AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

PETREL SUB-BASIN STUDY 1995-1996

SUMMARY REPORT

compiled by

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EXECUTIVE SUMMARY

AGSO's 1995-1996 Petrel Sub-basin Study has defined the structural and stratigraphic evolution of the sub-basin. Results of this work will help to promote and focus future exploration activity and reduce exploration risk, as well as provide an important input to on-going AGSO research in other parts of the Timor Sea region.

The study included:

- biostratigraphic reviews of key wells and intervals;
- sequence interpretation and regional mapping using AGSO's deep-seismic and industry data;
- geochemical (biomarker and isotope) analyses;
- hydrocarbon generation and expulsion models for the identified active petroleum systems; and
- thermal, flexural-isostatic and analogue basin modelling.

Major results and conclusions are:

- Of the three proven petroleum systems operating in the sub-basin, the Early Carboniferous Milligans and Permian Keyling-Hyland Bay systems have significant future potential.
- The oil-prone Milligans System, verified at the Turtle and Barnett wells, is largely restricted to the southern part of the basin (Carlton Sub-basin, Cambridge Trough and Keep Inlet Sub-basin). Considerable potential exists in untested stratigraphic and stratigraphic/structural plays, particularly along the flanks of the Cambridge Trough and immediately north of the Turtle-Barnett High.
- The Permian Keyling-Hyland Bay System, which was successfully tested at the giant Petrel and Tern fields, is gas/condensate-prone. Stratigraphic/structural plays on the northeast flank of the sub-basin offer the best potential for liquid hydrocarbons sourced from higher-quality coaly shales in the Keyling Formation. The distinct geochemical signature of the Keyling-Hyland Bay hydrocarbons may allow the identification of Permian-sourced hydrocarbons elsewhere in the Timor Sea region.
- The Petrel sub-basin has undergone a complex structural and stratigraphic history spanning the Early Cambrian to the present. 10 distinct basin phases (A-J) are identified; these phases have controlled the evolution of the sub-basin's petroleum systems.
- The sub-basin was initiated by crustal extension and tholeiitic extrusion in the Early Cambrian, followed by crustal sag throughout the Cambrian and ?Ordovician-Silurian (Basin Phase A). Sediments deposited during this phase were subsequently strongly eroded or deeply buried, and are non-prospective for hydrocarbons.

- Major rifting and upper-crustal extension occurred in the Late Devonian-earliest Carboniferous (Basin Phase B). The subsequent sag-dominated Carboniferous-Permian history was punctuated by a series of renewed upper and/or lower crustal extension-sag cycles (Phases C-F). Marine source rocks of the Milligans Petroleum System were deposited during the transgressive maximum of Phase C; coastal plain and deltaic source rocks of the Keyling-Hyland Bay Petroleum System were deposited at the beginning of Phase F.
- Regional compression (Fitzroy Movement), dated in this study as Ladinian - Sinemurian, reactivated faults along the basin margins (mainly in the southwest) and produced a series of inversion anticlines and monoclines within the basin fill (commonly above basement blocks or fractures), including the traps of the Tern and Petrel gas/condensate fields. Following the Early Jurassic, the sub-basin mainly underwent slow sag (largely an immature overburden section for the sub-basin's petroleum systems)
- The Petrel sub-basin is underlain by complex crust. A high-density zone (possibly resulting from the intrusion of igneous material into the lower crust and Precambrian Kimberley Block) underlies much of the central part of the basin. This may reflect the offshore continuation of the Halls Creek Mobile Zone, which was probably re-activated throughout the Palaeozoic. This zone of weakened/brittle crust, together with a series of basement fractures ('hardlinks'), have exerted a significant control on the location within the sub-basin of major depocentres and basement highs, and the distribution of the Milligans Petroleum System.
- Thermal modelling of the basin, as well as modelling of the geometric and isostatic response of the basin to deformation, indicate that the previously accepted concept of a single phase of rifting followed by thermal sag cannot explain the extreme thickness and subsidence history of the late Palaeozoic sediments in the Petrel Deep. A model is proposed in which the Late Devonian - Early Carboniferous basin geometry is the result of the flexural response to upper-crustal deformation, including a component of sub-resolution faulting along the basin axis above the offshore Halls Creek Mobile Zone. Following this deformation, it is suggested that Late Carboniferous basin accommodation space was largely created as a result of movement on a large NE-SW trending normal fault located at the northern extremity of the sub-basin in the vicinity of Gull-1. The development of this fault is attributed to initiation in the latest Namurian of NW-SE extension associated with the development of the Westralian Superbasin.

PREFACE

This record summarises the major results of AGSO's 1995-1996 Petrel Sub-basin Study. The record is not intended to be a 'stand-alone' product but to be used in conjunction with other products of the study which detail results, background information and analytical techniques. Some topics (notably structural framework and sequence stratigraphy) which are not covered by other reports of the study, are dealt with here in considerable detail; other topics (e.g. organic geochemistry) are essentially summaries of more detailed reports. In all cases the authorship of individual sections or sub-sections is indicated within the text.

Preferred citation:
Colwell, J.B. & Kennard, J.M. (compilers), 1996. AGSO Petrel Sub-basin Study 1995-1996, Summary Report. *AGSO Record 1996/40.*

OTHER PRODUCTS AVAILABLE FROM THE PETREL STUDY

Well Folio *(by J.M. Kennard).*
Provides well composites for 31 key wells in the basin, as well as 6 well-well cross-sections.

Map & Seismic Folio *(by J.B. Colwell, J.E. Blevin & D.J. Wilson).*
Includes 24 time-structure and time isopach maps as well as selected interpreted seismic lines.

Digital Database of Seismic Interpretations.
Covers ~ 8200 line km of AGSO deep- and conventional industry seismic data.

Petrel Stratigraphic Time Chart *(by P.J. Jones et al.).*
Shows latest understanding of the Petrel stratigraphy against biozonations and AGSO timescale.

Gravity Modelling Report *(AGSO Record 1996/41, by J.B. Willcox)*
Details 2-D gravity modelling undertaken on 3 of the AGSO deep-seismic lines.

Organic Geochemistry Report *(AGSO Record 1996/42, by D. S. Edwards & R. E. Summons). Includes digital file of geochemical data (spreadsheets).*

Geohistory Modelling Report *(AGSO Record 1996/43, by J.M. Kennard).*
Details geohistory subsidence and thermal maturation modelling of 20 wells and 6 pseudo-wells and hydrocarbon generation and expulsion models.

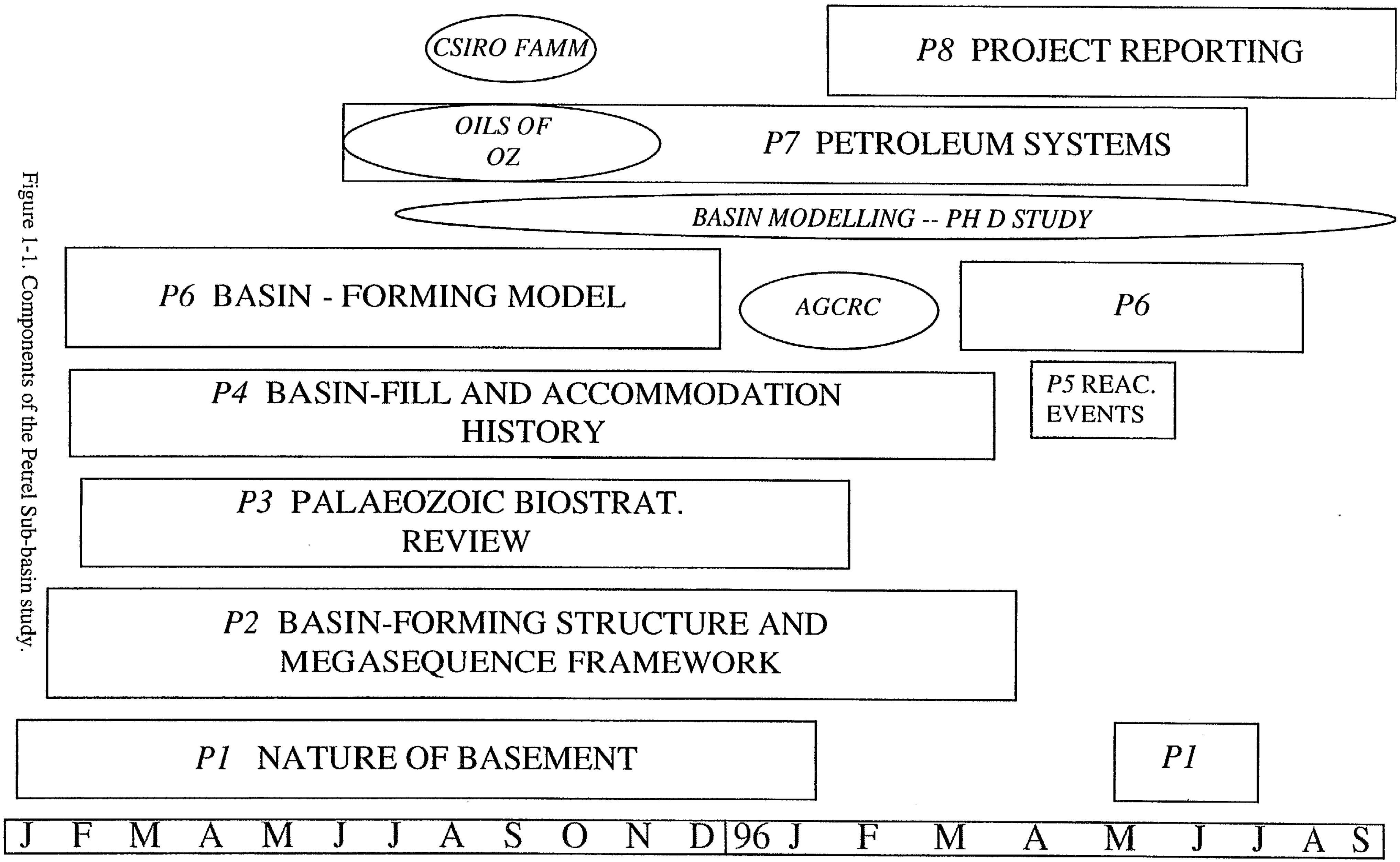

Figure 1-1. Components of the Petrel Sub-basin study.

CHAPTER 1

INTRODUCTION

by J.B. Colwell

The 1995-1996 Petrel Sub-basin Study was undertaken as part of AGSO's North West Shelf Project. The study was aimed at understanding the stratigraphic and structural development of the basin as a framework for more effective and efficient resource exploration. Specifically, it set out to:

- define the nature of the major basement elements and structures underlying the basin and their influence on the development of the basin through time;
- determine the nature and age of the events that have controlled the initiation, distribution and tectonic evolution of the basin;
- define the nature and age of the basin fill, and the processes that have controlled its deposition and deformation; and, importantly,
- determine the factors controlling the development and distribution of the basin's petroleum systems and occurrences.

Because of its relatively thick Palaeozoic section, the Petrel Sub-basin provides the opportunity to analyse and date the Palaeozoic tectonic events which may have influenced the subsequent development of the largely Mesozoic depocentres of the 'Westralian Superbasin' (Yeates et al., 1987) to the west. This 'superbasin' hosts all of the currently producing oil and gas fields on the North West Shelf, although older (Palaeozoic) discoveries have been made in the region in a number of areas, for example, the onshore Canning Basin (Blina, Lloyd, West Kora, Sundown, Boundary and West Terrrace oil fields), and the southern Petrel Sub-basin (e.g. Turtle, Barnett, Weaber, Garimala and Waggon Creek wells).

The Petrel Sub-basin Study used a systematic, sequence-stratigraphic, 'basement-up' approach to analyse the basin, which contrasts and complements the 'time-slice' approach used in the recent Australian Petroleum Systems (APS) study of the basin (McConachie et al., 1995, 1996). The present study had a number of major components (Fig. 1-1; see Chapter 2). In contrast to the APS study, it included major seismic, sequence stratigraphic and geochemical analyses.

In addition to AGSO's studies (this report and McConachie et al., 1995, 1996), two non-proprietary, multidisciplinary studies of the Petrel Sub-basin have been completed in recent years. These are a 1990 consultants' study of the Northern Territory part of the basin for the Northern Territory Geological Survey (Petroconsultants, 1990), and a petroleum prospectivity study made by the Bureau of Resource Sciences in 1994 in anticipation of acreage release (Maung et al., 1994). Key scientific papers on aspects of the basin's geology and evolution are: Laws & Kraus (1974), Edgerley & Crist (1974), Laws & Brown (1976), Laws (1981), Lee & Gunn (1988), Gunn (1988), Mory (1988, 1990, 1991), Mory & Beere (1988), Gunn & Ly (1989), and O'Brien et al. (1993, 1996).

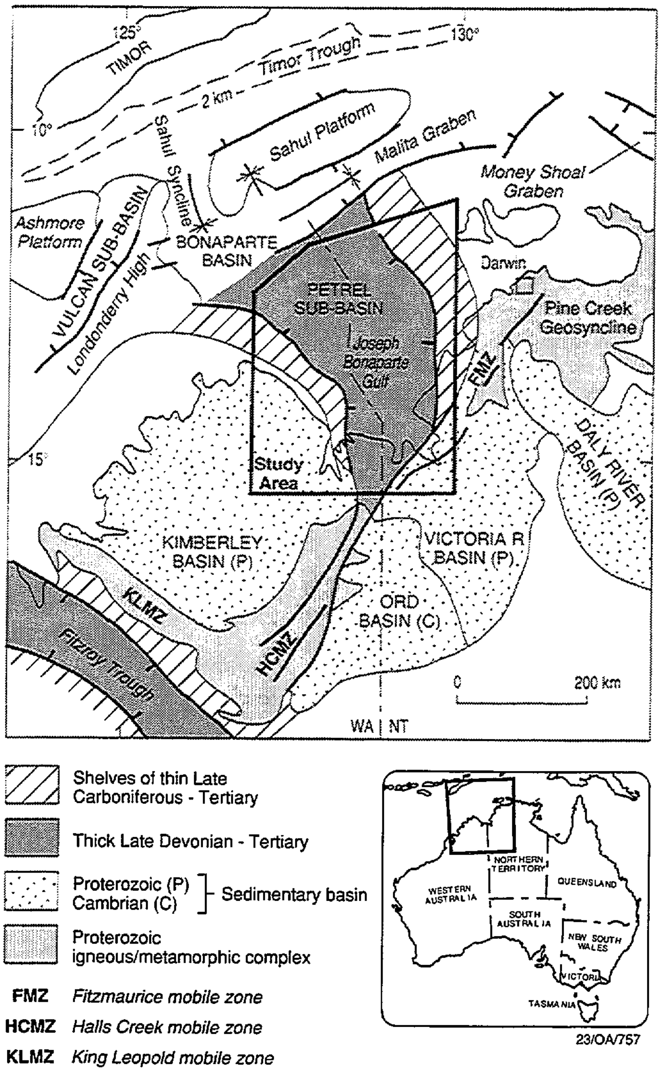

Figure 1-2. Location map. Base map after Gunn (1988).

Regional Setting

The Petrel Sub-basin lies off northwest Australia where it mostly underlies Joseph Bonaparte Gulf, extending onshore in the south (Fig. 1-2). It straddles the Northern Territory/Western Australia border. Over most of the basin, water depths are less than 100 m.

Originally, the Petrel Sub-basin was defined by Lee & Gunn (1988) as an area of the southern Bonaparte Basin with thick 'post-crustal opening sediments' interpreted as being underlain by oceanic crust. Since that time, there have been different interpretations of the temporal and spatial extent of the basin (e.g. Petroconsultants, 1990 and Hocking et al., 1994). In this study, as with the APS study (McConachie et al., 1995,1996), the sub-basin is taken to include all of the Phanerozoic rocks of the Bonaparte Basin lying inboard (southeastwards) of the Malita Graben. It is therefore broadly equivalent to the Bonaparte Gulf Basin as originally proposed by Laws & Brown (1976), and includes onshore features such as the Carlton Sub-basin (Moogarooga Deep) as well as offshore features such as the Petrel Deep, Keep Inlet Sub-basin, Lacrosse Terrace and Cambridge Trough (Fig. 1-3). It has a rock record extending from the Early Cambrian to the Quaternary (Fig. 1-4; Jones et al., 1996). Like parts of the Canning Basin to the south, the sub-basin was a major pericratonic depocentre during much of the Palaeozoic.

In map view, the Petrel Sub-basin is broadly V-shaped in outline. It is bounded by the Kimberley Basin to the southwest, the Halls Creek Mobile Zone to the south, the Fitzmaurice Mobile Zone and Ord and Victoria River Basins to the southeast, and the Darwin Shelf and Pine Creek Geosyncline to the northeast (Fig. 1-2). The sub-basin, which in simple terms has the form of a rift-dominated basal succession overprinted by a major 'sag' succession, deepens into the Malita Graben to the northwest.

Exploration History

Evidence for the existence of significant hydrocarbons in the Petrel Sub-basin comes from a variety of sources including petroleum wells and mineral exploration holes, and the occurrence of oil films in water wells. Early petroleum exploration in the basin led to the drilling of Spirit Hill-1 in the onshore part of the basin in 1960. This well recorded traces of residual oil in the Early Carboniferous sediments (Lavering & Ozimic; 1988a,b; Well Folio - Kennard, 1996a). Exploration continued through the 1960s with the drilling of Bonaparte-1 and -2, Kulshill-1 and -2, Moyle-1 and Keep River-1, all in the southern, onshore part of the basin. Several of these wells recorded traces of oil and/or gas. The most significant hydrocarbon occurrence in these wells was a gas flow of 3 - 0.2 MMCFD from Early Carboniferous strata in Keep River-1.

