continental break-up occurred and seafloor spreading began, the Scott Plateau was probably above sea level and providing a source of clastic sediments for the developing Browse Basin (Stagg, 1978).

The Ashmore Platform marks the northern limit of Browse Basin sedimentation, and consists of a large uplifted block of Triassic sediments underlain by an unknown thickness of Palaeozoic rocks. The Triassic section is unconformably overlain by Cretaceous claystones, although Ashmore Reef-1 well, drilled on the southern margin of the platform, intersected Triassic section overlain by volcanics of probable Middle Jurassic age (Wilmot & others, 1993), which in turn is overlain by a Late Jurassic sequence.

The Vulcan Sub-basin appears to connect with the northern Browse Basin across a complex saddle, which runs from the Ashmore Platform to the Londonderry Arch. The Sub-basin is a NE-trending Late Jurassic depocentre containing a number of intra-sub-basin terraces and graben (Patillo & Nicholls, 1990). An AGSO aeromagnetic study of the Vulcan Sub-basin (O'Brien & others, 1992) has shown that depth-to-magnetic-basement increases from 5-8 km in the northern Browse Basin to 10-12 km in the southern Vulcan Sub-basin, across a major NW-trending linear magnetic feature. O'Brien & others (1993) interpret the NW-trending feature to be a major transfer or accommodation zone formed during a Permo-Carboniferous NW-SE directed extensional episode that initiated the Westralian Superbasin system along the North West Shelf (Yeates & others, 1987).

STRUCTURAL HISTORY AND MARGIN DEVELOPMENT

AGSO deep crustal seismic and aeromagnetic studies of the Vulcan and Petrel Sub-basins to the north of the Browse Basin, have resulted in a new generalised structural history being proposed for the Timor Sea area (O'Brien & others, 1993). Given the significant and widespread nature of many of the structural events it is likely that the development of the Browse Basin was also strongly influenced by them. O'Brien & others (1993) suggested that seven major episodes of structuring have affected the Timor Sea region as summarised in Appendix 4:

1. **A major Late Devonian-Early Carboniferous** NE-SW directed extensional event, which initiated features such as the Petrel Sub-basin.

2. **A major Late Carboniferous-Early Permian** NW-SE directed extensional event, which initiated the Westralian Superbasin system, including the Browse Basin.

3. **A Late Permian-end Triassic** thermal subsidence phase with little faulting.

4. **A latest Triassic-Early Jurassic** N-S to NNW-SSE compressional event, which resulted in reactivation of the Permo-Carboniferous Westralian Superbasin fault systems.

5. **A latest Callovian-Early Oxfordian** NE-SW to NNE-SSW directed minor extensional event, which quickly led to continental break-up and seafloor spreading, which formed the Argo Abyssal Plain.

6. **A Late Jurassic-Early Cretaceous** NW-SW to NNW-SSW compressional event resulted in transpressional reactivation of the Permo-Carboniferous normal fault networks.

7. **A mid-Miocene to Recent** ENE-WSW compressional event related to collision along the northern edge of the Australian craton resulted in widespread fault reactivation.

Using the deep crustal seismic and aeromagnetic data, combined with regional, image-processed bathymetric and gravity data, O'Brien & others (1993) made a preliminary examination of the development of a large part of the north-western Australian margin (Fig. 5) in terms of modern extensional tectonic concepts, and attempted to subdivide the margin into upper and lower plate rifted margin provinces (UPRM and LPRM, respectively) using the models of Lister & others (1986, 1991) and Etheridge & others (1988, 1990). Recognition of these margin types is important to hydrocarbon exploration because they are each characterised by their own style of structuring, subsidence and thermal history, which, in turn, strongly control facies development, and hydrocarbon maturation and migration.

O'Brien & others (1993) suggested that the 650 km wide Vulcan-Sahul tectonic province (the Ashmore and Sahul Platform area; Fig. 5) formed as part of an UPRM during the Late Carboniferous to Early Permian. They suggested that other tectonic provinces of similar size are clearly visible on image-processed bathymetric data (O'Brien & others, 1993, Fig. 16) to the southwest and the northeast of the Vulcan-Sahul province (the Browse and the Calder tectonic provinces, respectively). These two adjacent provinces have, however, exhibited a somewhat different structural/subsidence behaviour to the Vulcan-Sahul province. Well subsidence studies (Struckmeyer, 1992) show that both the Browse and Calder provinces were characterised by rapid subsidence throughout the Cretaceous and Tertiary, where as the Vulcan-Sahul province remained relatively "high" during the same interval.

O'Brien & others (1993) speculated that the most likely explanation for these differences is that the two flanking provinces formed as LPRMs during the Late Carboniferous to Early

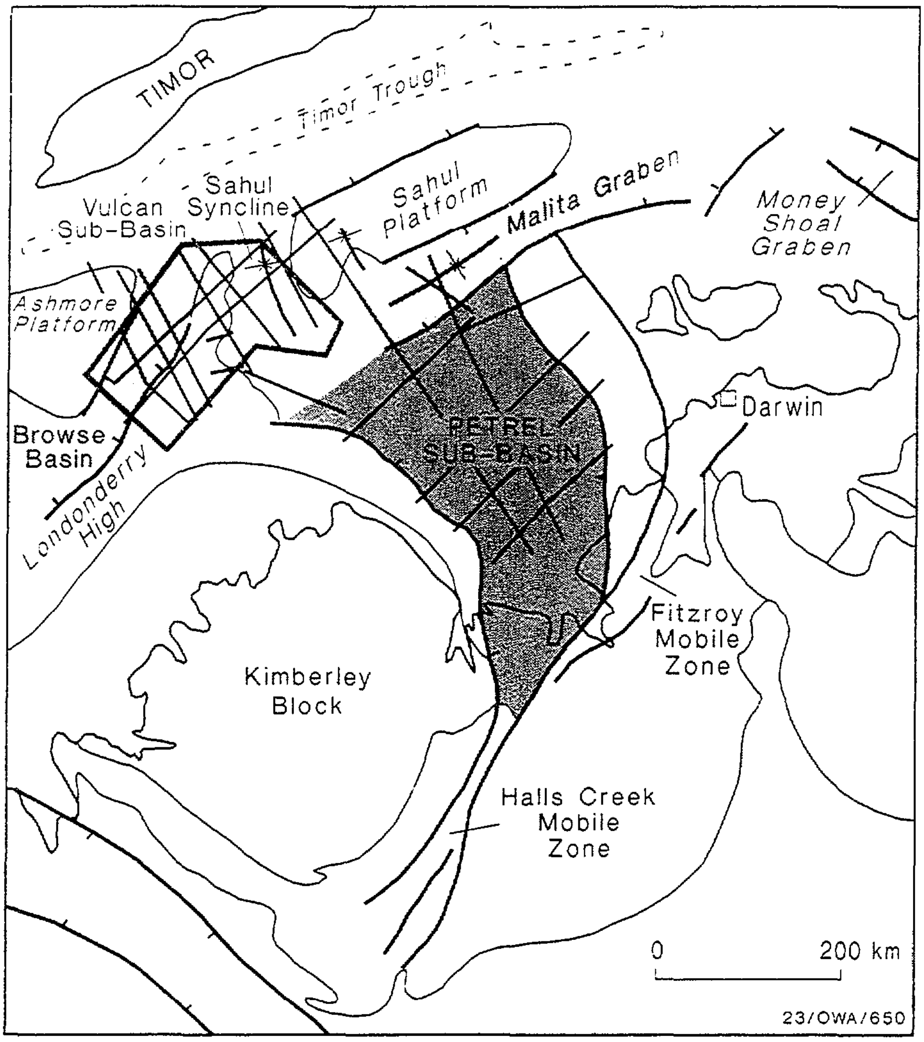

Figure 5. Geology of Timor Sea, north-western Australia showing the relationship between onshore and offshore tectonic elements. The positions of AGSO's deep crustal seismic lines are indicated, as well as the area covered by the Vulcan Sub-basin aeromagnetic survey (after O'Brien & others, 1993).

Permian, and are separated from the Vulcan-Sahul UPRM by major NW-trending accommodation zones. LPRMs characteristically subside at greater rates than do UPRMs (Etheridge & others, 1988), particularly during the post-extensional phase, because they are normally underpinned by highly thinned lower crust and upper mantle, and have experienced a higher heat-flow regime. The problem with this model is that O'Brien & others (1993) relate the different Cretaceous-Tertiary subsidence histories of the various margin provinces to Late Carboniferous-Early Permian extension. Although this event produced the widespread Late Permian-Triassic thermal sag subsidence phase, it is unlikely that it could be directly related to an event some 50 Ma later. Perhaps the latest Callovian-Early Oxfordian extension event that produced only minor upper crustal extension in the Vulcan-Sahul province, and lead to seafloor spreading in the Argo Abyssal Plain, was accompanied by some deep thinning beneath the Browse and Calder provinces, resulting in substantial thermal subsidence in these provinces during the Cretaceous. AGSO's deep crustal seismic surveys over the Browse and Calder provinces should allow the various models to be tested.

SEAFLOOR SPREADING HISTORY

The pattern of break-up in the Argo Abyssal Plain off north-western Australia is important to the development of the northern Exmouth Plateau, and Browse and offshore Canning Basins (Fig. 1). Larson (1975) first identified the anomaly series, which gave the original 160 Ma (late Oxfordian - ~145 Ma on the time scale of Burger,1990a, and ~ 155 Ma using Young & Claoue-Long,1991) break-up age, but recent drilling of the south-eastern Argo Abyssal Plain (Site 765) during Leg 123 of the Ocean Drilling Program (ODP) discovered much younger sediments overlying oceanic basement. A late Berriasian to earliest Valanginian age was initially suggested (Baumgartner & Marcoux, 1989; Gradstein, Ludden & others, 1990). However, a recent K/Ar age on a basaltic hyloclastite directly overlying basaltic basement and underlying the oldest sediments gave 155.3±3.4 Ma (Ludden, 1992). That is, mid-Callovian using Burger (1990a), or latest Oxfordian using Young & Claoue-Long (1991), which is based on calibration using the SHRIMP ion microprobe. Thus Site 765 drilled on magnetic anomaly M26 (late Oxfordian stage; Burger, 1990a) gives a minimum radiometrically derived break-up age of 155 Ma. This radiometric age is in agreement with the age calibration of the late Oxfordian stage using the Young & Claoue-Long (1991) timescale. Clearly this has significant implications for the timing of peak thermal conditions adjacent to much of the Northwest Shelf region.

Given that there has been Tertiary convergence between the northern Australian margin and the Indonesian Arc, and ongoing collision at least as young as Pliocene adjacent to Timor, it is probably reasonable to assume that the Argo Abyssal Plain spreading pattern and Oxfordian break-up, extended some distance to the northeast, seaward of the Bonaparte Basin. However, as continental break-up is thought to get progressively older in a clock-wise direction towards New Guinea (Veevers & others, 1991), it is possible that seafloor spreading began even earlier, perhaps in the Callovian, to the north of the western Arafura Basin.

STRATIGRAPHY

The Browse Basin contains over 11 000 m of Carboniferous to Recent sediment (Allen & others, 1978; Elliott, 1990) as summarised on the stratigraphic column in Figure 6. Regional geological considerations suggest that older Palaeozoic rocks may underlie the Browse Basin sequence (Passmore, 1980); however, the presence and lithology of such rocks is speculative as they have not been intersected by any wells in the basin.

The Browse Basin has no formally defined stratigraphic nomenclature and various authors have used a variety of informal terms, including Bonaparte Basin formation and group names. There is considerable variability in lithology throughout the basin, and a detailed stratigraphic analysis of the whole basin is needed before appropriate formal nomenclature can be applied and developed. The following brief summary of Browse Basin stratigraphy is based on the time-slice approach used by Wilmot & others (1993).

A mid-Carboniferous sequence of carbonates and thin interbedded sandstones deposited in a relatively shallow marine environment overlie low grade metamorphics of the Kimberley Block complex on the Prudhoe Terrace and outer Yampi Shelf area. The metamorphic rocks, which produce reflection events, may represent part of the early Gondwana and/or late Larapintine Petroleum System (Bradshaw, 1993, in press).

Permian interbedded clastics and carbonates overlie the mid-Carboniferous sequence. They appear to have been deposited in a basin sag in environments ranging from deltaic during the Early Permian, to shallow marine during the Late Permian. Regional uplift and erosion occurred in the late Permian, and appears to have mainly affected the Yampi Shelf/Prudhoe Terrace area. However, because the Permian sequence has not been intersected in the centre of the basin the extent of this structuring and erosional phase is uncertain. Beneath the northern Prudhoe Terrace the Permo-Carboniferous section has been extensively block faulted.

Seismic data indicate that a relatively thick and conformable Triassic section overlies Permian sequences in the centre of the basin. The Triassic section thins to the east and has been eroded from the eastern Yampi Shelf, and in some cases is truncated against major basin bounding faults. The Early Triassic sediments consist of marine claystones, siltstones and mudstones deposited during a major marine transgression. Late Triassic sediments consist of fluvio-deltaic sandstones and claystones; however, they are mainly carbonates in the southern Ashmore Platform area. An extensive erosional episode occurred during the Carnian to Ladinian (mid-late Triassic) and the resultant unconformity marks the boundary between the Westralian and the Gondwanan Petroleum Systems (Bradshaw, 1993, in press). Major regional uplift and faulting occurred towards the end of the Triassic and produced many of the key structural features that are part of the present day Browse Basin.

Seismic data indicate that a thick Jurassic trough occurs in the central part of the Browse Basin (in the vicinity of the Caswell well), and unconformably overlies the Triassic section. This trough extends southwest into the Rowley Sub-basin and northeast into the Bassett-Heywood area (Fig. 9). The Jurassic section, which consists of fluvio-deltaic to marginal marine siliciclastics, claystones and minor carbonates, thins onto the basin margins and intra-basin highs. Volcanic activity occurred during the Jurassic, mainly along the western and eastern margins of the basin. Tectonic activity and erosion associated with the onset of seafloor spreading in the Argo Abyssal Plain resulted in a major unconformity between Early-

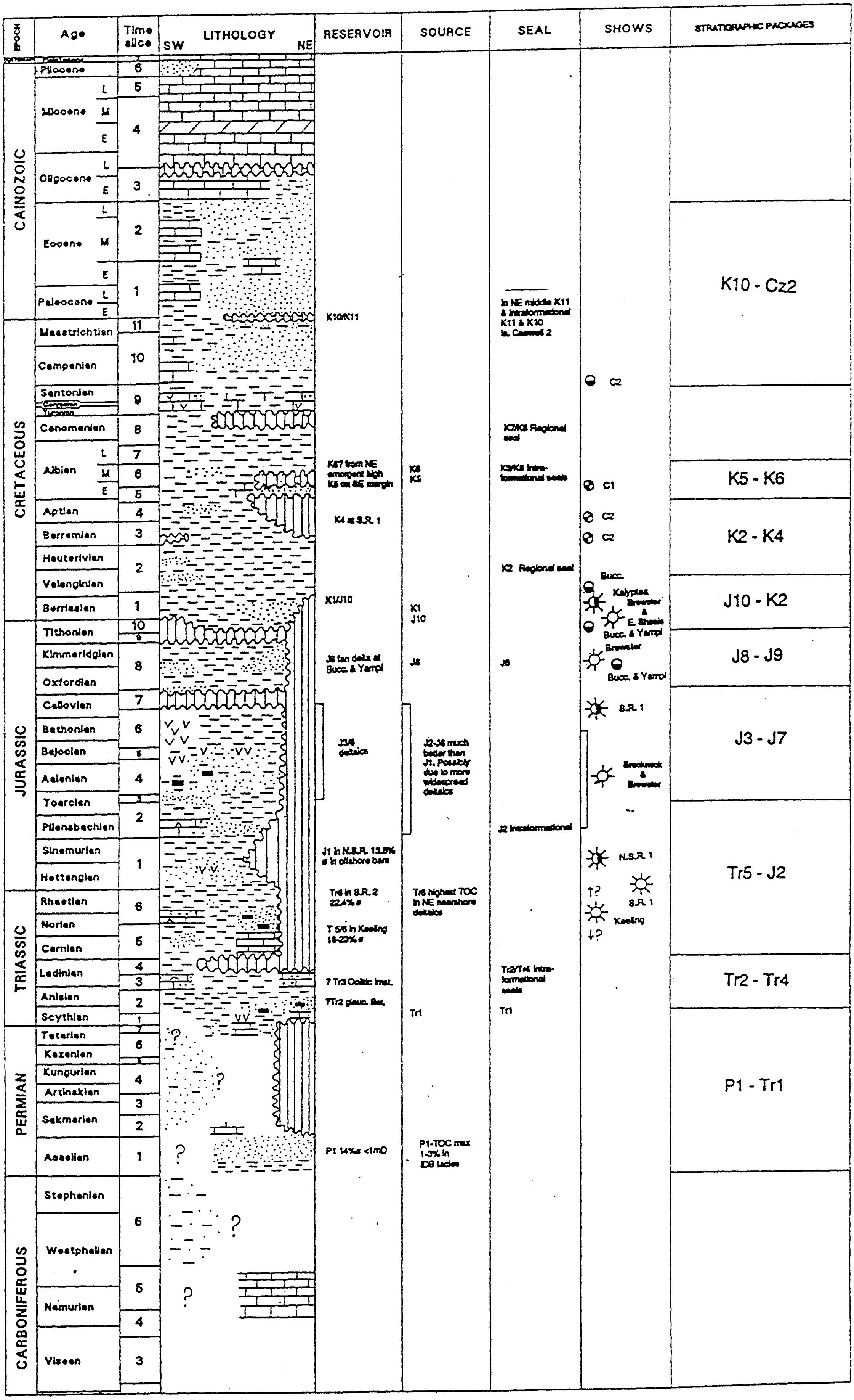

Figure 6. Summary stratigraphic column for the Browse Basin (after Wilmot & others, 1993).