In 1969, drilling commenced offshore with the spudding of Lacrosse-1 on a faulted reactivation anticline on the southwestern flank of the basin. This well encountered traces of gas and oil in the Late Carboniferous/Early Permian section. Since then approximately 30 wells have been drilled on a variety of traps ranging from salt diapirs to stratigraphic pinchouts, mainly in the offshore part of the basin. Many of these wells have yielded shows of oil and/or gas (Table 1-1). Major gas discoveries

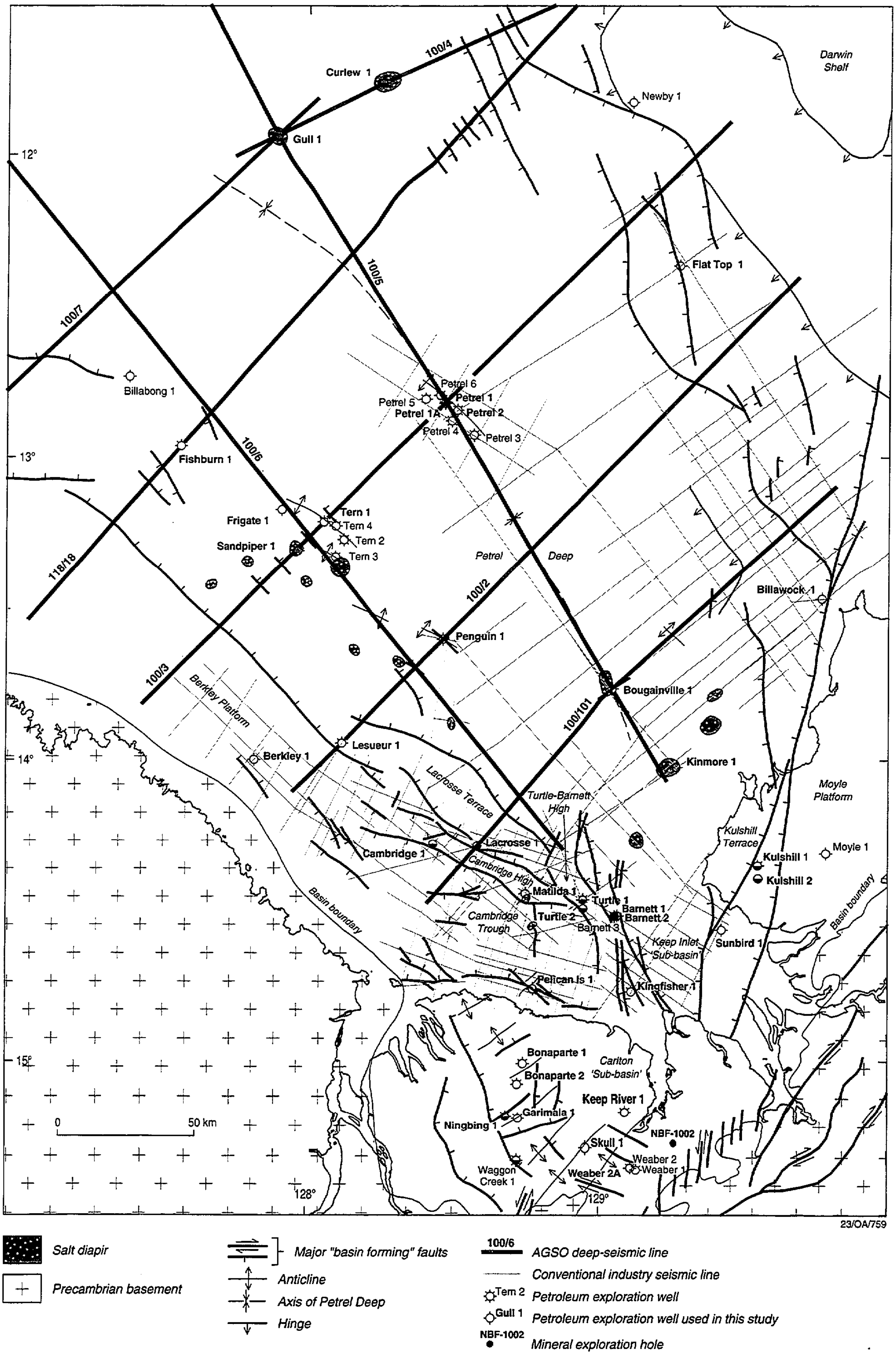

Figure 1-3. Major structures and location of wells and seismic lines used in the study.

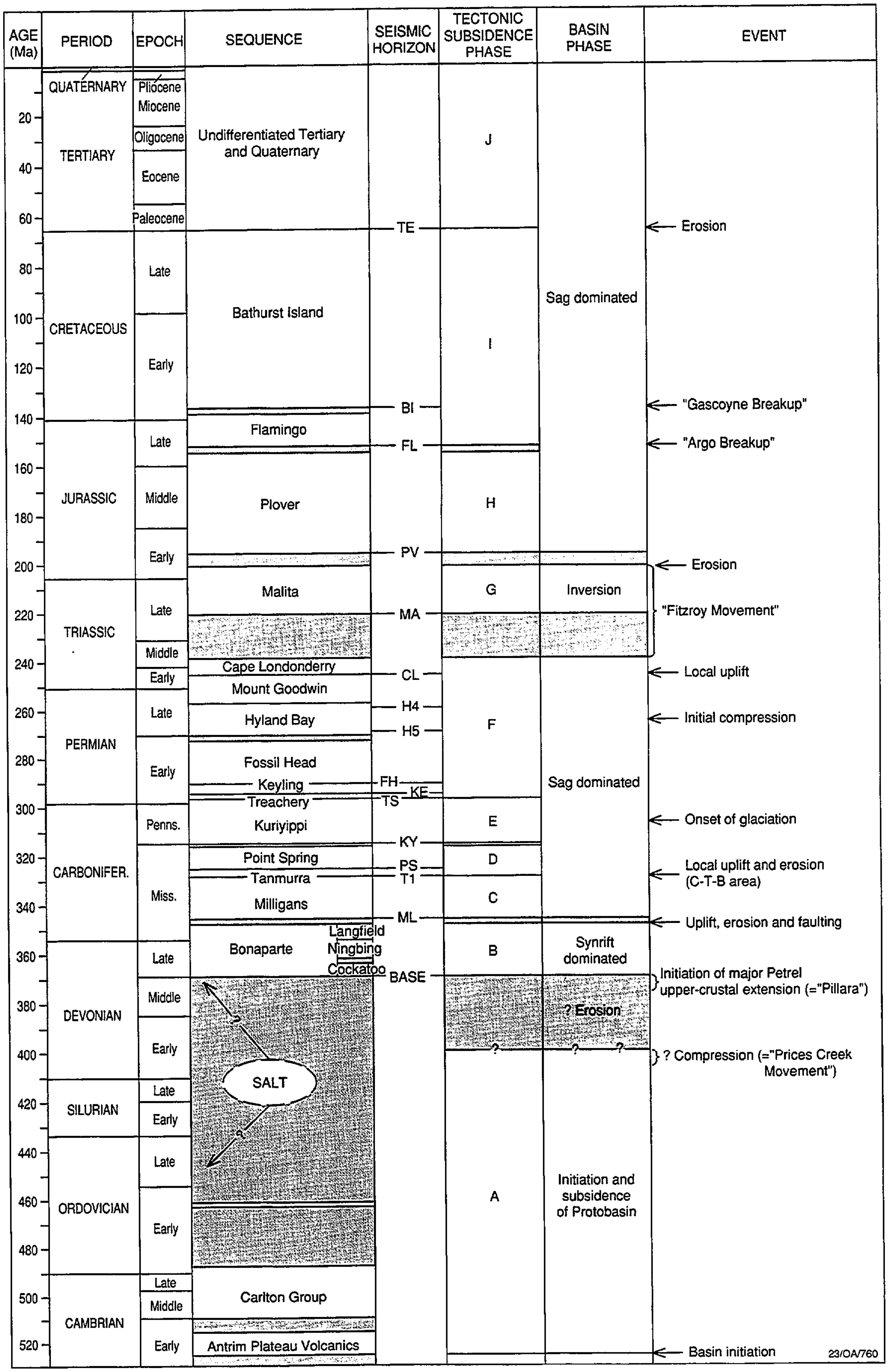

Figure 1-4. Stratigraphic column for the Petrel Sub-basin showing seismic horizons used in the study, tectonic-subsidence and basin phases, and major events affecting the basin.

Table 1-1. Details of Petroleum Exploration Wells

WELL	YEAR	STATUS	H/C SHOW	LAT.° S	LONG.° E
Barnett 1	1985	Dry	minor oil	14.53046	129.06135
Barnett 2	1989	O,G Suspended	gas & oil flows	14.53231	129.05221
Barnett 3	1990	Dry	oil	14.53425	129.05034
Berkley 1	1982	Dry	dry	14.00433	127.83147
Billabong 1	1992	Dry	v minor fluores	12.73919	127.4109
Billawock 1	1992	Dry	dry	13.47369	129.75564
Bonaparte 1	1964	Dry	minor gas show	15.01666	128.74166
Bonaparte 2	1964	Dry	gas flow	15.08527	128.72111
Bougainville 1	1972	Dry	fluores	13.77358	129.04180
Cambridge 1	1984	Dry	minor oil show	14.29043	128.43263
Curlew 1	1975	Dry	minor gas, oil show	11.77055	128.26388
Fishburn 1	1992	Dry	gas flow,?minor cond	12.96798	127.58435
Flat Top 1	1970	Dry	tr gas	12.37647	129.26552
Frigate 1	1978	Dry	no shows	13.17972	127.92361
Garimala 1	1988	Dry	gas flow	15.18791	128.72633
Gull 1	1971	Dry	tr gas	11.94138	127.91027
Keep River 1	1969	Dry	gas flow	15.16805	129.08944
Kingfisher 1	1994	Dry	minor hydrocarbon	14.77843	129.11074
Kinmore 1	1974	Dry	fluores, tr gas	14.03361	129.26244
Kulshill 1	1965	Dry	minor gas, oil shows	14.36305	129.54250
Kulshill 2	1966	Dry	minor oil shows	14.40500	129.54444
Lacrosse 1	1969	Dry	fluores, minor oil	14.29748	128.58269
Lesueur 1	1980	Dry	minor gas show	13.95261	128.12562
Matilda 1	1985	Dry	tr fluores	14.45482	128.74974
Moyle 1	1966	Dry	dry	14.31944	129.77527
Newby 1	1969	Dry	no shows	11.83527	129.10194
Ningbing 1	1982	Dry	minor gas and oil	15.18200	128.68083
Pelican Island 1	1972	Dry	fluores, gas, minor oil	14.77194	128.77416
Penguin 1	1972	Dry	gas flow	13.60777	128.46833
Petrel 1	1969	Suspended	gas flow	12.82638	128.47419
Petrel 1A	1970	Gas Well	gas flow	12.83111	128.47222
Petrel 2	1971	Gas Well	gas, cond. flow	12.85388	128.51388
Petrel 3	1982	Gas Suspended	gas, cond. flow	12.93526	128.56940
Petrel 4	1988	Gas Suspended	gas(minor cond.) flow	12.88844	128.49475
Petrel 5	1994	Gas Suspended	gas, cond. flow	12.81377	128.40818
Petrel 6	1994	Dry	minor gas	12.80093	128.45586
Sandpiper 1	1971	Dry	minor gas shows	13.31472	127.97638
Skull 1	1984	Dry	dry	15.28505	128.95468
Spirit Hill 1	1960	Dry	minor gas, tr oil	15.50555	129.07166
Sunbird 1	1994	Dry	fluores	14.57333	129.42144
Tern 1	1971	Dry	gas show	13.22083	128.06472
Tern 2	1982	Gas Suspended	gas flow	13.27860	128.13278
Tern 3	1982	Dry	dry	13.33560	128.10411
Tern 4	1994	Dry	gas flow	13.22986	128.10596
Turtle 1	1984	Dry	minor gas, oil flow	14.47660	128.94484
Turtle 2	1989	Dry	minor oil flow	14.50589	128.94581
Waggon Ck 1	1995	Gas Suspended	gas flow, oil shows	15.32383	128.71053
Weaber 1	1982	Dry	gas flow	15.35395	129.12960
Weaber 2	1988	Dry	dry	15.34875	129.10841
Weaber 2A	1988	Dry	gas flow	15.34763	129.10822
Weaber 3	1994	Suspended	gas flow	15.33402	129.12718

have been made in Late Permian strata at the Petrel (1969) and Tern (1971) fields; other significant gas discoveries have been made at Weaber-1, -2A, Fishburn-1 and Garimala-1. Turtle-1 and -2 and Barnett-1 and -2 were drilled in the southern offshore part of the basin in the 1980's with Barnett-2 (1985) yielding a sub-economic oil flow from the earliest Permian section. In late 1995 significant oil and gas shows were reported in the Early Carboniferous section from the Waggon Creek-1 well in the southern onshore part of the basin.

Overall, the evidence suggests that the Petrel Sub-basin has generated significant quantities of oil and gas. At least three petroleum systems appear to have been active within the basin and account for the distribution of oil and gas shows in rocks ranging in age from Late Devonian to Permian (McConachie et al., 1995, 1996; this report). Critical success factors apparent within the basin include reservoir quality, the preservation of early accumulations, and the timing of hydrocarbon generation versus structuring and the emplacement of seals.

Tectonic Setting

The Petrel Sub-basin occupies a pericratonic setting being flanked by the Proterozoic Kimberley Basin to the southwest, and the Cambrian Ord and Proterozoic Victoria River basins to the south and southeast (Fig. 1-2). The basin appears to be overprinted to the northwest by the mainly northeast-trending structures of the Westralian Superbasin (e.g. the Malita Graben). The Halls Creek Mobile Zone (HCMZ), and its associated extension, the Fitzmaurice Mobile Zone (FMZ), lie within Precambrian basement to the south and east. These mobile zones form part of the Halls Creek Province which is thought to lie astride an Early Proterozoic suture separating the concealed Archaean nucleus of the Kimberley Block from widespread attenuated transitional crust to the east (Hancock & Rutland, 1984). Onshore, the HCMZ is characterised by large, Proterozoic, left-lateral strike slip fault displacements (Plumb & Gemuts, 1976; Plumb, 1990). Significant reactivation of the major faults within the zone may have occurred up until at least the mid Carboniferous, probably as part of the Alice Springs Orogeny (D. Blake, AGSO, pers. comm.). Nicoll (1995) suggests a 200 km right-lateral displacement of Cambro-Ordovician rocks from the Petrel Sub-basin prior to Middle Devonian time, to form the Ord Basin to the south. A similar tectonic linking of the Petrel Sub-basin and Ord Basin was proposed by Mory & Beere (1988).

Veevers (1984) and earlier workers speculated that the Petrel Sub-basin may have initially developed in the Early Cambrian as part of a failed rift system associated with the spreading of the Tethyan Ocean located to the northwest. The main evidence for this was considered to be the Early Cambrian eruption of widespread tholeiitic basalt, the Antrim Plateau Volcanics. Subsequently, Gunn (1988) interpreted the gravity field of the offshore Petrel Sub-basin to reflect a progressive northwards increase in the intrusion of igneous material into the basin's basement, leading to the emplacement of oceanic crust along the axis of the basin in the northwest. An alternative interpretation of the gravity field is presented in Chapter 3 of this report.

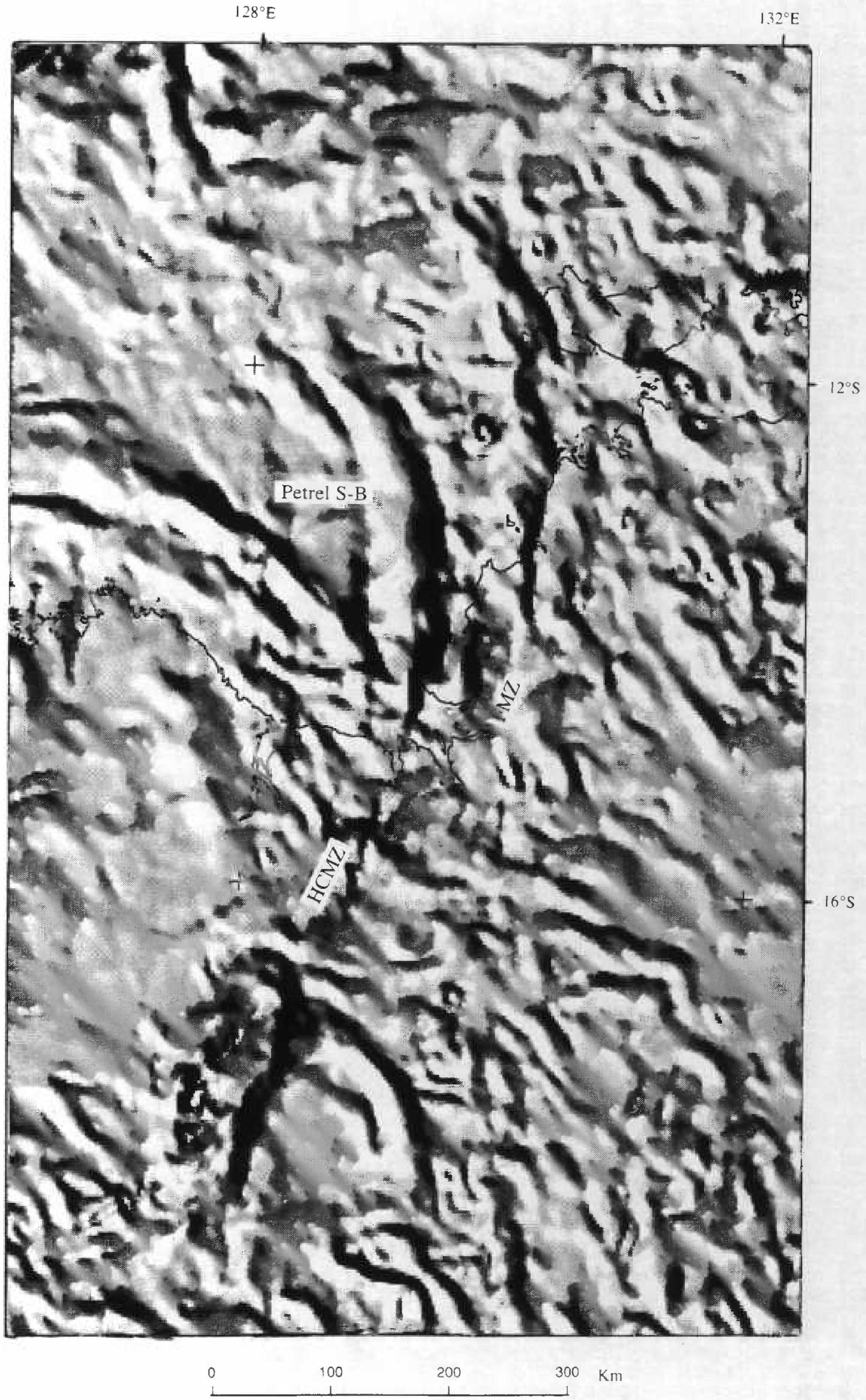

Figure 1-5. Horizontal gradient of the Bouguer Anomaly gravity field for the Petrel Sub-basin and surrounding areas (after Petkovic et al., 1996a). Image has a Sun azimuth of 45°. HCMZ: Halls Creek Mobile Zone; FMZ: Fitzmaurice Mobile Zone.