Middle Jurassic and Late Jurassic sequences. Another major, but less extensive erosional phase occurred during the Tithonian, and marks a facies change from low energy marine sediments to higher energy, nearshore sediments over the eastern margin of the basin. Low energy marine sediments were mainly deposited over the western and southern margins of the basin during this period.

This phase of sedimentation was followed by the widespread deposition of thick transgressive marine claystones of Early Cretaceous age. The seismic characteristics of this sequence vary from a westwards progradational unit at the base, to sheet drape at the top. An Albian/Aptian unconformity is recognised on seismic data over the north-eastern part of the Browse Basin, and may have resulted from uplift and erosion and/or a mid-Aptian sealevel fall. This unconformity marks a facies change from low energy marine claystones to a higher energy marine sandstone and siltstone sequence. Subsidence of the western margin of the basin may have continued during the Albian.

Relatively thick low energy marine claystone and mudstone sequences with minor calcarenite, siltstone and marl were deposited over much of the Browse Basin during the Albian and Cenomanian. During the Turonian to Santonian there was an increase in carbonate deposition throughout the basin in the form of marls, calcarenites and calcilutites. This may represent a change in oceanic circulation from restricted marine to open marine environments. A distinct Turonian unconformity underlies this section over most areas of the basin. During the Campanian and Maastrichtian carbonates continued to be deposited on the western margin, while a gradual regression lead to the deposition of clastics in the northeast.

Deposition continued throughout the Tertiary with several cycles of regression and transgression. During the Paleocene and early Eocene, a relatively thick mass flow sandstone sequence was deposited across the northern and north-eastern part of the basin. Clastic sedimentation
decreased towards the end of the Eocene and carbonate sediments were deposited during the rest of the Cainozoic.

HYDROCARBON ACCUMULATIONS

As mentioned above, Wilmot & others (1993) consider the Browse Basin to be a post Alice Springs Orogeny depocentre, containing Gondwanan and Westralian Petroleum Systems, separated by a major late Triassic unconformity. The Gondwanan System ranges in age from mid-Carboniferous to late Triassic, and has the potential for plays similar to the discoveries in the Petrel Sub-basin and onshore Perth Basin. To date all the successful plays in the Browse Basin are part of the Westralian System, such as the giant gas and condensate discoveries in Late Triassic-Early Jurassic nearshore to deltaic sands at Scott Reef-1 and North Scott Reef-1, and gas/condensate in mid-Jurassic deltaic sands at Brecknock-1. The thick Middle to Late Jurassic marine oil prone source rock that is characteristic of the Westralian System in the Barrow-Dampier, Vulcan and Papuan basins, is less well developed in the Browse Basin. However, the occurrence of significant hydrocarbon shows that other source intervals must be present.

The first significant gas and condensate discovery in the Browse Basin was made at Scott Reef-1 in 1971. In the following years a series of major gas and condensate discoveries, and some oil shows, were recorded throughout the basin - live oil in Heywood-1 in 1974; gas in Scott Reef-2A in 1977; live oil and gas in Caswell-1 in 1978; gas in Brecknock-1 in 1979; gas in Brewster-1A in 1980; gas and condensate in North Scott Reef-1 in 1982; oil and gas in Caswell-2 in 1983; and gas in Echuca Shoals-1 in 1984. Other minor hydrocarbon shows were obtained in Asterias-1 (1987), Barcoo-1 (1979), Buccaneer-1 (1990), Buffon-1 (1980), Delta-1 (1988), Discorbis-1 (1989), Gryphaea-1 (1987), Kalyptea-1 (1988), Keeling-1 (1990), Leveque-1 (1970), Lombardina-1 (1974), Londonderry-1 (1973), Lynher-1 (1971), Mount Ashmore-1 (1980), Prudhoe-1 (1974), Woodbine-1 (1979), and Yampi-1 (1973). The presence of an oil column has been inferred in Arquebus-1 (Haston & Farrelly, 1993), which was drilled in 1992 and is the most recently completed well in the Browse Basin. More detailed information on hydrocarbon discoveries and shows within the Browse Basin is given in Willis (1988), Cadman & others (1991), Lavering & Pain (1991), Morrison & Miyazaki (1991) and Wilmot & others (1993). A summary of hydrocarbon occurrences in the Browse Basin wells is given in Appendix 2, and the location of shows within the stratigraphic section is shown in Figure 6.

So far, six hydrocarbon discoveries have been made in the Browse Basin, and of these three are considered sub-economic (Scott Reef, Brecknock and Brewster), and three are considered uneconomic (Caswell, Echuca Shoals, Heywood) (Lavering & Pain, 1991). According to Woodside (1990) the Scott Reef gas field contains proven plus probable reserves of 377 billion cubic metres (13.3 TCF) of dry gas and 25 million kilolitres (158.5 million barrels) of condensate. The Brecknock accumulation is estimated to contain 138 billion cubic metres (5 TCF) of gas and 9 million kilolitres (57 million barrels) of condensate at 50% probability (Petroleum Division, Department of Minerals and Energy, WA, 1992).

OBJECTIVES OF THE STUDY

The Browse Basin survey is part of a major AGSO regional research program, which involves at least seven other deep seismic surveys (Appendix 1), designed to determine the broad structural framework of the north western Australian margin. The Browse Basin study has the following main objectives:

- Determine the regional structural framework of the Browse Basin and its relationship to adjacent features such as the Vulcan Sub-basin, Rowley Sub-basin, Scott Plateau and Kimberley Block;

- Define the broad deep-crustal structure of the region and develop a model explaining the tectonic, subsidence and thermal history of the basin in relation to the development of the continental margin and adjacent ocean basin (the Argo Abyssal Plain);

- Assess the effects of deep structure and reactivation on the development of known petroleum accumulations.