As noted by Elliott (1994) and Elliott et al. (1996), the southern part of the Petrel Sub-basin is a zone of convergence of many lineaments (or lineament 'corridors') which can be recognised on potential field and other data. This is illustrated in Figure 1-5 which displays the horizontal gradient of the Bouguer Anomaly field for the Petrel Sub-basin and surrounding areas (Petkovic et al., 1996a). The image shows prominent lineaments along the southwestern flank of the sub-basin corresponding to major structural features such as the Lacrosse Terrace (see Chapter 3 of this report) and the apparent offshore continuation of the Halls Creek Mobile Zone (part of the Lasseter Shear Zone of Braun et al., 1991) beneath the central and eastern parts of the basin. On the gravity image, the edge of the FMZ, which bifurcates from the HCMZ just south of the Petrel Sub-basin, is shown as a prominent lineament just to the east of the basin (Fig. 1-5).

According to White & Muir (1989), the HCMZ has acted as a transfer zone to extension, thrusting and inversion taking place in the broadly northwest-trending King Leopold Mobile Zone (KLMZ) that separates the Kimberley Basin from the Fitzroy Trough in the Canning Basin to the south (Fig. 1-2). The HCMZ and KLMZ mark regions of major crustal weakness reflected by the low mechanical strength of the faulted rocks developed along them, and have been subjected to numerous periods of structural reactivation (White et al., 1986). The HCMZ may have played an important role as an east-bounding accommodation zone along which Late Devonian - earliest Carboniferous extension in the Petrel Sub-basin and Fitzroy Trough were linked (AGSO North West Shelf Study Group, 1994). The western limit of the Petrel Sub-basin and Fitzroy Trough extension may have been along another complex accommodation feature, the postulated North West Shelf Megashear located to the northwest (AGSO North West Shelf Study Group, op. cit., fig. 6a).

CHAPTER 2

SCOPE OF THE STUDY

by J.B. Colwell

The great majority of AGSO's 1995-1996 Petrel Sub-basin Study was concentrated in the offshore part of the basin. Seismic lines were selected to provide an overall regional coverage and to tie wells, with the greatest density of lines being in areas of highest structural complexity, i.e. along the basin's southern, southwestern and eastern margins (Fig. 1-3). Approximately 2100 km of AGSO deep-seismic data (14.0 s TWT record length) and 6100 km of industry seismic data (5 or 6 seconds TWT record length) were used in the study (see Map & Seismic Folio - Colwell et al., 1996). Structural information derived from the seismic data was input to AGSO's NW Australia Tectonic Elements database. In addition, analogue modelling of the early (rift) history of the basin was undertaken as input into a wider, Timor Sea study (O'Brien et al., 1996) which also included an examination of recent high-resolution aeromagnetic data from the region (Gunn et al., 1995a, b).

Sequence stratigraphic analysis of 35 petroleum exploration wells (9 onshore and 26 offshore; Fig. 1-3) was undertaken in the study. Four of these wells (Kingfisher-1, Sunbird-1, Billawock-1 and Fishburn-1) are confidential and are not included in the Well Folio (Kennard, 1996a).

To supplement the biostratigraphic data already held in AGSO's STRATDAT database, biostratigraphic studies were made of selected intervals in the onshore (outcrop and subsurface) and offshore Petrel Sub-basin. This work included:

- a review of old collections of outcrop Cambrian and Ordovician trilobite material, plus an examination of associated conodont collections;
- a review and upgrade of the Palaeozoic biostratigraphy of both onshore and offshore petroleum exploration wells including resampling of several key wells for microflora and microfauna;
- the input of maturation-sensitive conodont alteration index (CAI) determinations from mineral and petroleum exploration holes into AGSO's ORGCHEM database;
- the preparation of a report on the Cambrian of the Bonaparte and Ord Basins (Shergold, 1995); and
- compilation of a summary stratigraphic chart detailing biostratigraphic zones, sequences and tectonic events (Jones et al., 1996).

Several approaches were applied to understand the deep-crustal structure and rift and subsidence histories of the basin:

- 2-D gravity modelling was undertaken along three AGSO deep-seismic lines (lines 100/2, 3 and 5, respectively; Gravity Modelling Report - Willcox, 1996);
- the Free-Air, Bouguer and horizontal gradient images for the gravity field (Petkovic, 1995; Petkovic et al., 1996a,b) were examined, particularly with respect to the offshore continuation of the Halls Creek Mobile Zone;

- WINBURY subsidence modelling was carried out on 20 wells (Geohistory Modelling Report - Kennard, 1996b);
- flexural isostatic modelling was applied to AGSO lines 100/3 and 5 as part of on-going research into the North West Shelf region being undertaken at the Australian Geodynamics Cooperative Research Centre (AGCRC; Baxter, 1996);
- a program of seismic-refraction data acquisition was undertaken along AGSO line 100/3 using ocean-bottom seismometers (Lee et al., 1996), and
- as part of a North West Shelf-wide study, a lineament analysis was made using magnetic, gravity and other data (Elliott et al., 1996).
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In addition to the above work, data were provided in support of on-going PhD studies, firstly at Sydney University and then at Bullard Laboratories, University of Cambridge (Baldwin et al., 1995).

Geochemical analyses (including carbon isotope and biomarker studies) were undertaken on samples of oils and their potential source rocks (Organic Geochemistry Report - Edwards & Summons, 1996). These results, together with thermal maturation modelling of 20 wells and 6 pseudo-wells, were used to predict the timing of hydrocarbon generation and expulsion (Geohistory Modelling Report - Kennard, 1996b). Structural, stratigraphic, geochemical and maturation/expulsion modelling data were used to analyse and evaluate the hydrocarbon prospectivity of the three active petroleum systems identified in the basin (see Chapter 7).

CHAPTER 3

STRUCTURAL FRAMEWORK

Reflection and refraction-seismic data (Map & Seismic Folio; Goncharov et al., in prep.), onshore mapping (e.g. Mory & Beere, 1988), and gravity (Petkovic et al., 1996a,b; Willcox, 1996) and magnetic data (e.g. Gunn et al., 1995a,b) indicate that the Petrel Sub-basin can be divided into a number of major structural elements (Fig. 3-1). The development and subsequent interplay of these elements has controlled the evolution of the sub-basin, including the creation of accommodation space and thermal/maturation histories.

DEEP-CRUSTAL STRUCTURE: OBSERVATIONS FROM MODELLING

Seismic Refraction Studies by P. Petkovic, A. Goncharov, C. Collins & C.-S. Lee

In order to identify major intra-crustal boundaries and to determine the velocity structure of the crust beneath the Petrel Sub-basin and the depth to Moho, a program of seismic refraction data acquisition was undertaken along AGSO deep-seismic reflection line 100/3. This work, which formed part of a North West Shelf-wide study (AGSO Survey 168; Lee et al., 1996), involved the placement of 15 ocean-bottom seismometer (OBS) stations along the line, as well as land stations on the Kimberley craton and on Bathurst Island (Fig. 3-2). The total profile length was approximately 500 km.

The refraction data are of variable quality, being subject to several types of noise of unresolved origins. The Petrel data are generally of good quality in the central OBS units, while the units on the flanks of the line have poor data recovery. The data were initially processed using bandpass filter and gain control to enhance arrivals. F-K filtering was used to improve signal to noise ratio for different types of noise. For details regarding the processing of these data see Petkovic & Fomin (in prep.).

A preliminary interpretation of the first arrivals of the vertical component, and selected reflections, is summarised in Figure 3-3. This model was obtained by iterative forward modelling using *MacRay 1.0.6*. This process involved tracing synthetic seismic rays through an initial model which had a given velocity distribution and layer geometry. The rays are traced for each shot through the model, which is then manually modified to give a better fit between observed and computed travel times in the next ray tracing session. The starting model for ray-tracing was based on the interpreted multi-channel reflection section along line 100/, supplemented by stacking velocities and well-velocity data. Details of the methods and constraints used in the modelling are given by Goncharov et al. (in prep.).

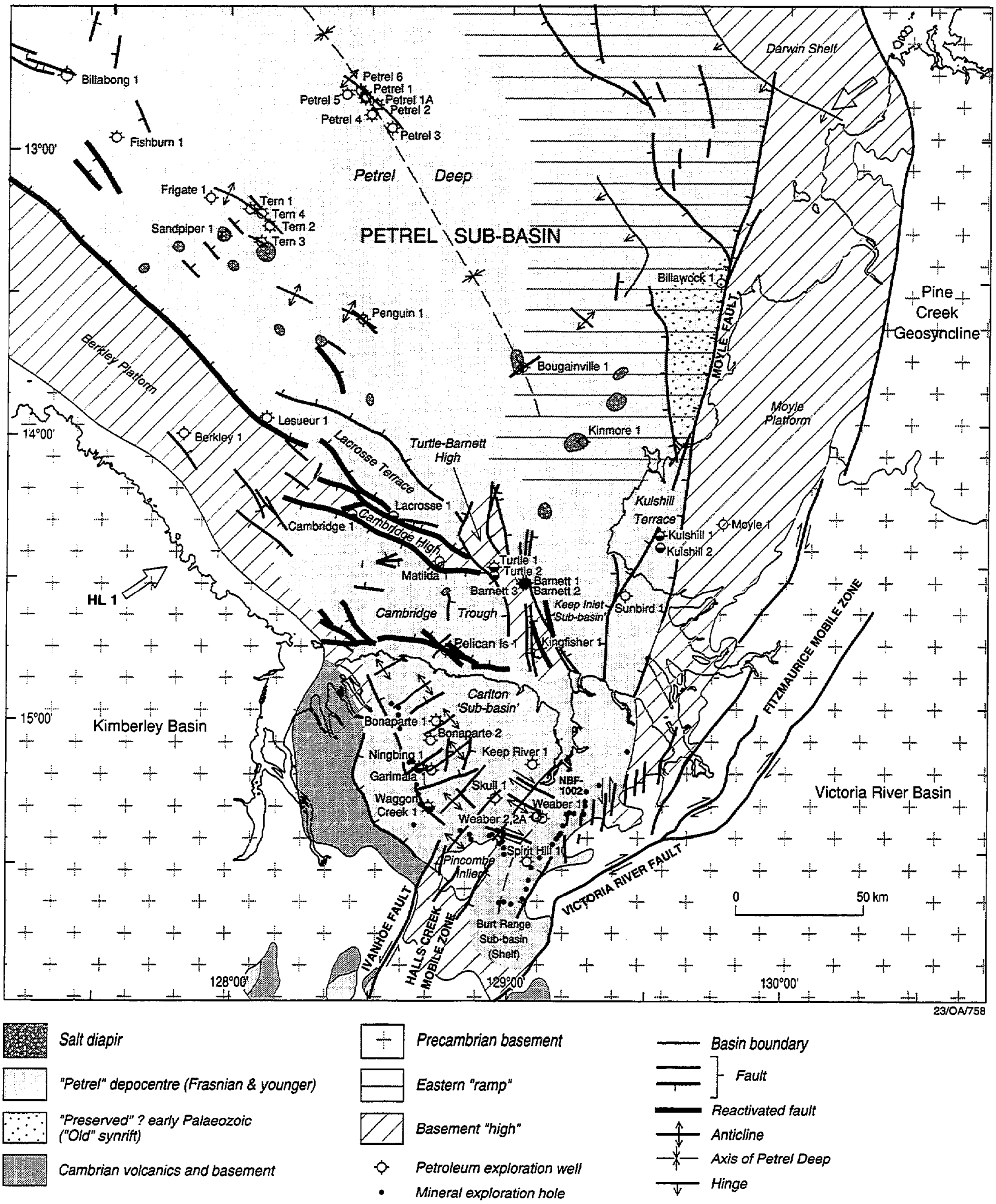

Figure 3-1. Structural elements of the Petrel Sub-basin. Onshore structures after Mory & Beere (1988) and Petroconsultants (1990). Hard link HL 1 after O'Brien et al. (1996). Salt diapirs partly after Gunn (1988).

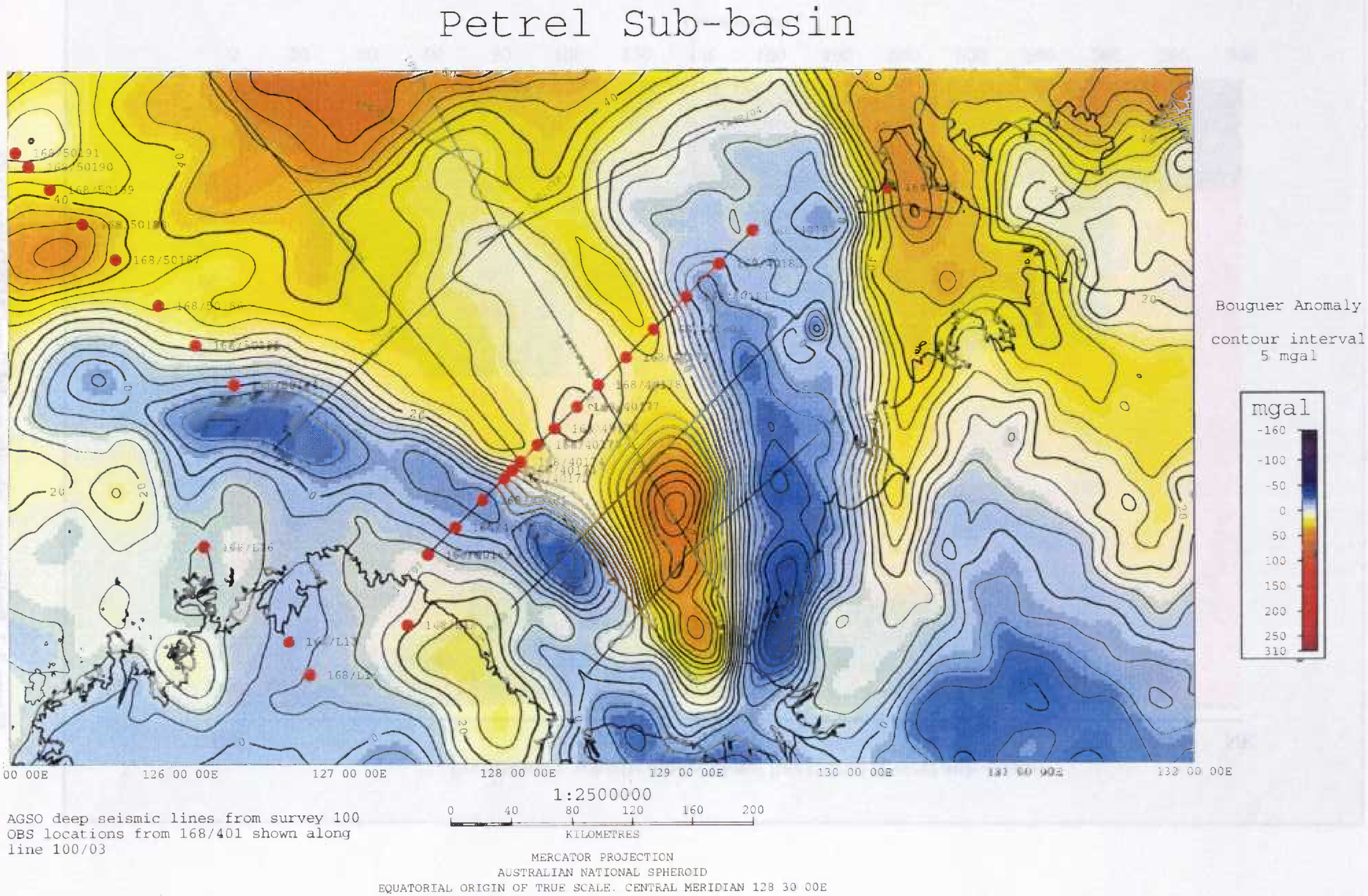

Figure 3-2. Location of seismic refraction stations (red dots) in the Petrel Sub-basin (along AGSO deep-seismic line 100/3) and in the surrounding area.