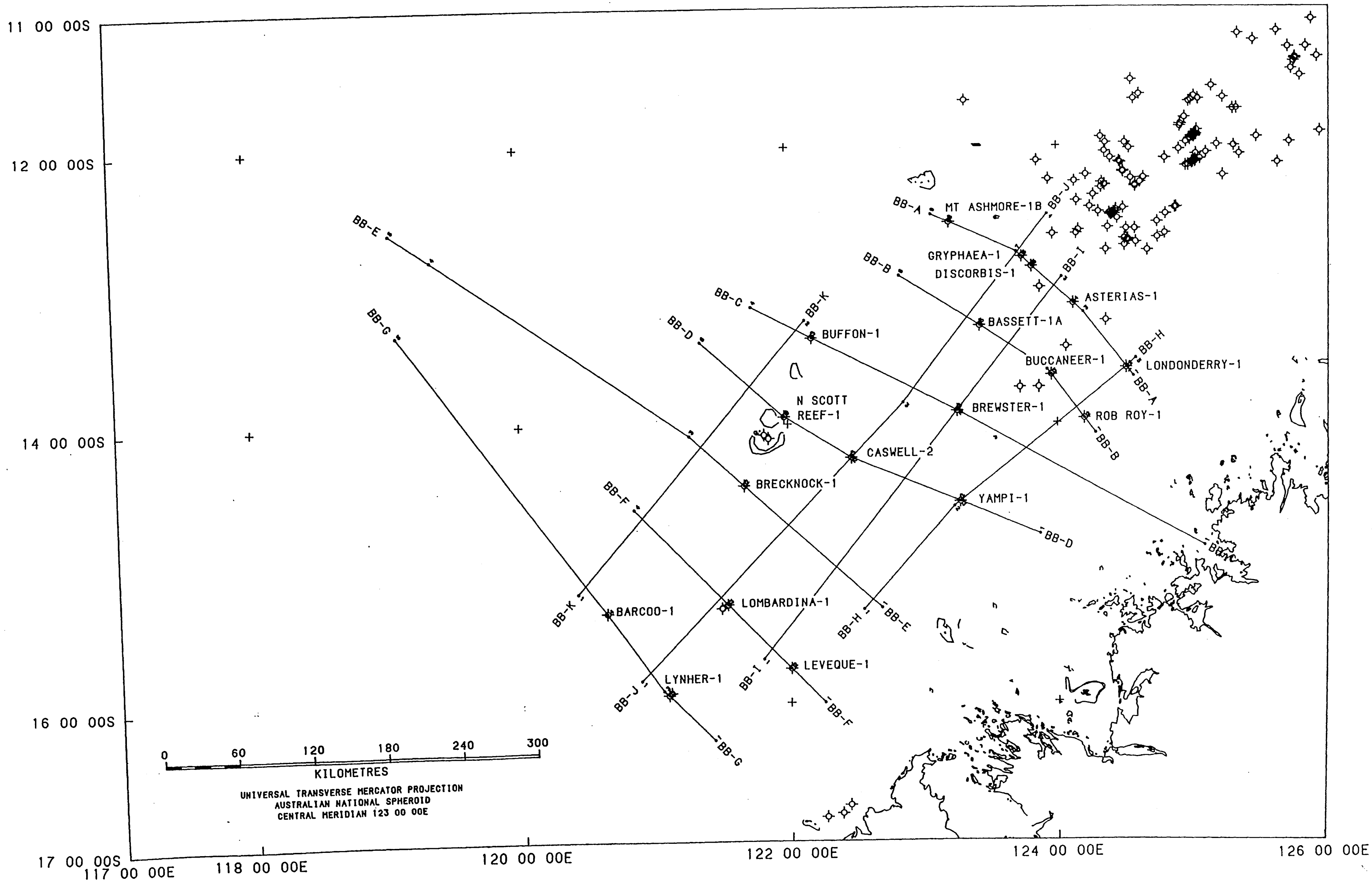

Figure 7. Proposed seismic lines for the Browse Basin survey (BB-A) and well locations.

Specific questions that will be examined by the collection of deep seismic reflection data over the Browse Basin and adjacent margin are:

1. The applicability of recent models of rifted margin and basin development to the Browse Basin area. For example, Lister & others (1986, 1991) and Etheridge & others (1988, 1989) propose that the formation of rifted continental margins and their sedimentary basins occurs by extension above and below sub-horizontal detachment faults in the mid to lower crust. They also propose that margins can be divided into upper or lower plate segments, each having their own characteristic structural style, and subsidence and thermal history. Can such detachments be imaged beneath the Browse Basin and Scott Plateau, and does the margin fit an upper or lower plate model?

2. What is the age, amount, and azimuth of the original extension that formed the Browse Basin and Scott Plateau and how does this relate to the development of the rest of the Westralian Superbasin System?

3. Has structural reactivation been a major factor in the development of the Browse Basin, as seems to be the case for the northern Carnarvon Basin to the south and the Vulcan Sub-basin to the north? What is the age, extent, and nature of any reactivation, and its relationship to the primary-basin forming structures and known hydrocarbon accumulations?

4. Are the margins of the Leveque Platform and Yampi Shelf offset by transfer or accommodation zones? Can such zones be imaged in the centre of the basin and have they been responsible for compartmentalisation of the basin, and consequent along strike variability in structural style and basin fill? What is the relationship of any such transfer zones to known hydrocarbon accumulations?

5. What is the exact structural relationship between the Browse Basin and the Vulcan Sub-basin to the north, and the Rowley Sub-basin to the south? Do these basins have similar development histories?

6. What is the structural relationship of the Browse Basin to the Kimberley Block basement platform in the east, and the Scott Plateau basement in the west?

7. Have older Palaeozoic basin systems, such as those of the Petrel Sub-basin and Canning Basin, played any part in the development of the Browse Basin?

8. What part has continental break-up and seafloor spreading in the Argo Abyssal Plain played in the development of the Browse Basin area?

PROPOSED PROGRAM

The proposed seismic lines for the Browse Basin survey are shown in Figures 7, 8, and 9. These lines total 3715 km , and tie 18 exploration wells (Appendix 5) in the Browse Basin/Scott Plateau region. The survey will also tie into AGSO's 1990 Vulcan Sub-basin deep seismic survey (Survey 98) to the northeast, and the forthcoming survey over the offshore

Canning Basin to the southwest, as well as the standard record-length Triassic Reef survey (95) in the vicinity of Barcoo-1 well. All major petroleum explorers in the Browse Basin area have been consulted during the planning process (Appendix 6).

Seven dip lines (BB-A to G) are proposed, which total 1731 km in length and have an average spacing of about 70 km, and are designed, where possible, to be orthogonal to the principal structural trends in the Browse Basin. Dip line BB-C has been extended east into York Sound and will form a crustal refraction transect across the basin that will use seismic recording stations on Browse Island and on the Kimberley coast, plus sonobuoys. These stations will obtain refraction and wide-angle reflection data during the shooting of line BB-C, in particular, but also other lines in the area. Four strike lines (BB-H to K), which total 1460 km in length and have an average spacing of about 60 km, are designed to link the dip lines along most of the major structural elements. Two of the dip lines (BB-E and BB-G) extend across the Scott Plateau to the Argo Abyssal Plain, and form margin-wide transects of the area. These extensions total about 525 km in length.

The 3715 km of seismic data acquisition planned for the Browse Basin area is clearly more than can be completed on a 30 day cruise. Recent experience with similar surveys has shown that given reasonable weather conditions and high equipment reliability, 3200 km of seismic data is certainly possible. The seismic lines have been prioritised into three categories as follows:

1. High priority lines - all dip and strike lines over the Browse Basin proper (totalling 2908 km) will be shot on this survey.

2. Medium priority - the strike line (BB-K) to the west of the Scott Reef Trend (283 km) will most likely be completed on this survey.

3. Lowest priority - the dip-line extensions across the Scott Plateau to the adjacent abyssal plain (totalling 525 km) will probably not be completed on this survey. It may be possible to shoot one of the extensions.

It is intended that any of the above lines not completed during the proposed Browse Basin survey, including data not collected as a result of adverse weather, serious equipment problems, or delays caused by external operational considerations, will be re-scheduled for acquisition during a Timor Sea/Browse Basin infill survey in late 1993, or during a supplementary seismic acquisition phase over the northern Scott Plateau (about 1000 km of data) planned for 1994.

The acquisition parameters and equipment that will be used on the Browse Basin survey (Appendix 7 and 8) are similar to most of MGPGP'S other deep seismic surveys over the North West Shelf, such as the SNOWS-1 and SNOWS-2 surveys over the northern Carnarvon Basin, and three surveys over the Bonaparte Basin - Timor Sea area. They are also the same as will be used on the SNOWS-3 survey over the offshore Canning Basin, following the Browse Basin survey. The parameters and procedures that will be used during the processing of the Browse Basin data will be similar to those employed by commercial companies during recent processing of other MGPGP deep seismic data from the North West Shelf region (Appendix 9).

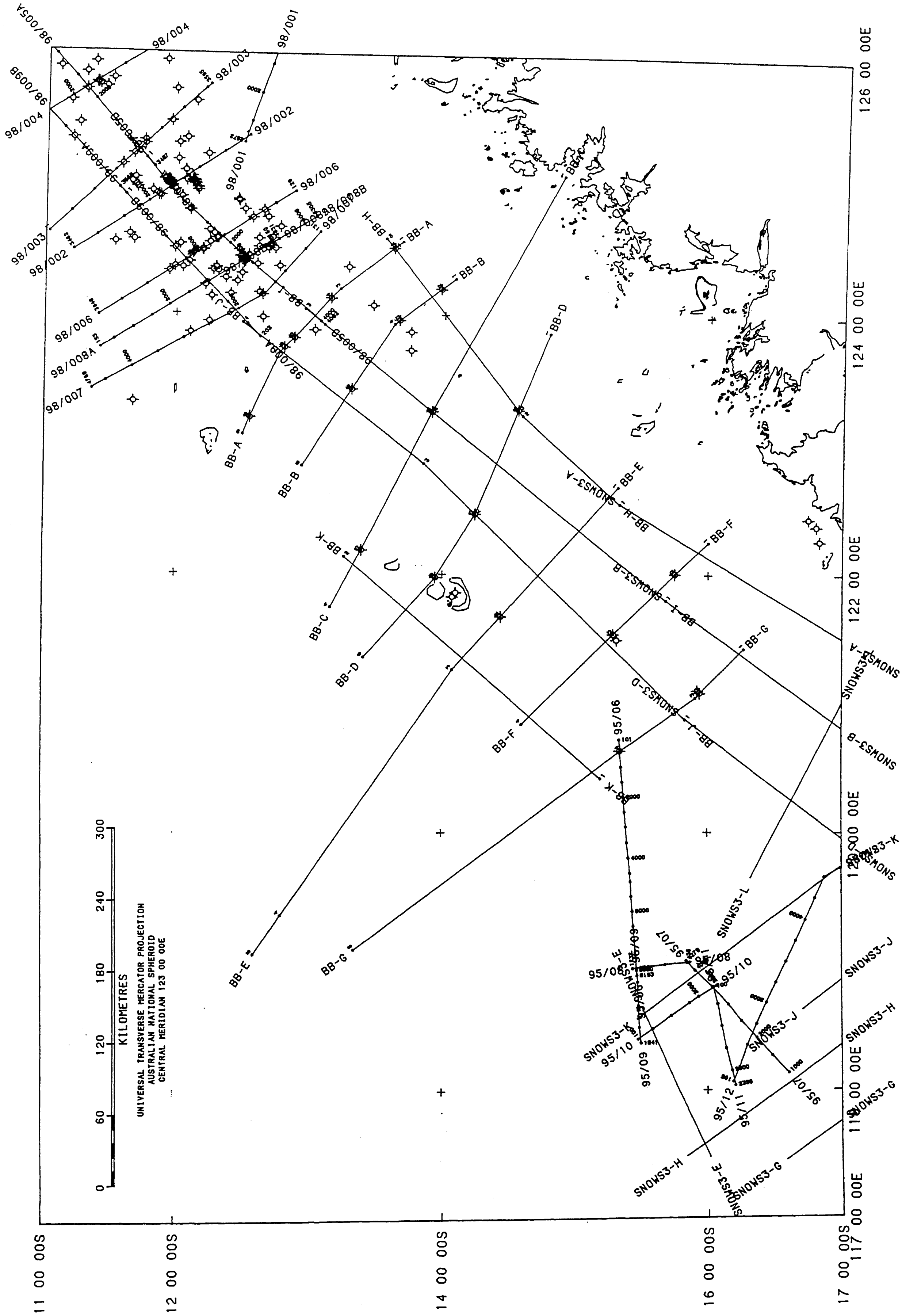

Figure 8. Proposed seismic lines for the Browse Basin survey (BB-A) and other AGSO seismic surveys in the region (surveys 95 and 98, and future SNOWS3). Also shows well locations.

A summary of each line and its specific objectives is given below, and the way points for each line are contained in Appendix 10.

BROWSE BASIN DIP LINES (1731 km ; tie 18 wells)

Line BB-A (211 km)
Crosses the SW margin of the Londonderry Arch; the complex saddle area separating the northern Browse Basin and the Vulcan sub-basin; and runs adjacent to the southern margin of the Ashmore Platform. Ties lines BB-H,I and J, and wells Londonderry-1, Asterias-1, Discorbis-1, Gryphaea-1 and Mount Ashmore-1B.

Line BB-B (203 km)
Crosses the northern margin of the Yampi Shelf; the northern Prudhoe Terrace; the northern part of the central Browse Basin; and the northern end of the Buffon Trend. Ties lines BB-H, I and J, and wells Rob Roy-1, Buccaneer-1 an Bassett-1A.

Line BB-C (408 km)
Extends WNW from the Kimberley coast at York Sound, across the margin of the Yampi Shelf, the Prudhoe Terrace, the Inner and Central Basin Arches, and the northern Scott Reef, Buffon and Seringapatam Trends of the Outer Browse Basin (Scott Plateau Saddle). During the shooting of this line it is planned to obtain deep velocity data by placing seismic recording stations on Browse Island and on the Kimberly coast, and using sonobuoys, to record refraction and wide-angle reflection data. Data will also be recorded by the 'land' stations during the shooting of other lines in the area. These data will aid the identification of deep crustal boundaries and the crust-mantle boundary, and will test the feasibility of using ocean-bottom seismometers (OBS's) on future North West Shelf surveys. Ties lines BB-H, I, J and K, and wells Brewster-1 and Buffon-1.

Line BB-D (314 km)
Extends across the margin of the Yampi Shelf, the Prudhoe Terrace, the centre of the Browse Basin and the Central Basin Arch, and the Scott Reef and Seringapatam Trends. Ties lines BB-H, I, J and K, and wells Yampi-1, Caswell-2 and North Scott Reef-1.

Line BB-E (206 km to way point 3 and the tie with line BB-K)
Crosses the western margin of the northern Leveque Platform, the southern Browse Basin, the southern Scott Reef Trend, and over the innermost part of the Scott Plateau. It is one of the lines that will be extended across the Scott Plateau to the Argo Abyssal Plain to form a margin transect. Ties lines BB-H, I, J and K, and the Brecknock-1 well.

Line BB-F (216 km)
Crosses the western margin of the central Leveque Platform, the major Lombardina-Lynher trend, the Barcoo Trend and the inner Scott Plateau. Ties lines BB-I, J, and K, and future lines SNOWS3-A and B, and wells Leveque-1 and Lombardina-1.

Line BB-G (173 km to the tie with line BB-K)
This is the southernmost dip line of the survey, and crosses the south-western margin of the Leveque Platform, the southern Browse Basin and the inner Scott Plateau. It is one of the lines

that will be extended across the Scott Plateau to the Argo Abyssal Plain to form a margin transect. Ties AGSO line 95/06, BB-J and K, and future lines SNOW3-B and D.

BROWSE BASIN STRIKE LINES (1452 km, tie 4 wells)

Line BB-H (296 km)
Extends SW from the southern Londonderry Arch to the northern Leveque Platform along the outer part of the Prudhoe Terrace. It will test for transfer/accommodation zones along the eastern margin of the Browse Basin. Ties lines BB-A, B, C, D,and E, and future SNOWS3-A line; in the north it will also tie with a strike line across the Londonderry Arch from the Petrel Sub-basin that will be shot on the current Malita survey. Ties Londonderry-1 and Yampi-1 wells.

Line BB-I (386 km)
Extends SW from the southern Vulcan Sub-basin, along the eastern part of the central Browse Basin and just west of the Leveque Platform. It will examine the nature of the boundary between the Vulcan Sub-basin and Browse Basin, and test for transfer/accommodation zones along the eastern margin of the Browse Basin, particularly outboard of the Leveque Platform. Ties Vulcan survey line 98/005B; BB-A, B, C, D, E, and F; future line SNOW3-B; and the Brewster-1A well.

Line BB-J (495 km)
Extends SW from the southern Vulcan Sub-basin, along the western part of the central Browse Basin and into the southern Browse Basin. It will examine the nature of the boundary between the Vulcan Sub-basin and Browse Basin; test for transfer/accommodation zones along the central part of the Browse Basin; and examine the change from the southern Browse Basin to the Rowley Sub-basin. Ties Vulcan survey line 98/009A; BB-A, B, C, D, E, F and G; future SNOWS3-D line; and Caswell-2 well.

Line BB-K (283 km)
This is a second priority line which runs SW along the Outer Browse Basin (Scott Plateau Saddle) to the west of the Scott Reef and Buffon Trends, and onto the inner Scott Plateau. It will test for transfer/accommodation zones along the western margin of the Browse Basin and inner Scott Plateau. Ties lines BB-C, D, E, and F.

MARGIN TRANSECTS (525 km)

Although these lines are in the lowest priority group for the Browse Basin survey, they are critical to understanding the development of the Browse Basin within the context of the evolution of the whole north-western Australian continental margin. Northwest extensions of two dip lines are proposed to create two deep crustal transects across the full width of the margin from unrifted cratonic basement near the coast, across the Browse Basin and adjacent Scott Plateau, and onto the Late Jurassic oceanic crust of the north-eastern Argo Abyssal Plain.