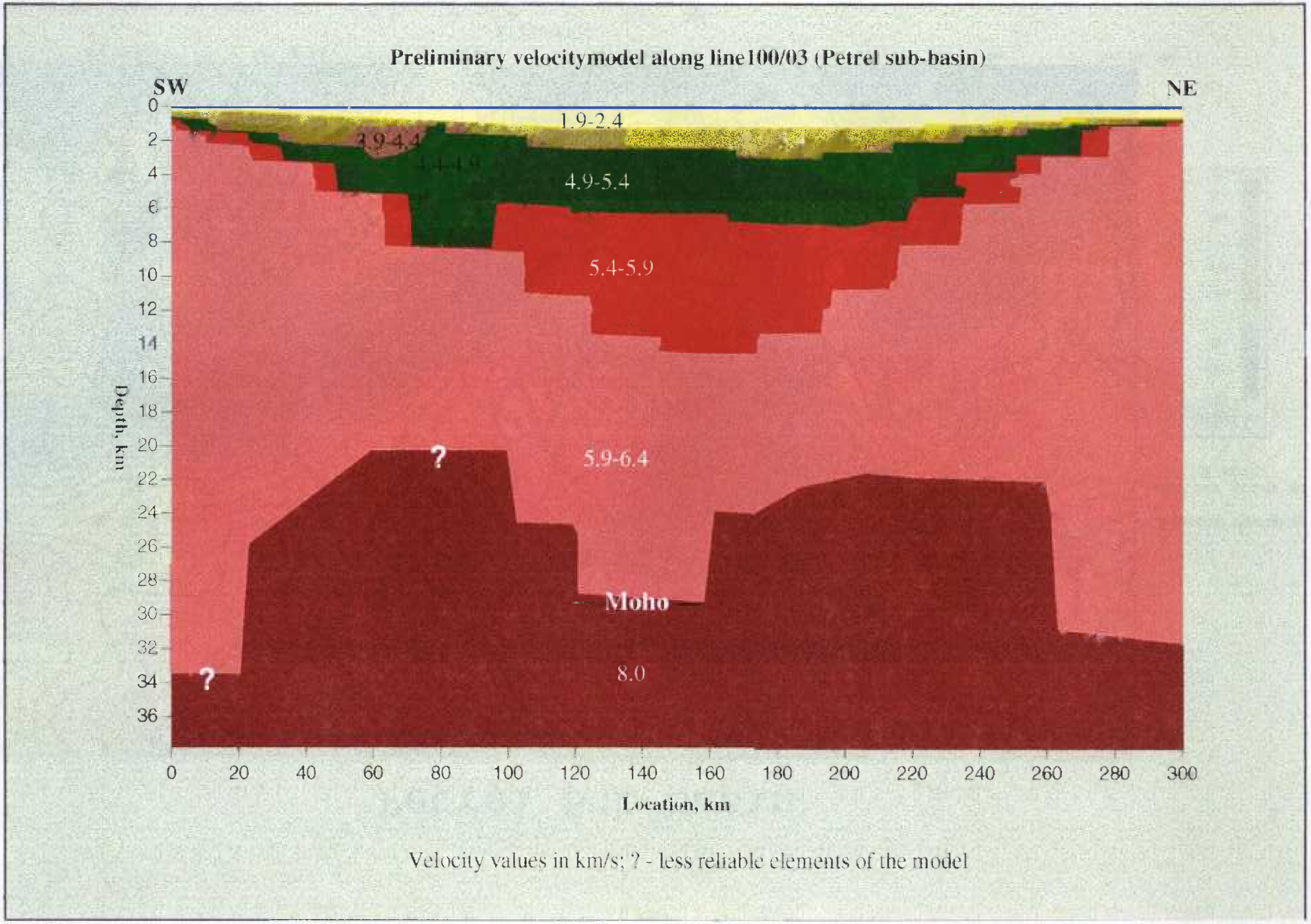

Figure 3-3. Preliminary velocity model along AGSO line 100/3.

The main results of preliminary modelling are:

- In the central part of the line, velocities in the depth range 3-8 km are between 4.9-5.5 km/s, which are significantly higher (by up to 1 km/s) than was expected *a priori.*

- There are no sharp velocity increases at depths of more than 6 km. However, there are some prominent reflections at depths of more than 6 km and up to 22-23 km depth in the central part of the line observed in the conventional reflection section. The origin of these reflections may be due to thin interlayering of high and low velocity material/layers in this part of the cross-section which is not imaged by the refraction method. Alternatively, the hypothesis of multiples from within the upper 6 km of the cross-section producing reflectivity at larger times in the reflection section must be re-considered more carefully.

- The velocity at depths of more than 15 km is very close to what can be expected in granites under low/average temperature conditions, which means that this part of the section can be treated as rocks of crystalline basement.

- The Moho topography in the central part of the line is unexpected. It forms a 'camel-like' structure with two highs separated by a relative low. The increased depth to Moho in the middle of this structure results in computed gravity values up to 50 mGal lower than experimentally observed within the gravity low. This discrepancy may be due to a large central gravity high to the southeast of the line. Three-dimensional gravity modelling is necessary to resolve this discrepancy.

- The preliminary processing and modelling completed so far has failed to identify a lower crust with velocities close to 7 km/s or higher.

Gravity Modelling by J.B. Willcox

As first noted by Caye (1968), the southern offshore part of the Petrel Sub-basin is characterised by a prominent gravity high which broadens and decreases in amplitude along the axis of the basin to the northwest (Figs 3-2 and 3-4). This high, which has an amplitude about 50 mGal greater than the surrounding field, is similar to a gravity high occurring within Proterozoic basic intrusives and metamorphics of the Halls Creek Mobile Zone to the south (Fig. 3-4; Anfiloff, 1988; Plumb, 1990).

The gravity high within the Petrel Sub-basin was attributed by Gunn (1988) to crustal thinning associated with Palaeozoic Petrel rift development leading to the intrusion of a broad axial dyke, with the dyke splitting to the northwest due to the emplacement of oceanic crust. Alternatively, O'Brien et al. (1996) suggested that although the gravity signature over the Petrel Sub-basin is related to deep thinning and associated partial melting and magmatism, its manifestation varies throughout the basin depending upon the degree of thinning, variations in the thermal state of the lithosphere, and the way in which the magmatic products are distributed through the lithosphere.

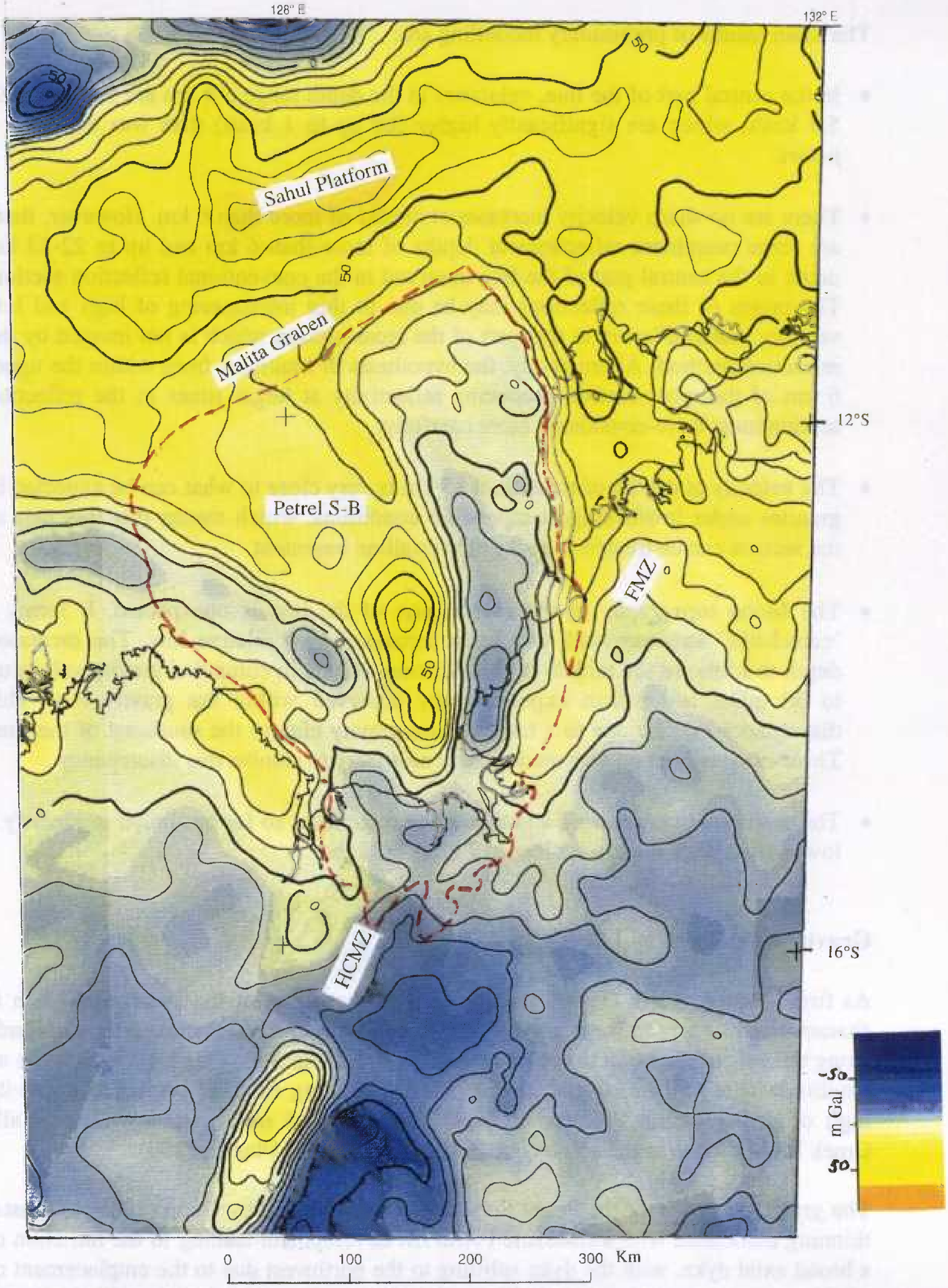

Figure 3-4. Bouguer Anomaly gravity field for the Petrel Sub-basin and surrounding region (after Petkovic et al., 1996a). Approximate boundaries of Petrel Sub-basin shown by the red dashed line. HCMZ: Halls Creek Mobile Zone; FMZ: Fitzmaurice Mobile Zone.

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Gravity modelling of the Petrel Sub-basin region was first carried out by Mory (1991). This was specifically aimed at testing the concept of Gunn (1988) that the axial part of the sub-basin was floored by oceanic crust. It attempted to distinguish whether it was the failed arm of a rift or had become an active spreading centre.

Mory's models are based on a northeasterly-trending profile passing through the Sandpiper-1, Tern-1, Petrel-1 and Flat Top-1 exploration wells. The modelling was relatively simplistic, in that it treated the Phanerozoic basin-fill sediments of the Petrel Sub-basin as a single body of density 2.6 tm^{-3} and considered the crust as made up of two basic layers. The high-density oceanic crust that was postulated to underlie the basin's axial zone, was found to generate a computed gravity high far in excess of the observed field. To compensate for this effect, Mory's model incorporated relatively low density bodies within the centre of the rift; these were presumed to be Silurian evaporites (ρ=2.4 tm^{-3}) or halite (ρ=2.2 tm^{-3}).

Mory (1991) concluded that:
(1) models in which oceanic basalt is present in the centre of the Petrel Sub-basin require a significant thickness of low density material (e.g. salt) which would be unstable beneath the overburden; hence, oceanic crust is unlikely to be present;
(2) the gravity high in the southern part of the basin confirms the presence of deep intrusions, probably emplaced during late Proterozoic or early Phanerozoic crustal thinning.

Three gravity models have been computed in the present study: AGSO lines 100/2 and 100/3 across the sub-basin, and part of line 100/5 along the basinal axis and tying the cross-basin lines; the location of the lines are shown in Figure 1-3 (see Gravity Modelling Report - Willcox, 1996). The modelling was constrained by events imaged on the AGSO deep-seismic reflection data and by the results of OBS refraction studies both along line 100/3 (this report), and over the Kimberley Basin/Block in the adjacent Browse Basin (Symonds et al., 1994).

The three computed gravity models were compared to smoothed on-line observations (5000 m stations) corrected for latitude and Eotvos effects - that is the Free-air anomalies (FAA). Theoretically, the FAA's may be expected to average zero over regions that are in isostatic equilibrium; however, the minimum size of features that are compensated is usually 200+ km across, the more local structures being supported by the crust. A good fit was obtained on all three profiles (Fig. 3-5). The results show convincing consistency in the models derived for the two across-basin lines (Willcox, 1996). Further, the seismic/gravity tie-line (Fig. 3-5c) provided a realistic result with minimal adjustment. The principal results are:

- The geometry of the Petrel Sub-basin as interpreted from the seismic reflection profiles makes little contribution to the broad gravity high and flanking negative lobes that occupy the region.

- A high-density zone (about 3.00 tm^{-3}) must underlie the main basinal area and must be relatively steep-sided. The upper surface of bodies corresponding to this zone are visible in parts of the seismic profiles (particularly line 100/3) and such bodies are suggested by the preliminary refraction results. The crustal geometry

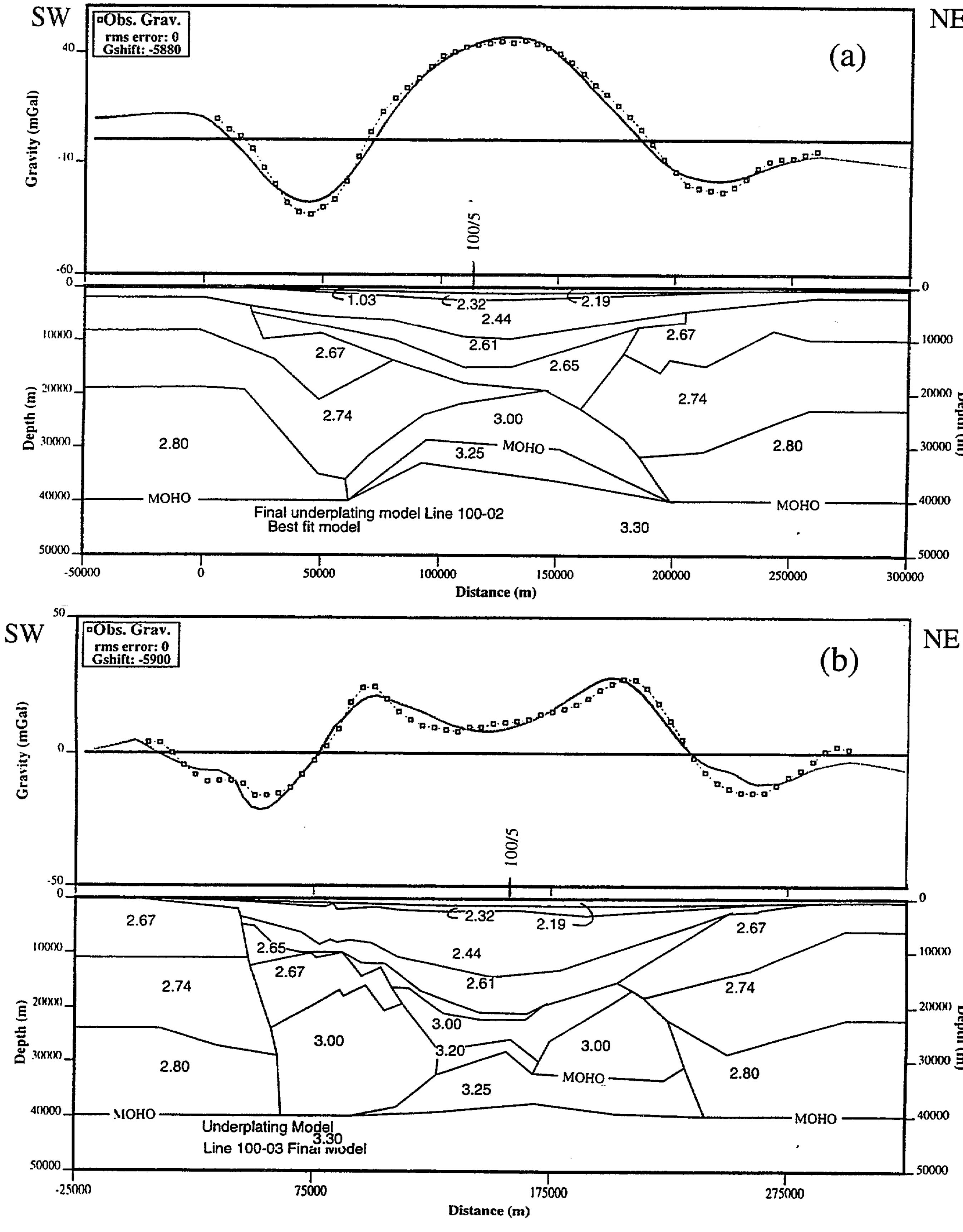
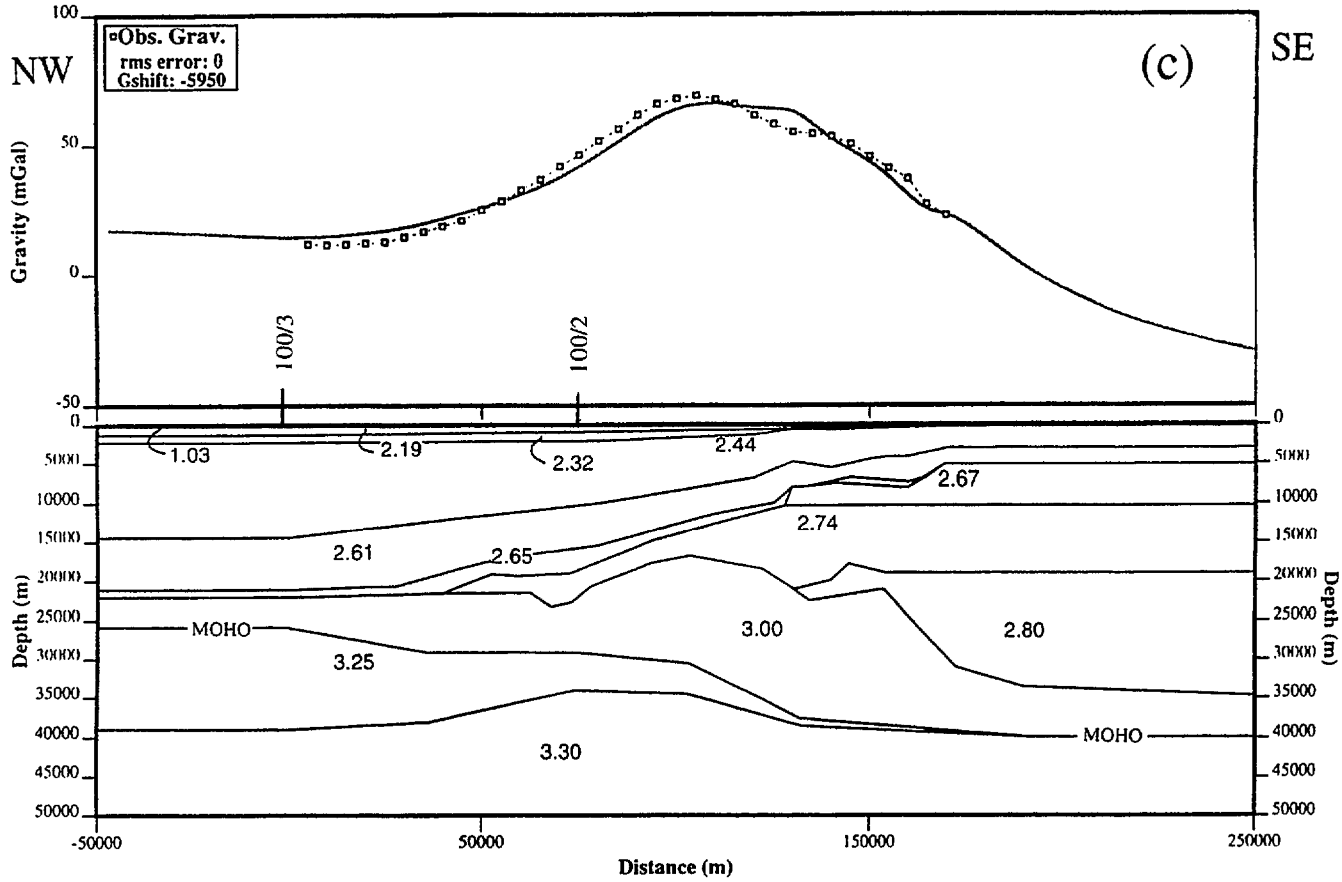


Figure 3-5. Gravity models
(a). 2-D gravity model based on seismic reflection line 100/2. Ties to line 100/5 as shown. Densities (tm^{-3}) are derived from seismic reflection velocities and refraction data. Model implies densification of the lower crust by intrusion (3.0 tm^{-3} zone) and underplating (3.25 tm^{-3} zone). Moho is taken to lie at the top of the underplated zone.
(b). 2-D gravity model based on seismic reflection line 100/3. Ties to line 100/5 as shown. Densities derived from seismic reflection velocities and refraction data. As in (a), the model implies densification of the lower crust by intrusion and underplating.



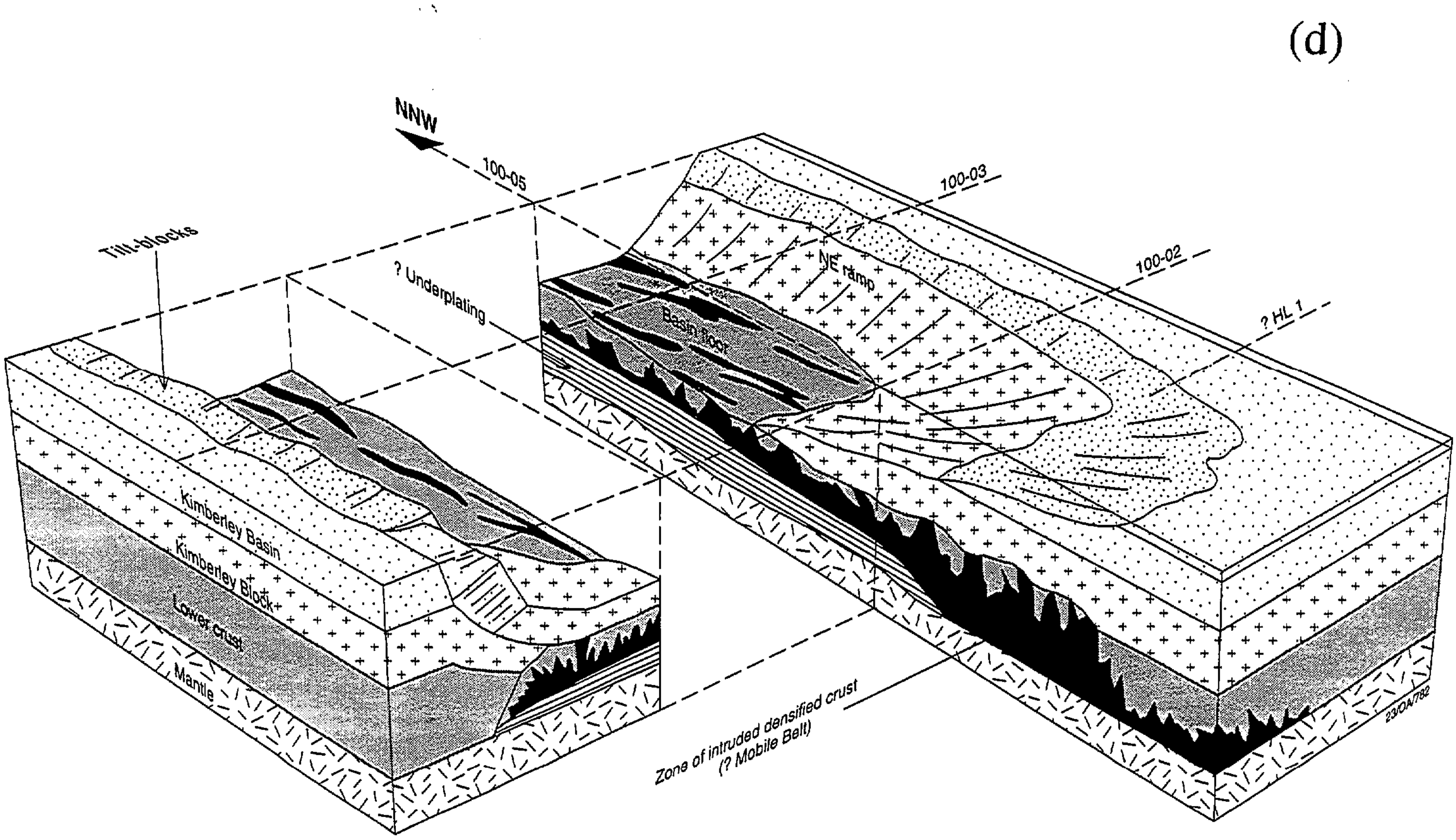


Figure 3-5 Gravity models (cont.)
(c) 2-D gravity model based on the axial tie-line 100/5. Ties to lines 100/3 and 100/2 as shown. Densities derived from seismic reflection velocities and refraction data. Model shows termination of the Kimberley Basin (2.67 tm^{-3}) and Kimberley Block (2.74 tm^{-3}), and implies thinning of the lower crust towards the NW.
(d) Conceptual isometric block diagram based on gravity modelling. Shows the basin geometry, and extent of the Kimberley Basin and Kimberley Block.

indicates that the high-density zone may result from the intrusion of dense material into rocks which originally made up part of the Precambrian Kimberley Block and the lower crust (see Fig. 3-5a,b). On the axial tie-line (Fig. 3-5c), the lower crustal body at the right-hand side (SE), which has a density of 2.80 tm^{-3}, is effectively replaced by the high-density material (3.00 tm^{-3}). It may partially replace or intrude the Kimberley Block basement, which thins to the left (NW) and terminates midway between the two dip lines. The high-density material forms a wedge that thins to the left (NW) and eventually directly underlies the syn-rift sediments of the Petrel Sub-basin.

- On the basis of the gravity modelling, the dating of igneous intrusion into the lower crust remains unresolved. The possibilities are that it could be (1) Proterozoic, associated with melts which produced features such as the Hart Dolerite; (2) Early Cambrian and related to the Antrim Plateau Volcanics; or (3) a product of the Late Devonian - earliest Carboniferous rifting which gave rise to the Petrel Sub-basin itself. The gravity anomaly maps indicate that the intrusive zone appears to be an arcuate prolongation of the Halls Creek Mobile Zone through the Bonaparte Gulf region (Figs 1-5 and 3-4). On this basis it could be inferred to be a pre-basinal feature - a fundamental crustal lineament which may have controlled development of the Petrel Sub-basin. However, its width corresponds closely to that of the Petrel rift, and indeed, widens and becomes more complex to the north-northwest as does the sub-basin. This suggests some genetic link or control between the intrusions and the development of the sub-basin.

- The crust thins significantly under the Petrel Sub-basin, with the Moho shallowing from about 40 km to 28 km on the inboard line (100/2) and to 26 km on the outboard line (100/3). The crustal thinning appears to be confined approximately to the width of the sub-basin. The axial line shows that the Moho shallows north-northwestwards from about 40 km to about 26 km and that the the Petrel sag-phase sediments thicken in the same direction.

- A 'best fit' of the observed and calculated gravity is obtained if the material immediately underlying the thinned crust and the Moho comprises a lens with a density in the range 3.20 - 3.25 tm^{-3}. On the axial line, this sub-Moho body is seen as a northwest-thickening wedge. This could be interpreted as underplating.

- The modelling also suggests that the Kimberley Basin section probably underlies both sides of the Petrel Sub-basin and is consistently about 10 km thick. It appears to have been downfaulted, particularly along the southwestern high-displacement side of the sub-basin, and forms the ramp on the low-gradient northeastern flank. The Kimberley Basin section is probably not present within a broad (100 km wide) zone along the sub-basinal axis. However, modelling of line 100/5 indicates that Kimberley Basin sediments (or some of similar density) are probably present to the southeast.

- Although tests of the geometry of the eastern ramp of the sub-basin are inconclusive, the models tend to favour a minimum angle for the ramp, with its head near the NE hinge and its foot in the most SW location.

- A convincing fit on all three profiles can be obtained through minor adjustments to the shape of the crust/mantle interface (Moho). The high sensitivity of the model to the Moho configuration (owing to the large density contrast) is, of course, a limiting factor in the modelling process. The aim of this modelling process was not to obtain a perfect fit, but to test various possibilities related to basin formation.

INTRA-BASEMENT STRUCTURES by J.B. Colwell, J.E. Blevin & G.W. O'Brien

Fractures ('Hard links')

Regional aeromagnetic and Landsat data across the Kimberley Basin, show at least two NE-trending lineament corridors (fracture zones) extending from north of the Canning Basin in the south, to the Petrel Sub-basin in the north (Fig. 3-6). These fracture zones (HLs on Fig. 3-6) were originally interpreted to be the onshore continuations of offshore accommodation zones (O'Brien et al., 1993). They were reinterpreted by O'Brien et al. (1996) as basement 'hard links' that sub-divide the Petrel Sub-basin into three adjacent rift compartments: the southern-most 'Barnett Compartment', located inboard of the Turtle and Barnett wells; the 'Tern Compartment', extending out as far as the Petrel and Tern Gas Fields; and the 'Curlew Compartment', occupying the outer-most part of the basin (Fig. 3-6). An almost identical sub-division of the rift architecture of the basin was proposed by O'Brien et al. (1993) based upon the distribution of salt diapirs in the basin and an apparent associated switch in basement rift architecture. The Barnett Compartment is characterised by complex structuring in the Turtle-Barnett area with possibly the major fault throws (high-displacement margin) being on the NE side of the basin. In the Tern Compartment, the major fault throws shift to the SW flank of the basin, while in the Curlew Compartment, major throws possibly relay to the NE flank (Fig. 3-6), although the seismic evidence in this area is far from clear.

Detailed mapping of industry and AGSO seismic data undertaken as part of the present study provides some support to the O'Brien et al. (1993, 1996) assertion of the existence of major accommodation zones or hard links within the basement of the sub-basin. This evidence includes:

(i) the marked change in structural style between AGSO lines 100/3, 118/18 and 100/7+4 (see Enclosure 7 of Map & Seismic Folio - evidence for hard link HL 0) as noted originally by O'Brien and co-workers;

(ii) the termination of major faults, the Cambridge Trough and Lacrosse Terrace in the vicinity of Lesueur-1, major structuring beneath Bougainville-1, and the termination of an area of 'old syn-rift' west of Billawock-1 (Fig. 3-1 - evidence for hard link HL 1); and,

(iii) the juxtaposition of the eastern end of the Lacrosse Terrace against the Turtle-Barnett High northwest of Turtle-1 (Fig. 3-1 - possible evidence for a NNE-trending hard link through Matilda-1 passing just to the east of Bougainville-1; this may correspond to the western edge of the HCMZ).

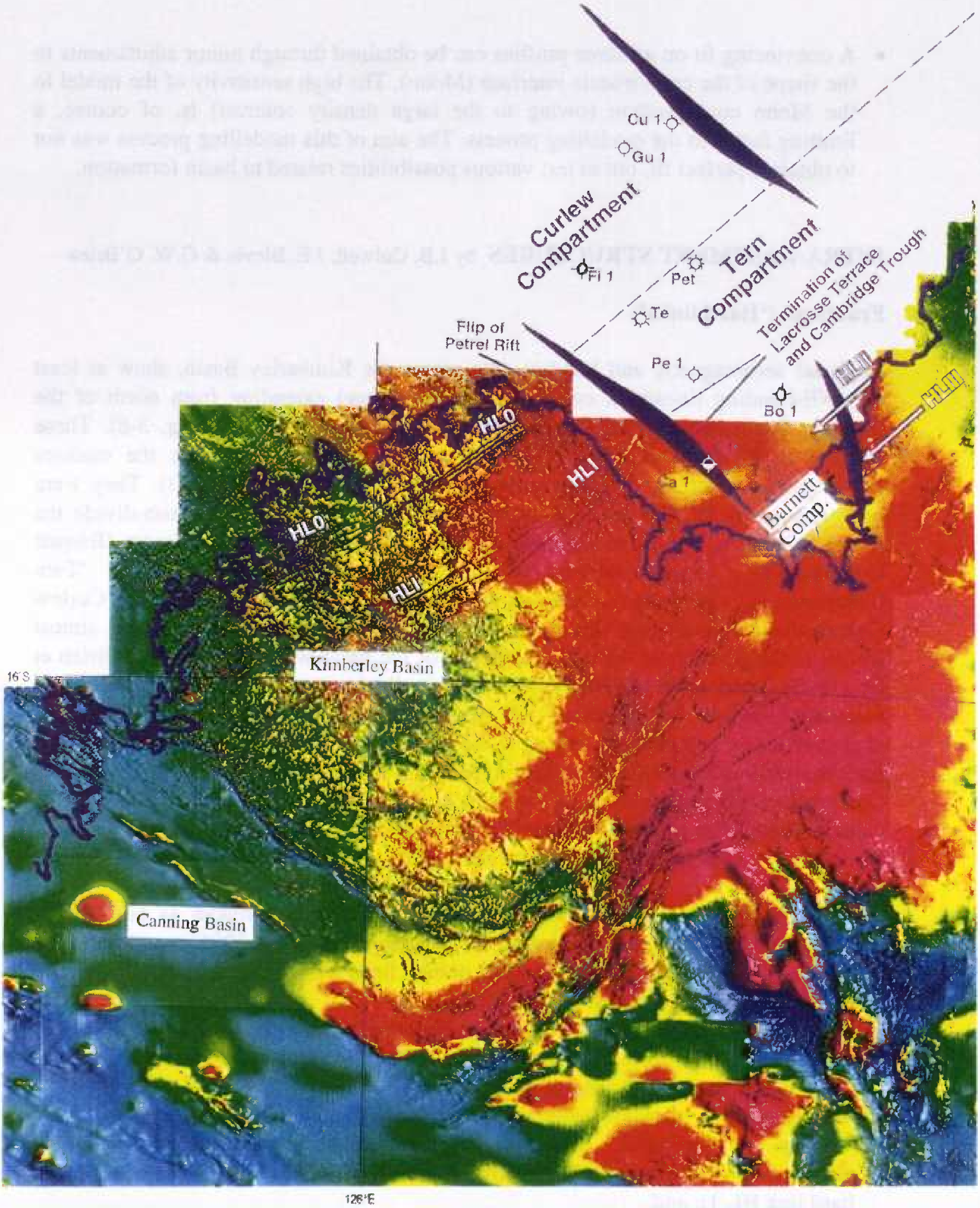


Figure 3-6. Total magnetic intensity image of the Kimberley Block and surrounds (after O'Brien et al., 1996) derived from AGSO's Australian Magnetic Anomaly Map. Note the postulated NE-trending basement fracture systems/hard links (HLs).

Halls Creek Mobile Zone

As noted in the tectonic setting section of this report, onshore the Halls Creek Mobile Zone is a region of major crustal weakness characterised by mainly northerly-trending faults of various displacements and ages. Its geology consists of a complex mixture of basic intrusives, granites, volcanics and metamorphic rocks (Plumb, 1990). Offshore, gravity data indicate that the zone extends within basement beneath the central and eastern parts of the Petrel Sub-basin (Fig. 1-5). It appears to have a NNE-trend in the southern onshore part of the basin and then curve north and then NW in the offshore. It may strongly influence the mostly-northerly fault trends seen in the southern part of the basin, for example around the Turtle-Barnett High, and on the basin's eastern flank. These trends are oblique to the largely northwesterly trends which characterise the basin's southwestern flank (Fig. 3-1).

The offshore continuation of the HCMZ may have played a significant part in the development of the Late Devonian - earliset Carboniferous Petrel rift and of the overlying Carboniferous to Tertiary sag-dominated basin. At the very least, the inherent lithospheric weakness of the HCMZ would have tended to partition extensional faulting. Also, left-lateral strike-slip movement on faults within the HCMZ, which appears to curve to the west (Fig. 1-5), may have contributed an oblique-slip component to the opening of the Petrel rift.

Other Structures

The AGSO deep-seismic lines give some indication of the nature and structure of the pre-rift section. On the flanks of the Petrel Sub-basin (e.g. on the Berkley Terrace - SW end of AGSO lines 100/2 & 3), basement consists of two distinct layers: a zone of relatively bland seismic character (here interpreted to be relatively flat-lying Kimberley Basin section), underlain at a depth of about 5 seconds TWT (~10 km) by more heterogeneous material, possibly Archaean rocks of the Kimberley Block (see Map & Seismic Folio, enclosures 2 and 3). Gravity modelling suggests that the Kimberley Basin and Block extend at least part way beneath the main Petrel depocentre (see Fig. 3-5).

Relatively high-amplitude dipping events imaged within basement on both industry and the AGSO deep-seismic lines could be either early Palaeozoic ?carbonates (e.g. beneath the Lacrosse Terrace) or Proterozoic dolerites (e.g. beneath the Berkley Platform and Cambridge High). The dips show broadly consistent trends: generally to the southeast beneath the Berkley Platform and Cambridge High; to the south or southwest beneath the Lacrosse Terrace; and to the southwest or west beneath the Turtle-Barnett High. These trends reflect the rotation of fault blocks, and regional tilting.