Line BB-E extension (288 km)
Lowest priority line that extends BB-E across the northern Scott Plateau, the ocean-continent boundary, and onto the Late Jurassic oceanic crust of the Argo Abyssal Plain north of

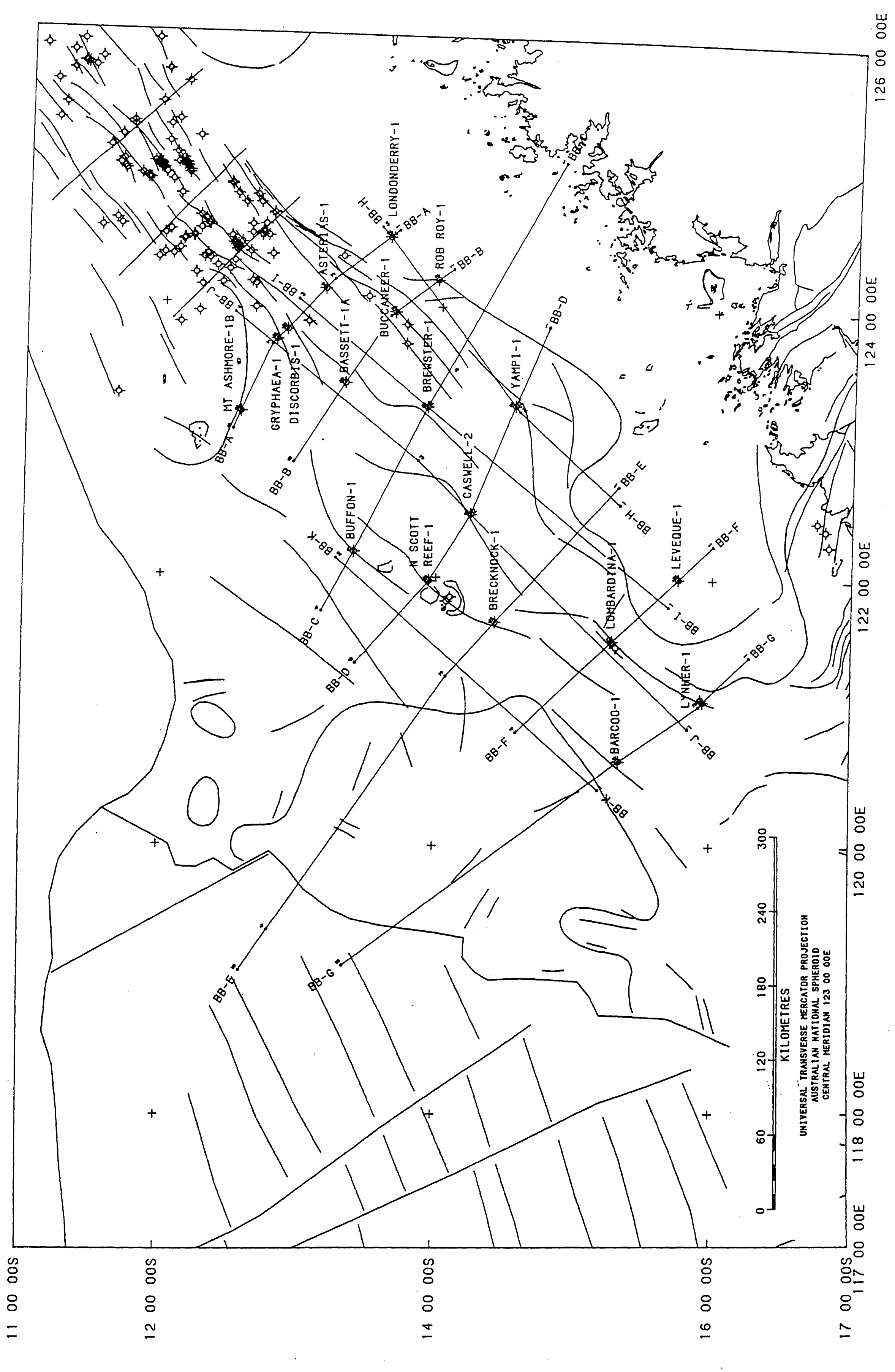

Figure 9. Proposed seismic lines for the Browse Basin survey (BB-A) with respect to the major stuctural elements in the region. Also shows other AGSO seismic surveys in the region (surveys 95 and 98, and future SNOWS3) and well locations.

magnetic anomaly M23. This line will examine the outer part of the continental margin adjacent to the Browse Basin and attempt to image deep crustal features that underpin the whole margin. It may cross a major transfer zone controlling the northern margin of the Scott Plateau. It will also examine the nature of the continent-ocean boundary and the seismic characteristics of old oceanic crust.

Line BB-G extension (236 km)
In the low priority category, but not as low as the line BB-E extension. It extends the southern most dip line BB-G across the central Scott Plateau, the ocean-continent boundary, and onto the Late Jurassic oceanic crust of the Argo Abyssal Plain, crossing magnetic anomaly M24. This line will examine the outer part of the continental margin adjacent to the Browse Basin and attempt to image deep crustal features that underpin the whole margin. It will also examine the nature of the continent-ocean boundary and the seismic characteristics of old oceanic crust.

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APPENDIX 1

AGSO DEEP SEISMIC PROGRAM IN THE NORTH WEST SHELF REGION.

Date	Area	Kilometres shot	Wells tied
12/90	Vulcan Sub-basin	1894	20
5/91	Petrel Sub-basin	2090	8
6/91	Dampier-Barrow Sub-basins, Exmouth Plateau	1654	20
6/92	Dampier-Barrow-Beagle Sub-basins, Exmouth Plateau	2868	21
1/93*	Timor Sea	3611	14
5/93	Malita Graben, Petrel Sub-basin & Browse Basin	~3000	4
6/93	Browse Basin	~3000	18
9/93	Offshore Canning Basin	~3000	
11/93	Timor Sea in-fill	2500+	
1/94 - 7/94	Northern Scott Plateau - Roti Basin - Browse Basin	2500+	
"	Canning Basin in-fill - eastern Exmouth Plateau	2500+	
"	Gascoyne - Exmouth Sub-basins	2500+	
	TOTAL (to end April, 1993)	**12117 km**	
	ANTICIPATED TOTAL (to July 1994)	**~31 000 km**	

* 730 km of this survey were shot in the Australia-Indonesia Zone of Co-operation Area A for Nopec Australia.

Note: Program beyond the end of 1993 is indicative only.

APPENDIX 2

BROWSE BASIN WELL SUMMARY (After Wilmot & others, 1993).

WELLNAMES	WATER DEPTH(M)	COMPANY SPUD DATE COMP. DATE	WELL STATUS	TD (m) MSL AGE AT TD	HYDROCARBON OCCURRENCE	STRUCTURAL TYPE
ADELE ISLAND 1	0	Oberon Oil	P & A	785.5		No closure
	(4m ASL)	29/7/82-17/8/82		Pre-Permian		
ASHMORE REEF 1	36.6	BOCAL	P & A	3902.2	Minor gas shows	Anticline
	RT 12.2m	16/10/67-2/4/68		U.Triassic	volcanic section	
				(Norian)		
ASTERIAS 1	194.6	BHPP	P & A	4382.6	Minor flrs, residual	Fault Block
	RT 17.4m	14/6/87-15/9/87		L.Jurassic	oil from SWC	
				(Tithonian)		
BARCOO 1	720	Woodside	P & A	5098	Moderate flrs from	No closure
	RT 11m	14/12/79-12/7/80		U.Triassic	SWCs, weak gas	
				(Norian)		
BASSETT 1	364	Woodside	P & A	2698	No shows	Faulted
	RT 8m	26/5/78-28/7/78		M.Cretaceous		Anticline
				(Albian)		
BRECKNOCK 1	543	Woodside	P & A	4289	Gas/Condensate	Drape
	RT 11m	31/7/79-12/12/79		E.Triassic	Discovery	Anticline
				(Anisian)		
BREWSTER 1A	256	Woodside	Suspended?	4695	Gas discovery	Drape
	RT 8m	23/5/80-19/12/80		M.Jurassic	(logs)	Anticline
				(Toarcian)		
BROWSE IS. 1	0	SANTOS	P & A	401	No shows	
	(2.9m ASL)	15/5/86		Tertiary?		
BUCCANEER 1	156.1	SHELL	P & A	3558.8	Residual oil show	Downdip fault
	RT 15.2m	26/2/90-12/4/90		E.Triassic	from SWC	play
				(Anisian)		