Evidence of folding and faulting within probable Proterozoic basement is seen on several of the AGSO deep-seismic lines. On line 100/101 an anticline is imaged at depth within the Lacrosse Terrace around 5.6 seconds TWT (Map & Seismic Folio, enclosures 1 and 7). Similar folds are observed in the same area on the cross-tie line 100/6. A marked change in seismic character within basement on line 100/6 at about its intersection with line 100/2 (Map & Seismic Folio, enclosure 6) may mark an increased igneous component within basement beyond that point.

RIFT-RELATED STRUCTURES by J.B. Colwell, J.E. Blevin & D.J. Wilson

Late Devonian (?late Givetian/Frasnian) - earliest Carboniferous (Tournaisian) upper-crustal extension produced a series of rift-related structures, particularly in the south and southwest of the basin (Gunn, 1988; O'Brien et al., 1993; this study, Fig. 3-1; Map & Seismic Folio, plates 1 and 2). These structures lie to the southwest of the axis of the main post-late Tournaisian basin 'sag' ('Petrel Deep', Fig. 3-1) indicating a possible partitioning between the mechanisms controlling upper-crustal extension and the subsequent sag-dominated phase of the basin's development - possible reasons for this are discussed in Chapter 5 of this report.

Rift-related extensional structures are bounded by major normal faults (and/or fault systems) and include planated basement platforms such as the Berkley and Moyle Platforms, horst blocks (e.g. the Cambridge High), rotated fault blocks such as the Lacrosse Terrace, and grabens such as the Cambridge Trough (Fig. 3-1).

Berkley Platform

The Berkley Platform is an area of planated basement which essentially forms an offshore extension of the Proterozoic Kimberley Basin. It dips to the northeast and is bounded on its northeastern margin by a major down-to-basin fault (Map & Seismic Folio, plate 2 and enclosure 7). Its landward extent approximates to the Kimberley coastline which, from its linear nature, may be fault controlled. The platform is overlain by up to 1.6 seconds TWT (~2.5 km) of Late Carboniferous and younger sediments (Map & Seismic Folio).

Where penetrated (60m at Berkley-1), the basement of the Berkley Platform consists of tholeiitic dolerite which has yielded a maximum Proterozoic Sm-Nd model age of $2.1 \pm 0.1 \times 10^9$ years (Magnet Metals, 1983). This rock has petrological and geochemical similarities to the Kimberley Basin Hart Dolerite (SHRIMP age of 1790 ± 4 Ma; pers. comm. R.W. Page and Shen-Su Sun, AGSO, September 1996).

Moyle Platform

The Moyle Platform forms the eastern (largely-onshore) flank of the Petrel Sub-basin where it consists of shallow basement rocks probably equivalent to those of the Pine Creek Geosyncline and Victoria River Basin (Fig. 3-1). It is bounded on its eastern side by major faults of the Fitzmaurice Mobile Zone, and on its western side by the Moyle Fault. It passes northward into the Darwin Shelf.

The only sub-surface knowledge of the sediments overlying basement on the Moyle Platform comes from the Moyle-1 exploration well (Brophy, 1966). This well intersected approximately 500 m of ?Late Carboniferous - Early Permian section overlying Proterozoic crystalline basement (Petroconsultants, 1990). The thin Palaeozoic sedimentary section in Moyle-1 and thick equivalent section in the Kulshill-1 well just to the west (see Fig. 3-1) indicate a major (~ 4000 m) down-to-basin throw of basement along the Moyle Fault in this area. Further to the north, around Billawock-1, the throw appears to be considerably less, the fault bifurcates, and then passes into a series of shorter, broadly northwesterly-trending fault segments or splays (Fig. 3-1).

Cambridge High

The Cambridge High (Gunn et al., 1995a,b) is an eastward-dipping, narrow basement horst block extending from the Berkley Terrace in the west to the Turtle-Barnett High in the east (Fig. 3-1; Map & Seismic Folio, plates 1 and 2). It is bounded by reactivated normal fault systems and flanked by major depocentres to the south (Cambridge Trough) and to the north (Lacrosse Terrace/Petrel Deep).

Isopach mapping and geometric relationships on seismic lines (see Map & Seismic Folio) indicate that the faults along the southwest and northeast margins of the Cambridge High were active during rifting and created accommodation space which filled with thick syn-rift sediments of the 'Bonaparte Formation'. The southwest-bounding fault was inverted during the Middle Triassic-Early Jurassic Fitzroy Movement, whereas the northeast-bounding fault was reactivated during Tanmurra deposition (Early Carboniferous) and subsequently inverted during the Fitzroy Movement. The effect of removing the Fitzroy Movement offsets from these faults is shown in Figure 3-7.

Initially, much of the syn-rift sediment in the southern Petrel Sub-basin appears to have been trapped south of the Cambridge High and adjacent Turtle-Barnett High. As the available accommodation space was filled, syn-rift sediments (see Fig. 3-7) spread out as a series of alluvial fans across the highs and onto the developing Lacrosse Terrace to the north, and beyond. Movement on the faults bounding the Cambridge High during the late Tournaisian at the end of the 'syn-rift' phase led to widespread erosion of syn-rift sediments across the high (see Figs. 3-8 and 3-9).

The nature of the basement rocks comprising the Cambridge High is known only from Cambridge-1 well which intersected quartz dolerite at its base (see Well Folio). This rock has a Proterozoic pyroxene K-Ar minimum age of 1379 ± 10 Ma (Western Mining Corporation, 1985). Whether the rock represents a widespread igneous sheet, as has been suggested by Gunn et al. (1995a,b) based on aeromagnetic data, or local intrusion, is a matter of conjecture.

Turtle-Barnett High

The Turtle-Barnett High is a fault-bounded, approximately N-S-trending, high-standing basement block which juxtaposes the Cambridge High and Lacrosse Terrace in the southern offshore part of the basin (Fig. 3-1). The high is imaged on industry seismic lines as well as at the very southeastern end of AGSO line 100/6 (Map & Seismic Folio, enclosures 6 and 9).

The position and trend of the high suggest that it may be related to reactivation of faults along the western edge of the Halls Creek Mobile Zone. Fault movements along its northwestern flank appear to post-date the formation of the main down-to-basin faults which form the northern margins of the Cambridge High and Lacrosse Terrace (see Map & Seismic Folio, enclosure 6). However, during much of the Late Devonian-

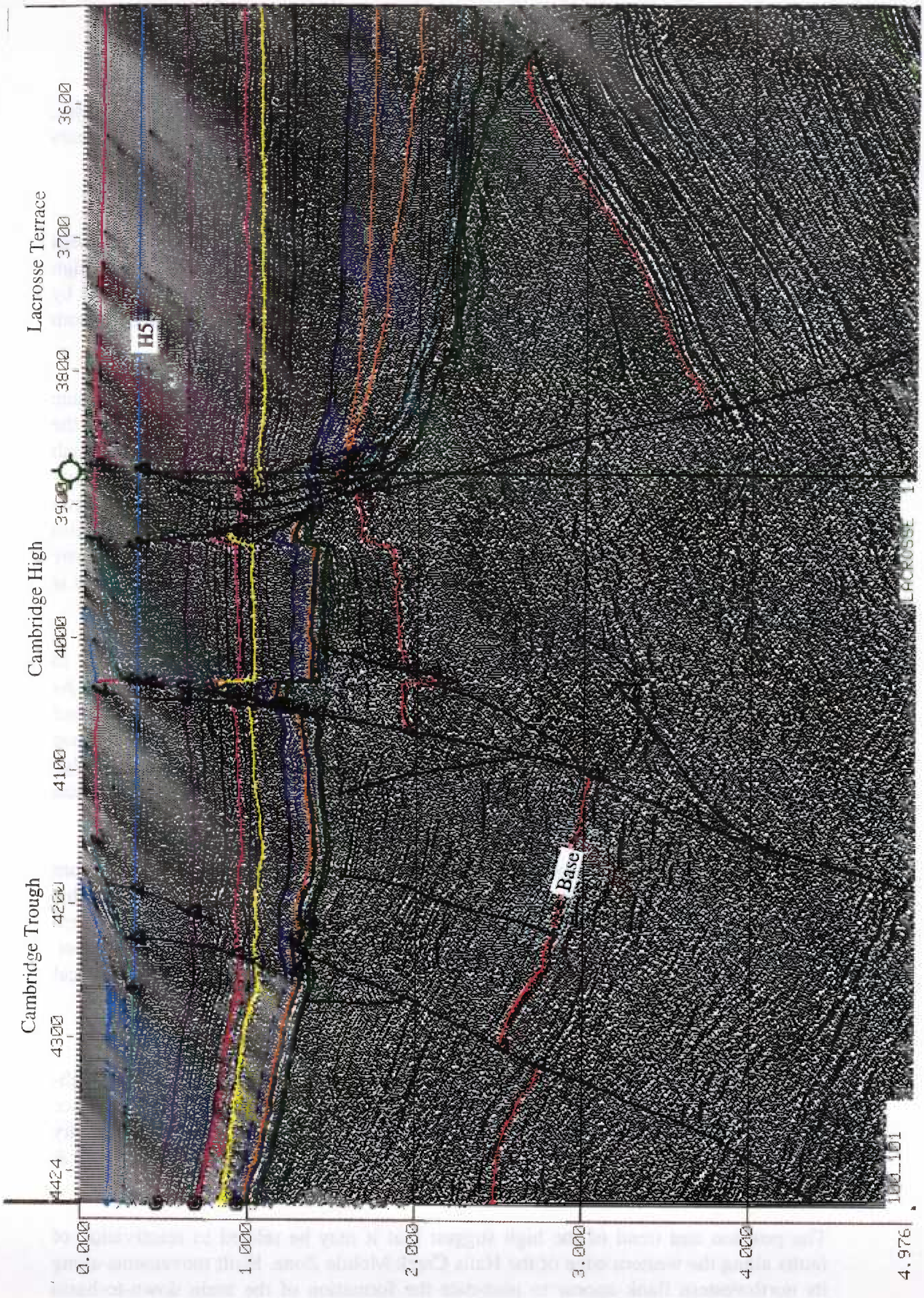


Figure 3-7. Interpretation of the southwestern end of AGSO line 100/101 over the Cambridge High flattened on the H5 horizon to remove the effects of the 'Fitzroy Movement' fault reactivation.

LINE CB80-25

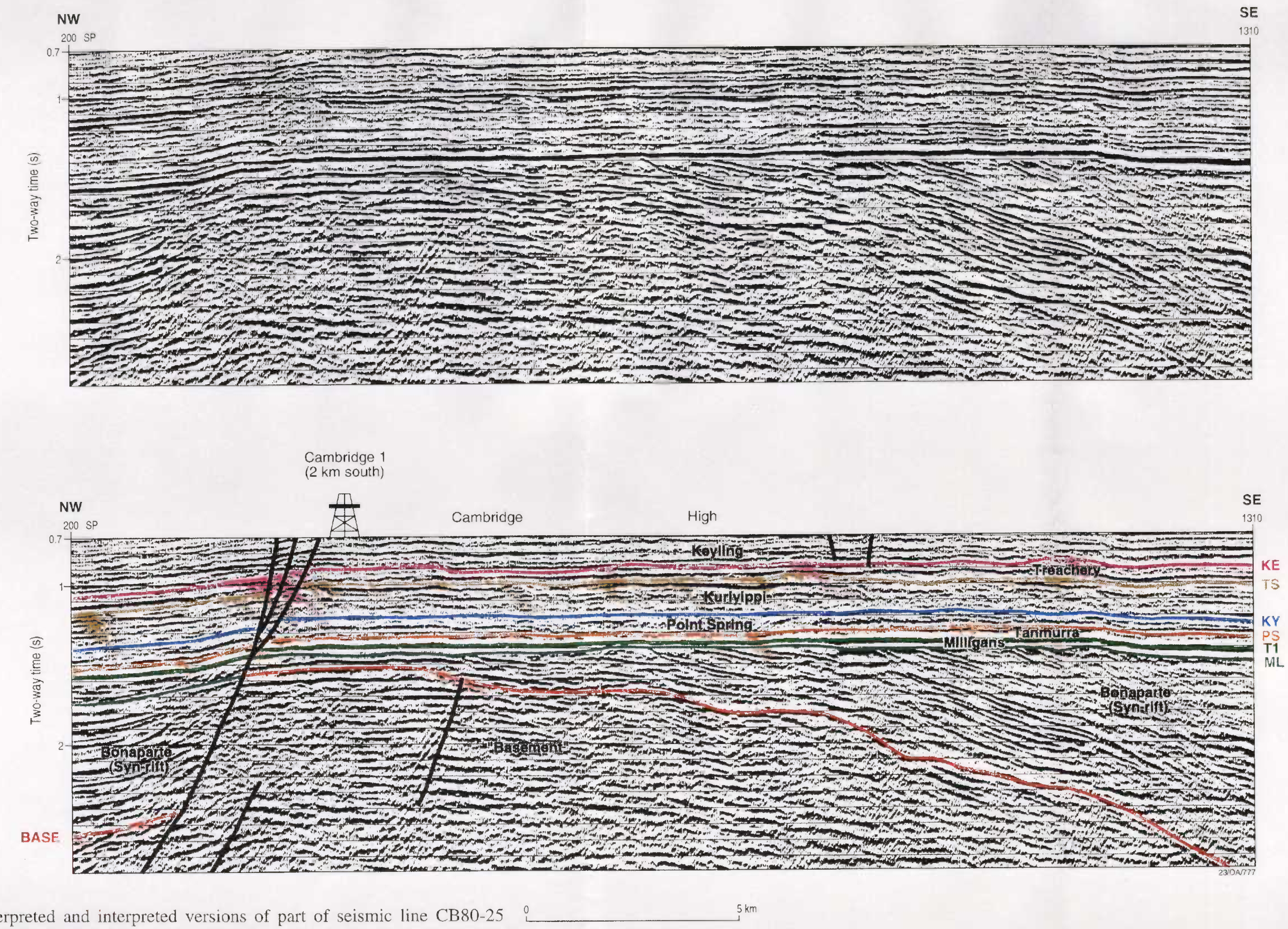


Figure 3-8. Uninterpreted and interpreted versions of part of seismic line CB80-25 showing late Tournaisian erosion of tilted syn-rift sediments (Bonaparte Megasequence) across the Cambridge High.

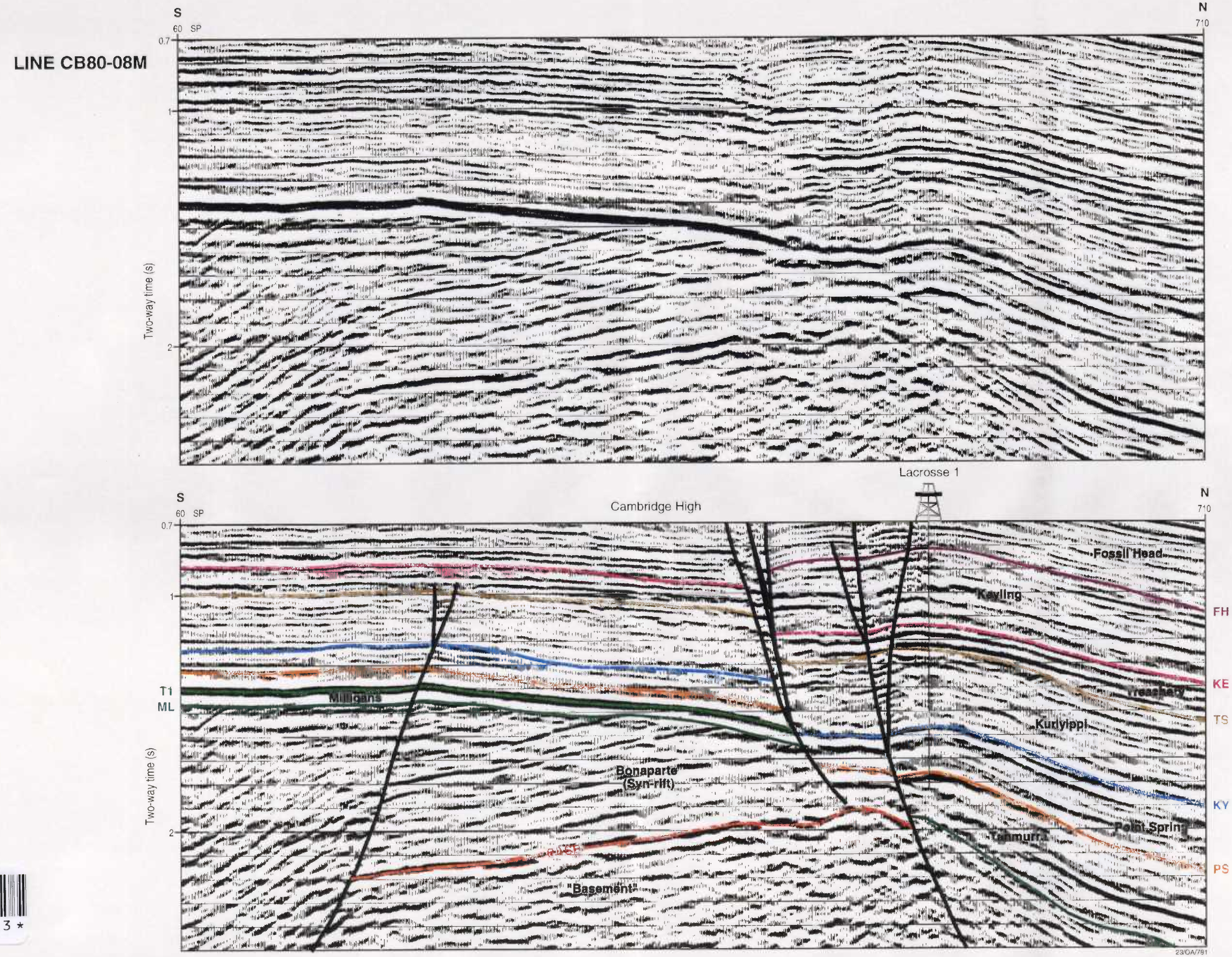


Figure 3-9. Uninterpreted and interpreted versions of part of seismic line CB 80-08M showing late Tournaisian erosion of tilted syn-rift sediments (Bonaparte Megasequence) across the Cambridge High.

0 5 km

earliest Carboniferous (i.e. during syn-rift deposition), the Turtle-Barnett High was a high-standing feature probably shedding sediment into the adjacent developing depocentres of the Cambridge Trough and Keep Inlet Sub-basin. Like the adjacent Cambridge High, the feature was covered by sediments of the upper Bonaparte Megasequence late in syn-rift times (Map & Seismic Folio, enclosure 9C). It was probably uplifted and eroded during the late Tournaisian at the end of the 'syn-rift' phase.

Of the five wells drilled on the high (all on drape anticlines) none reached pre-rift basement (Well Folio; Maung et al., 1994). The oldest sediments intersected are non-fossiliferous shales of the ?Bonaparte Megasequence (basal 25 m in Barnett-2; see Well Folio). Prominent, high-amplitude, dipping reflectors present within basement may be of Proterozoic age similar to features imaged within definitive Proterozoic basement of the Berkley Platform located to the northwest (see Map & Seismic Folio, enclosure 9A).

Lacrosse Terrace

The Lacrosse Terrace lies in the southwestern part of the basin adjacent to the main down-to-basin fault (Fig. 3-1). It is a rotated 'basement' block overlain by syn-rift (Bonaparte Megasequence) and younger sediments. Where imaged on AGSO line 100/101, the terrace is approximately 15 km wide and dips back to the southwest due to rotation on the major bounding fault to the southwest (see Map & Seismic Folio, plates 1 and 2, enclosures 1 and 7).

Contrary to the depiction on some maps (e.g. in Edgerley & Crist, 1974; Lee & Gunn, 1988; Petroconsultants, 1990), the Lacrosse Terrace is largely restricted to the area between the Turtle-Barnett High and Lesueur-1 (Fig. 3-1). Northwest of Lesueur-1 along the main down-to-basin fault system, the Lacrosse Terrace dies out as it merges into a series of deeper fault blocks imaged only on the AGSO deep-seismic data (compare lines 100/101, 2 and 3 on Enclosure 7, Map & Seismic Folio). Over most of its length, its upper surface can be imaged on all seismic data at depths of between 3 and 4 seconds TWT.

The pre-rift rocks forming the Lacrosse Terrace have a distinctive seismic character (Map & Seismic Folio, enclosure 1). Within the upper part of the block (1 second TWT thick), the section consists of moderately continuous, high-amplitude reflectors alternating with more-transparent layers. The high-amplitude reflectors parallel the top of the block. This well-layered zone is underlain by more-indistinctly layered units which are in turn underlain at a depth of about 5.8 seconds TWT by folded, high-amplitude events.

The age and lithology of rocks within the Lacrosse Terrace block are unknown. The rocks are seismically distinct from the adjacent Cambridge High which at Cambridge-1 was shown to be of Proterozoic age. It is suggested here that the section in the block above the folded events may be largely of Cambrian-Ordovician age. This is based mainly on analogy with the Canning Basin where the pre-salt Ordovician section has a very similar seismic character (see fig. 8 units A0-A2 of Romine et al., 1994). The folded, high-amplitude events deeper within the block are probably of Proterozoic age. The bulk of the Lacrosse Terrace block therefore represents the earliest (pre-Petrel-rift) phase of the basin's history. It is interesting to note that, although earliest Ordovician sediments of the Carlton Group crop out onshore on the southwest flank of the basin (Pretlove Hills; Jones, 1971), younger (middle) Ordovician sediments are known in the basin only from the presence of reworked conodonts (Nicoll, 1995).

Deep Fault Blocks

A number of fault blocks can be seen on the AGSO deep-seismic lines basinward of the shallow flanking platforms and terraces (see Map & Seismic Folio). These blocks, which offset the top pre-rift 'BASE' horizon, are commonly poorly imaged. Indeed, the faults which bound them have been variously interpreted on lines 100/2 and 100/3 as mainly down-to-basin northeast-dipping (O'Brien et al., 1993; Goleby et al., 1993; this report, the Map & Seismic folio), or as antithetic to the main, northeast-dipping, basin-bounding fault (O'Brien et al., 1996). Both interpretations are valid on the basis of the available seismic data, although O'Brien et al. (1996) claim that the latter interpretation better explains syn-rift relationships. All interpretations agree that major faults offsetting basement at the southwestern end of line 100/101 are down-to-basin (northeast-dipping) whereas those in a similar position on line 118/18 are antithetic to the main basin-bounding fault and dip to the southwest (Map & Seismic Folio, enclosures 1, 4 and 7).

'Eastern Ramp'

Basement underlying the eastern margin of the offshore Petrel Sub-basin is generally poorly imaged on both industry and the AGSO deep-seismic data. This is partly due to the presence of multiple seismic energy within the section and possibly partly due to complex faulting within basement.

North of the Kulshill Terrace, within the 'Tern Compartment' (O'Brien et al., 1993, 1996), the eastern margin appears to have the form of a southwest-dipping ramp, here termed the 'Eastern Ramp' (Fig. 3-1). On all current data sets, basement of the Eastern Ramp is difficult to define. Where it can be imaged clearly, usually its shallow eastern part, it is commonly offset by faults of small throw dipping to the west or east (Map & Seismic Folio, enclosure 7).

'Old Syn-rift' Basin

Industry seismic data on the eastern flank of the basin to the south and southwest of Billawock-1 shows the presence of a highly-structured 'old syn-rift' section overlying basement (Fig. 3-1; Map & Seismic Folio, plate 9, enclosure 9F,). The section is largely confined to the area between two west-dipping, down-to-basin fault systems and appears to be cut by a number of northwest-dipping fault planes or detachment surfaces. It is overlain in places by 'normal' syn-rift section of the Bonaparte Megasequence (hence the name 'old syn-rift').

The section is not penetrated at Billawock-1 and therefore its interpretation remains uncertain. We suggest that it is the remnant of an early Palaeozoic rift basin which formed prior to the development of the main Petrel rift to the west. The presence of the northwest-dipping fault planes may indicate a NW-SE extension direction, i.e. approximately orthogonal to the later (Late Devonian to earliest Carboniferous) main phase of Petrel extension.

Kulshill Terrace

The term 'Kulshill Terrace' has been variously applied to features in the southeast of the basin. Here its usage is restricted to the onshore part of the basin to the west of the Moyle Fault (Fig. 3-1). Two wells have been drilled in this area (Kulshill-1 and -2); both intersected thick Palaeozoic sections.

Cambridge Trough

The Cambridge Trough (Gunn et al., 1995a,b) is a major, Late Devonian - Early Carboniferous, 'Bonaparte-Milligans' depocentre lying to the south of the Cambridge High (Fig. 3-1; Map & Seismic Folio, plates 1 and 2). Its geology is probably largely continuous with that of the onshore Carlton Sub-basin which lies to the south of a reactivated, east-west ?wrench fault zone extending through the Pelican Island area. Sediments in the trough onlap the Berkley Platform to the west, and are bounded to the east by the Turtle-Barnett High (Fig. 3-1).

Seismic mapping shows that during syn-rift deposition of most of the Late Devonian - earliest Carboniferous Bonaparte Megasequence, the Cambridge Trough was a graben or half graben. The thickest syn-rift sediments accumulated against the actively-growing northern-bounding fault system or in isolated depocentres adjacent to its complexly-faulted southern boundary (Map & Seismic Folio, plate 9). Subsequently, during Early Carboniferous (late Tournaisian-Visean) deposition of the overlying Milligans Supersequence, the trough acted as a 'sag' and the thickest Milligans sediments accumulated in the centre of the trough and in the Carlton Sub-basin in the south (Map & Seismic Folio, plate 10). By the late Visean (Tanmurra times), the Cambridge Trough had filled and ceased to exist as a discrete structural entity (Map & Seismic Folio, plate 4).

Carlton Sub-basin (Moogarooga Deep)

The term 'Carlton Sub-basin' was used by Laws (1981) for the major onshore depocentre lying to the north of the Pincombe Ridge. In this report, the name is used in a similar manner for the major Late Devonian-Carboniferous depocentre lying between the Pincombe Inlier and the Pelican Island fault system (Fig. 3-1). It is broadly synonymous with the term 'Moogarooga Deep' (Garside, 1982).

The geology of the Carlton Sub-basin is known primarily from outcrop (e.g. see Mory & Beere, 1988) and from petroleum exploration wells in the region. These wells (e.g. Bonaparte-1 , -2, Garimala-1, and Keep River-1; Fig. 3-1) intersected up to 4700 m of mainly Late Devonian and Carboniferous section (including a maximum of 2140 m of Milligans Supersequence in Keep River-1), and have been used in the present study to subdivide and correlate the Bonaparte and Milligans successions based on sequence stratigraphic concepts (see Well Folio, plate 37).

No systematic attempt was made to interpret and map seismic data in the onshore part of the basin. Many of these data are of old vintage, poor-quality, and of limited areal coverage. There are no direct onshore-offshore seismic ties.

Keep Inlet Sub-basin

As with the names of other structural elements in the southern Petrel Sub-basin, the term 'Keep Inlet Sub-basin' has been applied inconsistently over the years. In this study it is used for the poorly-developed depocentre lying east and southeast of the Turtle-Barnett High (Fig. 3-1; Map & Seismic Folio). It extends onshore in the south to the northeast of Keep River-1 (Blake, 1984; Gunn, 1988) and possibly to the east as part of the Kulshill Terrace.

Seismic mapping shows that offshore the Keep Inlet Sub-basin was periodically a significant separate depocentre, primarily during deposition of the Bonaparte (syn-rift), Milligans, Point Spring, Treachery and Keyling sequences (Map & Seismic Folio). During deposition of the Early Permian Keyling sequence in particular, the Keep Inlet Sub-basin was a major depocentre (Map & Seismic Folio, plate 16). This depocentre deepened to the northeast (836m of Keyling sediments in Kulshill-1), possibly due to growth on the Moyle Fault.

'SAG' DEPOCENTRE (PETREL DEEP) by J.E. Blevin & J.B. Colwell

A new term 'Petrel Deep' is proposed here for the main Petrel depocentre which lies north of the Turtle-Barnett High and Keep Inlet Sub-basin, northeast of the Berkley Platform and Cambridge High, and west of the Moyle Fault (Fig. 3-1). Although primarily filled with 'sag' sediments, it developed initially as part of the Late Devonian - earliest Carboniferous rift system. During existence of this rift system, sediments of the 'Bonaparte Formation' (Bonaparte Megasequence) were deposited in a series of grabens and half grabens adjacent to high-standing platforms or fault blocks.

The Petrel Deep contains in excess of 9 seconds TWT (up to ~20 km) of largely sag-phase Late Devonian and younger sediments (Map & Seismic Folio, enclosures 7 and 8, plate 24). Overall, its sediments thicken into its NW-trending axis, as well as to the northwest where its geology apparently continues across a NE-trending fault zone into the Malita Graben (Fig. 1-2).

Through time, various changes have occurred in the locus of maximum sedimentation in the deep. These can be seen in plates 9 to 23 of the Map & Seismic Folio. These changes are a function of: (i) the amount and direction of sediment input (for example, distribution of the Treachery sequence down the axis of the basin on line 100/5- see plate 15), and (ii) structuring (for example, the distribution of the Malita sequence following the folding associated with the Middle Triassic-Early Jurassic Fitzroy Movement - see plate 19).

As discussed by Baxter in Chapter 5 of this report and by Baxter (1996), the very thick sedimentary section in the Petrel Deep (and the offset of its axis from the main rifted flank of the Petrel Sub-basin) cannot be explained by simple thermal cool-down following the Late Devonian - earliest Carboniferous rifting event. Other factors or events have to come into play to continue to drive the basin down; these may include lower crustal thinning, oblique movement on faults within basement, and flexure against a major fault to the northwest. In particular, the marked thickening of the Kuriyippi sequence to the northwest (see Map & Seismic Folio, plate 13) apparently reflects structuring and tectonic events associated with a postulated major NE-SW trending normal fault located in the vicinity of Gull-1 adjacent to the eastern margin of the Malita Graben (Baxter, 1996, this report).

INVERSION STRUCTURES by J.B. Colwell, G.W. O'Brien & J.E. Blevin

As pointed out by O'Brien et al. (1993, 1996), many of the structures within and along the flanks of the Petrel Deep, and to a lesser extent other depocentres within the Petrel Sub-basin, appear to have developed due to the reactivation of older, rift-related structures. In particular, regional intra-plate compression associated with the Middle Triassic (Ladinian) - Early Jurassic (Sinemurian) Fitzroy Movement (Forman & Wales, 1981; see Chapter 4 for discussion of age of associated unconformity and syntectonic Malita sequence) produced numerous inversion structures and resulted in widespread uplift and erosion along the flanks of the basin, particularly the southwestern flank. This uplift, with its associated change in river drainage patterns, led to a switch in sedimentation from fluviatile coastal braid-plain deposits of the upper Cape Londonderry sequence to continental 'redbeds' of the overlying Malita sequence which were probably deposited largely within essentially land-locked drainage basins (O'Brien et al., op. cit.; Chapter 4 of this report). Some features which have traditionally been interpreted as salt-related turtle-back anticlines (e.g. Tern and Penguin; Lee & Gunn, 1988; Gunn & Ly, 1989) are clearly seen on the AGSO deep-seismic data to be principally inversion anticlines (O'Brien et al., 1993).

Three general types of reactivation/inversion structures are recognised in the basin (O'Brien et al. , 1996; this report):

(1) Fault inversions such as those that produced the small anticlines drilled at Lacrosse-1 (Map & Seismic Folio, enclosures 1 and 7) and Lesueur-1 (enclosures 2 and 7). As shown in Figure 3-1, many of the broadly NW-orientated fault systems on the southwestern side of the basin were reactivated by reverse and/or strike slip movements. In some cases (e.g. at Lesueur-1) the fault reactivation continued until at least the Early Cretaceous. At Bougainville-1, a complex faulted anticline is probably the product of both fault reactivation and salt injection.

(2) Symmetric-to-asymmetric inversion anticlines overlying deeply-buried basement fault blocks, such as those at Tern-1 and Penguin-1 (Fig. 3-1; Map & Seismic Folio, enclosures 2, 3 and 7). These structures are attributed to minor reverse movements of basement fault blocks leading to flexuring in the overlying sedimentary section.

(3) Inversion anticlines and backward-facing monoclines along the axis of the Petrel Deep such as the Petrel structure, and the 'nose' northeast of Bougainville-1 on line 100/101 (Fig. 3-1; Map & Seismic Folio, plate 7, enclosures 1, 3 and 7). These structures appear to have largely developed due to minor NE-SW shortening of the basin depocentre during Fitzroy Movement compression.

Onlap of the Malita sequence onto the underlying section (e.g. Map & Seismic Folio, enclosures 3 and 7) shows that most of the folding within the Petrel Sub-basin occurred during the Middle Triassic-Early Jurassic Fitzroy Movement. There is

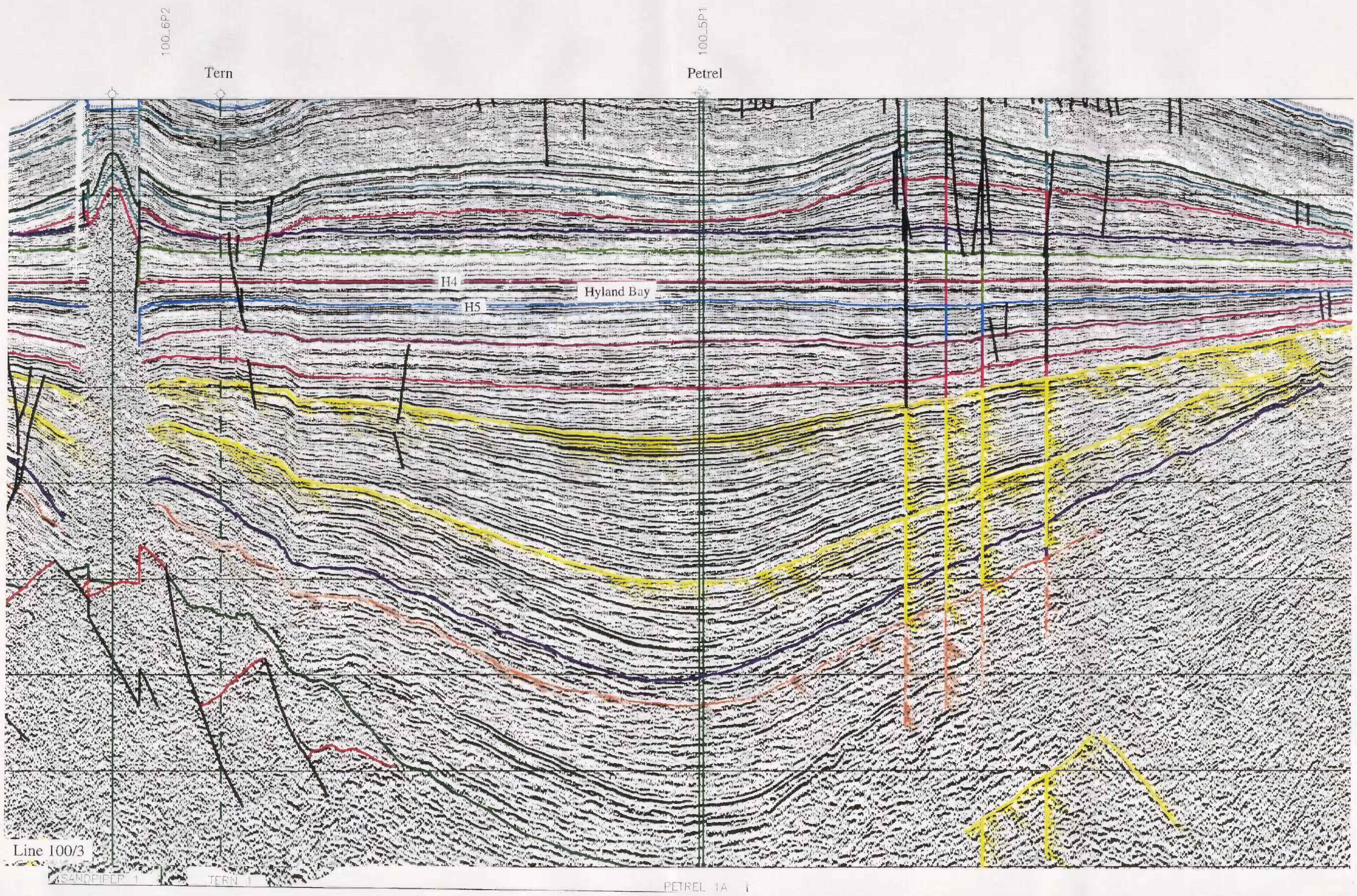


Figure 3-10. Interpretation of part of AGSO line 100/3 flattened on the H4 seismic horizon.

evidence, however, of some significant earlier compression. Flattening of line 100/3 on the H4 (Late Permian) seismic horizon shows that both the Tern and Petrel features started to form at the beginning of or during deposition of the Late Permian Hyland Bay sequences (Fig. 3-10). Also, a fold in the northwest part of the basin on line 100/7 Part 1 (S.P. 1000-2200) developed, presumably as part of this initial compressive phase, either at the end of Late Permian Hyland Bay or during Late Permian-Early Triassic Mount Goodwin times (Map & Seismic Folio, enclosure 7E).