WELLNAMES	WATER DEPTH(M)	COMPANY SPUD DATE COMP. DATE	WELL STATUS	TD (m) MSL AGE AT TD	HYDROCARBON OCCURRENCE	STRUCTURAL TYPE
BUFFON 1	533 RT 10m	Woodside 4/1/80-3/8/80	P & A	4777 E.Jurassic (Hettangian)	Gas show Minor fluorescence	Faulted Anticline
CASWELL 1	345 RT 8m	Woodside 16/8/77-13/1/78	P & A	4089 E.Cretaceous (Hauterivian)	Oil discovery/ RFT? or free oil in mud	Drape Anticline
CASWELL 2	344 RT 17m	Woodside 1/4/83-6/11/83	P & A	4983 L.Jurassisc (Tithonian)	Oil recovery - RFT Live oil SWCs	Drape Anticline
DELTA 1	205 RT 25m	ELF AQUIT 26/2/88-16/4/88	P & A	2875 U.Cretaceous (Campanian)	No flrs, minor gas	Drape Anticline
DISCORBIS 1	202 RT 22m	BHPP 8/8/89-21/11/89	P & A	4174 E.Triassic (Anisian)	Minor fluorescence Weak gas shows	Faulted Anticline
ECHUCA SHOALS 1	194 RT 17m	Woodside 8/11/83-29/2/84	P & A	4367 U.Permian (Tatarian)	Gas discovery RFT and logs	Drape over Fault block
GRYPHAEA 1	199.6 RT 17	BHPP 17/9/87-24/11/87	P & A	3932.6 E.Triassic (Anisian)	Minor oil shows	Fault block
HEYWOOD 1	35 RT 10m	BOCAL 7/4/74-14/7/74	P & A	4562 U.Jurassic (Oxfordian)	Gas/oil shows	No closure Velocity pull-up

WELLNAMES	WATER	COMPANY	WELL	TD (m) MSL	HYDROCARBON	STRUCTURAL
	DEPTH(M)	SPUD DATE	STATUS	AGE AT TD	OCCURRENCE	TYPE
		COMP. DATE				
KALYPTEA 1	215.3	BHPP	P & A	4152	Gas shows	Drape anticline
	RT 17.7m	17/9/88-3/12/88		E.Cretaceous		
				(Hauterivian)		
		Sidetrack		4557.3		
		12/12/88-26/3/89		(Berriasian)		
KEELING 1	194	NORCEN	P & A	3124	Gas discovery	Faulted
	RT 11m	16/12/89-18/1/90		U.Triassic		Anticline
				(Norian)		
LEVEQUE 1	77.7	BOCAL	P & A	889.9	No shows	No closure
	RT 9.45m	22/8/70-6/9/70		PrePermian?		
LOMBARDINA 1	145	BOCAL	P & A	2825	No shows	Faulted
	RT 30m	15/5/74-21/7/74		E.Jurassic		Anticline
				(Hettangian)		
LONDONDERRY 1	90	BOCAL	P & A	1132	No shows	No closure
	RT 13m	28/9/73-8/10/73		PrePermian		Strat. test
LYNHER 1	57.9	BOCAL	P & A	2715.3	No shows	Faulted
	RT 9.45m	24/12/70-16/2/71		E.Triassic		Anticline
				(Anisian)		
MT ASHMORE 1	623	Woodside	P & A	2644	Minor fluorescence	Anticline
	RT 11m	26/7/80-26/10/80		U.Triassic		
				(Carnian)		
NTH SCOTT REEF 1	442	Woodside	P & A	4763	Gas discovery	Drape
	RT 8m	6/2/82-18/6/82		U.Triassic		Anticline
				(Rhaetian)		
PRUDHOE 1	175	BOCAL	P & A	3292	No shows	No closure
	RT 30m	13/9/74-12/11/74		E.Permian		

WELLNAMES	WATER DEPTH(M)	COMPANY SPUD DATE COMP. DATE	WELL STATUS	TD (m) MSL AGE AT TD	HYDROCARBON OCCURRENCE	STRUCTURAL TYPE
ROB ROY 1	102 RT 9.45	BOCAL 27/1/72-28/2/72	P & A	2276.4 PrePermian	Minor fluorescence	No closure Strat. test
SCOTT REEF 1	49.7 RT 9.45	BOCAL 18/2/71-9/6/71	Suspended	4720.8 E.Triassic (Rhaetian)	Gas discovery	Drape Anticline
SCOTT REEF 2	56 RT 8m	Woodside 27/4/77-9/8/77	P & A	4812 E.Jurassic (Hettangian)	Minor gas shows water saturated	Drape closure over horst block
WOODBINE 1	189 RT 8m	Woodside 6/3/79-22/5/79	P & A	3494 U.Triassic (Rhaetian)	Minor fluorescence	No closure? Cret. drape over horst block.
YAMPI 1	91 RT 13m	BOCAL 3/6/73-27/9/73	P & A	4163 E.Permian (Sakmarian)	Residual oil show from core 3173m	No closure? Low side fault play

APPENDIX 3

SEISMIC SURVEYS OVER THE SCOTT PLATEAU AREA (After Stagg & Exon, 1981)

Year	Organisation	Ship	Seismic source	Recording	Display	Processing	Comments
1967	BMR (Australia)	*Wyrallah*	21 kJ-sparker	Single-channel analogue	EGG electrostatic recorder	NA	Inadequate penetration
1968	BMR (Australia)	*Robray 1*	21 kJ-sparker	Single-channel analogue	EGG electrostatic recorder	NA	Inadequate penetration
1971	*Shell International Petroleum Mij. (Netherlands)	*Petrel*	Airguns (6.4 l)	24-channel digital	2-fold CDP stack with no move-out corrections produced on-line by an optical method. Also variable area (processed)	Inshore ends of each line processed—24-fold CDP stack with deconvolution and time-variant filtering after stack. Variable area display	Both 2-fold and 24-fold stacks are good-quality records
1971	Lamont-Doherty Geological Observatory (USA)	*Vema*	Airgun (0.83 l)	Single-channel analogue	Lamont-designed electrostatic recorders	NA	Inadequate penetration
1972	*Gulf Research and Development Co. (USA)	*Gulfrex*	Aquapulse	24-channel digital	Variable area	24-fold CDP stack with deconvolution and time-variant filtering after stack. All lines processed	Good-quality records
1972	*BMR (Australia)	*Hamme/ Lady Christine*	120 kJ sparker	6-channel analogue	EPC electrostatic recorder	About 60% of lines have been digitally processed (6-fold stack). Variable area display	Fair to good quality for BMR Continental Margin Survey data. Processed data are fair quality
1972	JOIDES (USA)	*Glomar Challenger*	Airguns (0.5 l)	Single-channel analogue	Electrostatic recorders	NA	Inadequate penetration
1976	*Woods Hole Oceanographic Institution (USA)	*Atlantis II*	Airguns (2.0 l)	Single-channel analogue	Hewlett-Packard electrostatic recorder	NA	Fair quality—similar to unprocessed BMR 1972 records
1977	*BGR (West Germany)	*Valdivia*	Airguns (18.0 l)	24-channel digital; single-channel analogue	24-channel recorded on EPC electrostatic recorders. Single-channel recorded on Edo-Western electrostatic recorder. Near-trace gathers variable area	Near-trace gathers only	Fair to good quality

* Results of these surveys used in this study.
NA = not applicable.

APPENDIX 4

GENERALISED STRUCTURAL HISTORY FOR THE TIMOR SEA AND ADJACENT AREAS (based on O'Brien & others, 1993).

Late Devonian to Early Carboniferous ***Major extension event*** Extension along NW-trending rift systems, such as the Petrel Sub-basin takes place in the Late Devonian to Early Carboniferous. A true rift event producing classic extensional geometries. Virtually all of the large structures within the post-rift sequence are located over the LPRMs, as the large displacement and through-going nature of the structures on those margins reactivate readily, as well as allowing salt migration from the deep, pre-rift sequence.
Late Carboniferous - Early Permian ***Major extension event.*** Initiation of the Westralian Superbasin by continental extension/rifting. Thinning of pre-existing crust to 25 to 50% of original thickness via lower crustal thinning. Formation of NE-trending normal and NW-trending transfer fault arrays, at least in some instances by the reactivation of pre-existing Proterozoic basement fracture systems. Orthogonal overprinting of the NW-trending Late Devonian-Early Carboniferous rift system. This is the major basin-forming event in the region and was responsible for most of the crustal thinning and thermally-driven subsidence.
Late Permian - End Triassic. ***Thermal subsidence.*** Post-rift sequence thickens gradually to W/NW; little or no fault-related growth; up to 10-14 km of largely unstructured terrestrial to shallow marine sediment deposited in some places.
Latest Triassic - Early Jurassic ***Regional structuring event.*** Also in Petrel Sub-Basin, Carnarvon, Arafura & Canning Basins. NS to NNW compression; oblique reactivation of Permo-Carboniferous, Westralian Super-Basin fault systems; some strike-slip component on Permo-Carboniferous faults. Event leads to low amplitude crustal scale buckling producing broad, synclinal basins with intervening faulted anticlinal features. Some uplift along Vulcan Sub-Basin / Londonderry High Boundary Zone.
Latest Callovian- Early Oxfordian ***Regional structuring event.*** Far field effects of continental break-up result in rapid, low strain crustal NNE extension in the Vulcan Sub-Basin (extension was typically <5%). This event may produce different effects on other parts of the margin. An array of extensional half-grabens developed via the reactivation of the underlying Permo-Carboniferous normal faults. Grabens were offset across the underlying primary Permo-Carboniferous transfer faults. Extension was quickly followed by continental break-up, leading to the formation of the Callovian Unconformity. Subsidence following break-up, when combined with rising eustatic sea-level, causes rapid flooding of terrestrial half-grabens), resulting in restricted deep water marine environments favourable to source rock deposition (e.g. Lower Vulcan Formation). Probably minor strike-slip movement on many faults.
Late Jurassic - Early Cretaceous ***Regional structuring event.*** NW-NNW compression slows and possibly stops sea-floor spreading in the Argo Abyssal Plain in the Tithonian. Transpressional reactivation of Permo-Carboniferous normal fault networks causes prominent uplift along the south-eastern margins of the half-grabens in particular (e.g. the development of the Skua, Challis and Jabiru Horsts as significant features in the Vulcan Sub-basin). Significant uplift along major bounding NE bounding fault systems. Some strike-slip movement on many faults, with complex structures developing at the intersections of the NS, NW and NE-trending structural fault sets. Falling eustatic sea-level, in conjunction with tectonically-induced uplift, results in the shedding of large amounts of siliciclastic sediment from the horsts.
Mid-Miocene to Recent ***Regional structuring event.*** ENE-WSW compression related to collision and subduction along northern continental boundary. Dominated by reactivation of underlying faults; localised flexure of thinnest parts of pre-Permian crust.

APPENDIX 5

WELLS TIED ON THE BROWSE BASIN SURVEY

WELL	LATITUDE	LONGITUDE
ASTERIAS-1	130903.3S	1240716.5E
BARCOO-1	152037.0S	1203812.2E
BASSETT-1A	131836.7S	1232535.3E
BRECKNOCK-1	142608.1S	1214025.5E
BREWSTER-1	135444.3S	1231532.7E
BUCCANEER-1	133944.6S	1235720.7E
BUFFON-1	132332.9S	1221104.1E
CASWELL-2	141428.1S	1222814.8E
DISCORBIS-1	125251.9S	1234847.9E
GRYPHAEA-1	124838.3S	1234421.6E
LEVEQUE-1	154506.9S	1220022.2E
LOMBARDINA-1	151715.2S	1213218.8E
LONDONDERRY-1	133648.1S	1243047.0E
LYNHER-1	155619.2S	1210503.7E
MOUNT ASHMORE-1B	123331.3S	1231226.6E
NORTH SCOTT REEF-1	135653.0S	1215829.0E
ROB ROY-1	135810.6S	1241201.6E
YAMPI-1	143327.0S	1231638.4E

For other information on these wells see Appendix 2.

APPENDIX 6

COMPANIES CONSULTED DURING PREPARATION OF CRUISE PROPOSAL

During preparation of this cruise proposal, the following exploration companies were contacted to provide input. I am grateful to the staff of those companies that took the time to provide advice, information and support.

Amoco Australia Petroleum Company
Ampol Exploration Ltd
BHP Petroleum Pty Ltd
BP Developments Australia Ltd
Bridge Oil Ltd
Chevron International
Command Petroleum Holdings NL
Idemitsu Minerals Australia Ltd
Kufpec Australia Pty Ltd
Mobil Exploration and Producing Australia Ltd
Norcen International Ltd
Peko Wallsend Operations Ltd
Santos Ltd
Shell Company of Australia Ltd
TPCL Resources Ltd
Woodside Offshore Petroleum Pty Ltd

APPENDIX 7

SEISMIC ACQUISITION PARAMETERS FOR THE BROWSE BASIN SURVEY

Seismic Cable Configuration

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

Seismic Source

Sleeve gun capacity	50 litres (3000 cu in)
Gun pressure	1800 psi (normal)
	1600 psi (minimum)
Shot interval	50 m
Shot rate	19.4 s @ 5 knots
	21.6 s @ 4.5 knots

Recording Parameters

Fold	4800%
Record length	16 s
Sample interval	2 ms

APPENDIX 8

EQUIPMENT TO BE UTILISED ON BROWSE BASIN SURVEY

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 levellers; 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: 3.5 KHz (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 9

PROCESSING PARAMETERS FOR BROWSE BASIN SEISMIC DATA

Resample to 4 ms
Static correction for gun delay
Gain correctionFshape, low cut filter 3-5 Hz
FK filter
Wavelet processing - decon using Taner's exponential method
NMO velocity analysis every 4 km
Anti-alias filter - interleaved 192-fold CDPs
Radon demultiple - Tau-Q rejection used to attenuate multiples
NMO-DMO velocity analyses every 2 km
Mute
NMO-DMO stack
Static correction for gun and cable depths
Decon after stack
Migration
Bandpass filter
Scaling
Mild 5 trace mix

APPENDIX 10

WAY POINTS FOR BROWSE BASIN SURVEY

LINE	WP	COMMENTS	LATITUDE	LONGITUDE	LINE LENGTH (KM)	LINE LENGTH (NM)
BB-A	1	SOL	134030.0S	1243345.0E	211.19	113.97
	2	LONDONDERRY-1	133648.1S	1243047.0E		
	3		131300.0S	1241130.0E		
	4	ASTERIAS-1	130903.3S	1240716.5E		
	5	DISCORBIS-1	125251.9S	1234847.9E		
	6	GRYPHAEA-1	124838.3S	1234421.6E		
	7		124630.0S	1234200.0E		
	8	MOUNT ASHMORE-1B	123331.3S	1231226.6E		
	9	EOL	123015.0S	1230430.0E		
BB-B	1	SOL	140430.0S	1241700.0E	203.16	109.64
	2	ROB ROY-1	135810.6S	1241201.6E		
	3	BUCCANEER-1	133944.6S	1235720.7E		
	4		133730.0S	1235530.0E		
	5	BASSETT-1A	131836.7S	1232535.3E		
	6	EOL	125645.0S	1225000.0E		
BB-C	1	SOL	145245.0S	1250500.0E	407.58	219.96
	2	BREWSTER-1	135444.3S	1231532.7E		
	3	BUFFON-1	132332.9S	1221104.1E		
	4	EOL	131005.0S	1214430.0E		
BB-D	1	SOL	144730.0S	1235200.0E	314.20	169.56
	2	YAMPI-1	143327.0S	1231638.4E		
	3	CASWELL-2	141428.1S	1222814.8E		
	4		135649.4S	1215836.0E		
	5	NORTH SCOTT REEF-1	135653.0S	1215829.0E		
	6	EOL	132500.0S	1212115.0E		
BB-E	1	SOL	151900.0S	1224100.0E	493.74	266.45
	2	BRECKNOCK-1	142608.1S	1214025.5E		
	3		140445.0S	1211545.0E		
	4		124830.0S	1192200.0E		
	5	EOL	123630.0S	1190400.0E		
BB-F	1	SOL	160000.0S	1221512.6E	216.44	116.81
	2	LEVEQUE-1	154506.9S	1220022.2E		
	3	LOMBARDINA-1	151715.2S	1213218.8E		
	4	EOL	143600.0S	1205045.0E		
BB-G	1	SOL	161600.0S	1212530.0E	409.33	220.90
	2	LYNHER-1	155619.2S	1210503.7E		
	3		155430.0S	1210245.0E		

	4 BARCOO-1	152037.0S	1203812.2E		
	5 EOL	132100.0S	1190600.0E		
BB-H	1 SOL	151945.0S	1223300.0E	295.62	159.54
	2	143530.0S	1231400.0E		
	3 YAMPI-1	143327.0S	1231638.4E		
	4 LONDONDERRY-1	133648.1S	1243047.0E		
	5 EOL	133300.0S	1243500.0E		
BB-I	1 SOL	154100.0S	1214800.0E	386.14	208.39
	2 BREWSTER-1A	135444.3S	1231532.7E		
	3 EOL	125730.0S	1240218.0E		
BB-J	1 SOL	155000.0S	1205245.0E	495.18	267.23
	2 CASWELL-2	141428.1S	1222814.8E		
	3	135115.0S	1225130.0E		
	4 EOL	123000.0S	1235600.0E		
BB-K	1 SOL	151200.0S	1202515.0E	282.70	152.56
	2 EOL	131600.0S	1220800.0E		
			TOTAL:	**3715.28**	**2005.01**