SALT-RELATED STRUCTURES by J.E. Blevin & J.B. Colwell

Since the earliest days of seismic acquisition, salt piercement structures (salt diapirs) have been known from the offshore part of the Petrel Sub-basin (e.g. Egerley & Crist, 1974). These structures are widely distributed (Figs 1-3 & 3-1), particularly in the south within the 'Barnett Compartment' (e.g. the Matilda, and Kinmore structures), on the southwestern flank of the Petrel Deep ('Tern Compartment'), and in the north at Gull and Curlew ('Curlew Compartment'). The distribution of the salt diapirs was related by O'Brien et al. (1993) to the distribution of 'high-displacement margins' through the basin. The diapirs are typically between 3 and 10 km across, some with well-developed salt-withdrawal rim-synclines or 'moats', and pierce to varying stratigraphic levels (see Map & Seismic Folio). In many cases, the salt has moved (as indicated by the bowing up of overlying sediments) as recently as the Tertiary.

Petroleum plays associated with salt have been widely drilled in the basin. Three wells (Kinmore-1, Pelican Island-1 and Sandpiper-1) intersected salt near their base (see Well Folio), while Bougainville-1, Curlew-1, Gull-1, Matilda-1 and Tern-3 were drilled on salt-related structures, but did not reach salt.

In addition to the salt diapirs, various workers (e.g. Durrant et al., 1990; McConachie et al., 1995, 1996) have interpreted salt layers deep within the basin. No clear evidence has been seen in the present study to support such interpretations. Although the original distribution or extent of the salt is unknown, it is suggested here that because of the age of the basin and the amount of sediment loading (particularly in the Petrel Deep), most of the salt originally present in the deeper parts of the basin has probably formed diapirs or moved up fault planes (e.g. at Pelican Island-1). As the basin was loaded, the salt may, of course, have moved laterally over considerable distances before commencing its ascent.

The age of the salt in the Petrel Sub-basin remains unresolved. Mid-Late Devonian palynomorphs were recovered from cuttings some 150 m within the salt diapir at Sandpiper-1 (Arco, 1971), indicating a minimum age for the salt. Evidence from the AGSO deep-seismic data suggest that the diapirs either penetrate or are sourced from within the Late Devonian - earliest Carboniferous Bonaparte Megasequence. Two possibilities are considered likely based largely on analogy with the onshore Canning Basin: either sourcing within a 'pre-rift' Late Ordovician to ?Early Silurian succession, or within the 'syn-rift' Devonian section of the Bonaparte Megasequence (see Chapter 4).

CHAPTER 4

SEQUENCE STRATIGRAPHY

by J.M. Kennard

INTRODUCTION

Sequence stratigraphic concepts and models (Vail, 1987; Posamentier & Vail, 1988; Posamentier et al., 1988; Sarg, 1988; Van Wagoner et al., 1990; Wornardt, 1991) have been utilised to interpret well and seismic sections. Major sequence boundaries were identified on seismic sections by onlap and truncation surfaces, or abrupt changes in seismic facies. In wells they were identified by abrupt facies shifts on lithologic and electric logs or by gaps in the biostratigraphic record; these boundaries were then tied to seismic sections via synthetic seismograms or time-depth plots derived from velocity data.

Depositional sequences have been interpreted at a variety of scales to reflect both the tectonic evolution of the basin, and the development of the basin's petroleum systems. Within the prospective Late Devonian - Jurassic section, the interpreted sequences range from less than 100 m to 1000 m thick, and have a duration of about 1-20 million years (except the Early-Late Jurassic Plover sequence, which has a duration of about 40 million years). These sequences represent third-order and second-order sequences (*sequences* and *supersequences,* respectively) as defined by Haq et al. (1988) and Vail et al. (1991). Within the non-prospective Cretaceous-Tertiary section (largely an immature overburden section for the basin's petroleum systems), only two *supersequences* have been interpreted, each of about 65-70 million years duration, and up to 1500 m thick.

Sequence stratigraphy analysis of the pre-rift Cambrian-?Silurian succession has not been undertaken in this study; the lithostratigraphy of this succession is described by Mory & Beere (1988).

The stratigraphic distribution of the sequences and their relationship to established biozones and lithostratigraphic units are shown on the Petrel Sub-basin Stratigraphic Time Chart (Jones et al., 1996) and summarised in Figure 1-4.

Sequence Nomenclature

Each sequence has been named according to the major *lithostratigraphic* unit that it encompasses (either in part or in full). This nomenclature was adopted since, apart from the Late Devonian - earliest Carboniferous succession, the previously defined major lithostratigraphic units generally do not show evidence of marked diachroneity, and there is thus a close, but by no means an exact, correlation between major lithostratigraphic units and sequences (*supersequences, megasequences*). Where major lithostratigraphic units have been subdivided into a number of smaller scale sequences (generally third-order *sequences*), they are identified by an abbreviation of the name of the corresponding lithostratigraphic unit combined with a numeral (e.g., Sequences Tan 1 and Tan 2 within the Tanmurra Formation; Sequences Mill A1, Mill A2, Mill A3 etc., within the *A. largus* zone of the Milligans Formation).

Sequence nomenclature for the Late Devonian - earliest Carboniferous 'Bonaparte Formation', however, is more problematic. Basinal facies within this succession are commonly difficult to differentiate from the Early Carboniferous Milligans Formation, and have hitherto been relatively poorly dated. However new microfloral and microfaunal (ostracod and conodont) determinations undertaken during the course of this study (C.B. Foster, P.J. Jones, R.S. Nicoll), and revised biostratigraphic correlations of assemblage zones undertaken for the 1996 AGSO Time Scale, including the newly recognised *Grandispora sp. cf. G. praecipua* zone (Foster, 1990a) and an improved understanding of the ostracod zonations (Jones, this study), have significantly helped to define and correlate Late Devonian - Early Carboniferous sequences within the well sections.

Age of Sequences

The age of the sequences are based on biostratigraphic data summarised for each well on the 1:5 000 scale well composites in the Petrel Sub-basin Well Folio (Kennard, 1996a), and the age relationships of the biozones as shown on the AGSO 1996 Time Chart (Young & Laurie, 1996). These ages are summarised on the Petrel Sub-Basin Stratigraphic Time Chart (Jones et al., 1996).

UNNAMED EVAPORITIC UNIT

Seismic data indicate that salt diapirs are widespread throughout the offshore portion of the Petrel Sub-basin (Figs. 1-3 and 3-1; Map & Seismic Folio, plate 1,), and these diapirs have been intersected in three wells (Kinmore-1, Pelican Island-1 and Sandpiper-1). Several other wells have been drilled on the flanks of salt diapirs, but did not reach the inferred salt (Bougainville-1, Curlew-1, Gull-1, Kulshill-1, Matilda-1 & Tern-3). The original stratigraphic relationships and age of this remobilised salt is uncertain; the diapirs penetrate Early Carboniferous (Milligans Supersequence) to late Tertiary sediments, and seismic data suggest that they either penetrate or are sourced from within the Late Devonian Bonaparte Megasequence. The best indication of the age of the salt is at Sandpiper-1, where Mid-Late Devonian palynomorphs (including *Ancyrospora*) were recovered from cuttings some 150 m below the top of the penetrated salt diapir, and spores of Devonian/Carboniferous boundary age were recovered from cuttings 123 m above the top of the diapir (ARCO, 1971). Due to salt intrusion, however, these palynomorphs could have been derived from either the original salt succession, or they may be from younger units that have been incorporated into the diapir; they thus indicate a Mid-Late Devonian minimum age for the salt.

Based on regional data, two stratigraphic intervals are considered equally likely for the original salt-bearing succession: 1) a 'pre-rift' Late Ordovician to Early Silurian succession, based on the widespread occurrence of thick halite and playa deposits of this age in the Canning Basin (Kennard et al., 1994; Romine et al., 1994); and 2) a 'syn-rift'

Mid-Late Devonian succession that correlates in part with the alluvial fan, aeolian, fluviatile and shallow marine facies of the Cockatoo Supersequence.

BONAPARTE MEGASEQUENCE

This megasequence encompasses all sediments of Late Devonian (Frasnian-Famennian) to earliest Carboniferous (Tournaisian) age, and is equivalent to the 'syn-rift' megasequence mapped on seismic data (Map & Seismic Folio, plate 9). This megasequence is named after the 'Bonaparte Formation' as defined by Beere & Mory (1986) and Mory & Beere (1988); namely the succession of shale, siltstone, sandstone and minor sandy limestone between 2280 and 3210 m in Bonaparte-1. Although the base of the megasequence is not penetrated in onshore wells, elsewhere (e.g., Cambridge-1 and onshore outcrop) it unconformably overlies Proterozoic or Cambrian rocks. It is separated from similar overlying basinal facies of late Tournaisian-Visean age (*Grandispora sp. cf. G. praecipua* and *A. largus* palynozones; Milligans Supersequence) by an angular unconformity. In onshore wells, the megasequence is subdivided into three supersequences (Cockatoo, Ningbing and Langfield Supersequences), but limited biostratigraphic data in offshore wells generally precludes subdivision of basinal facies (e.g. Barnett-2, Cambridge-1).

Cockatoo Supersequence

The Cockatoo Group (Mory & Beere, 1988) unconformably overlies Proterozoic and Cambrian rocks, and is best known from outcrops in the southern and western onshore portions of the basin. The group comprises a major transgressive, continental to shallow-marine succession, and has a maximum outcrop thickness of 1620 m on the Burt Range Shelf, increasing to 2730 m in the Ragged Range Outlier to the south of the Carlton Sub-basin (Mory & Beere, 1988). Basal alluvial fan and alluvial plain conglomerates and sandstones border the eastern faulted margin of the onshore basin in the south, and grade basinward (northward) into fluvial and aeolian sandstones, and then deltaic and shallow-marine sandstones, shales and dolostones. The Cockatoo Group ranges from Early to Late Frasnian age (Jones & Druce, 1966; Druce, 1969).

Probable shallow-marine equivalents of the Cockatoo Group are intersected in several onshore wells (Bonaparte-1, Keep River-1, Kulshill-1, Ningbing-1 and Spirit Hill-1), and these units are here accordingly assigned to the Cockatoo Supersequence. They comprise very fine grained, siliceous sandstones, shales and minor carbonates, and although the section intersected in Kulshill-1 contains scattered marine fossils and plant remains, these units are undated.

Ningbing Supersequence

This supersequences comprises the Famennian reef complex of the Ningbing Group which forms an exhumed linear reef belt in the Ningbing Ranges up to 500 m thick (Playford et al., 1966; Mory & Beere, 1988). The reef complex contains flat-lying carbonate platformal facies, steeply-dipping marginal slope carbonates, and gently-dipping to flat-lying basinal shales with minor pelagic and detrital carbonates. The margin of the platform is constructed by massive cyanobacterial reefs with little or no primary porosity, and the marginal slope deposits are estimated to descend to palaeodepths of up to 200 m to the basinal facies (Mory & Beere, 1988). The outcropping reef complex forms a major transgressive-regressive cycle (that is, *supersequence*); the platform margin backsteps landward in the early Famennian, and then progrades basinward in the mid-late Famennian (Mory & Beere, 1988, figs 80, 91).

The Ningbing Supersequence is intersected in several onshore wells in the Carlton Sub-basin (Bonaparte-1, Keep River-1, Kulshill-1, Ningbing-1 and possibly Garimala-1 and Spirit Hill-1). Keep River-1 penetrated a 1020 m thick reefal and platformal carbonate section across the Pincombe Ridge, overlain by 140 m of marginal slope and basinal facies (maximum penetrated thickness of the Ningbing supersequence). Ningbing-1 (outboard of the outcropping reef tract) intersected an upper-slope cyanobacterial buildup overlain by basinal shales. In all other well sections, basinal clastic facies are present. Two reef units are recognised within the Ningbing Supersequence in the Carlton Sub-Basin; a thick basal reef unit which probably comprises several third-order sequences, and an upper marginal slope to basinal unit (Sequence N2; equivalent to the basal portion of the 'Bonaparte Beds' in Ningbing-1, and the 'Unnamed Formation' in Keep River-1) which transgresses the lower reef complex. This upper unit records a drowning and backstepping of the reef complex, similar to that documented in the outcropping reef complex (Mory & Beere, 1988). Both units are assigned to the mid-late Famennian (upper *crepida* - upper *marginifera* conodont zones, and *R. lepidophyta* palynozone,).

Langfield Supersequence

This supersequence comprises the Langfield Group (Beere & Mory, 1986) which crops out in the Burt Range Shelf and has a maximum thickness of 900 m. It consists of two carbonate to clastic sequences (Burt Range Formation - Enga Sandstone, Septimus Limestone - Zimmerman Sandstone; Mory & Beere, 1988), each comprising a lower peritidal to shallow shelf carbonate transgressive systems tract, and an upper progradational shoreline siliciclastic highstand systems tract. Both sequences are of Tournaisian age; the lower sequence ranges from early-middle Tournaisian, the upper from middle-late Tournaisian (Mory & Beere, 1988).

The Langfield Supersequence has been intersected in numerous mineral exploration holes on the margins of the Carlton Sub-basin (Rowley & Lee, 1986; Mory & Beere, 1988) and in several onshore petroleum wells (Bonaparte-1, -2, Garimala-1, Keep River-1, Spirit Hill-1 and Weaber-1). The base of the supersequence is marked by prominent gamma and sonic log shifts, and the top by an angular unconformity beneath the Milligans supersequence. The supersequence is absent (?eroded) in Ningbing-1. The most complete section occurs in Keep River-1 (670 m thick) where at least 5 third-order sequences are recognised. These sequences are poorly dated (Early Carboniferous ostracods and conodonts). Only one or two sequences are recognised in Bonaparte-1, -2, Garimala-1, and Spirit Hill-1, but they are difficult to correlate. These sequences have a lower-mid Tournaisian age (*G. frustulentus* palynozone; *W. atypha* to *C. cesarensis* ostracod zones). In view of the widespread uplift and erosion of the Langfield Supersequence prior to the deposition of the Milligans Supersequence, many of the younger sequences intersected in Keep River-1 have probably been eroded from the western and southeastern margins of the Carlton Sub-Basin (e.g., Bonaparte-1, 2, Garimala-1, Ningbing-1, Spirit Hill-1).

MILLIGANS SUPERSEQUENCE

This supersequence is named after the Milligans Formation as defined by Mory (1991). Mory nominated the interval 497-2280 m in Bonaparte-1 (previously part of the type 'Bonaparte Beds') as a reference section for the formation since the type section (44 - 155 m in Milligans No. 1 Bore; Veevers & Roberts, 1968) represents only a small part of the unit. Le Blanc (1964) originally assigned the same interval in Bonaparte-1 to the 'Milligans Beds' in the original well completion report. The Bonaparte-1 reference section consists of silty shale and interbedded very fine to fine sandstone, argillaceous siltstone and bioclastic limestone.

Several previous studies have attempted to subdivide and correlate the Milligans succession intersected in onshore and offshore wells (e.g., Mory & Beere, 1988; Lee & Gunn, 1988; Petroconsultants, 1990). Such attempts have largely been based on well-well correlations, and have hitherto been hampered by a poor understanding of faunal and palynofloral biostratigraphic zone relationships, and the longevity of the *A. largus* palynozone which spans the Visean. Based on a tentative subdivision suggested by Playford (1971), Wood (1989) proposed a revised informal preliminary subdivision of the *A. largus* zone and applied this subdivision to several onshore wells (Garimala-1, Bonaparte-1, 2, Ningbing-1, Skull-1, and Spirit Hill-1). In addition, Foster (1990a) proposed a new palynofloral assemblage zone (*Grandispora sp. cf. G. praecipua*) based on palynomorphs recovered from the sub *A. largus* interval intersected in Barnett-2 and Turtle-1. These data have been incorporated into the present study (see accompanying Well Folio), but problems still arise due to firstly, conflicts between Wood's (1989) subdivisions and the conodont zones and ostracod assemblages (e.g., Ningbing-1, Spirit Hill-1), and secondly, uncertainties about the relationship of the *Grandispora sp. cf. G. praecipua* zone with established faunal zones and assemblages (conodonts, ostracods, forams).

The Milligans Supersequence in the Bonaparte-1 reference section has a latest Tournaisian to late Visean Age (incorporating the *A. largus* palynozone, *M. spinosa - Amphissetes sp. B* ostracod zones, Mamet foraminiferal zones 9-15, and the *A. milliganensis* brachiopod zone). The older *Grandispora sp. cf. G. praecipua* interval in Barnett-2 and Turtle-1 is also assigned to the Milligans Supersequence since it unconformably overlies an uplifted and tilted succession of the Bonaparte Megasequence (see Fig. 4-1; Map & Seismic Folio, section C of enclosure 9).

Petroconsultants (1990) attempted a subdivision of the Milligans succession based on sequence stratigraphic concepts, using the section intersected in Keep River-1 as a reference section. An alternative sequence-based subdivision and correlation is attempted here, based on new and revised biostratigraphic data undertaken as part of this study, and the recognition of eight (?)third order sequences in the Bonaparte-1 reference section. These sequences occur within the *A. largus* zone, and are designated Mill A1-8 in the accompanying Well Folio. The *Grandispora sp. cf. G. praecipua* interval in Barnett-2 and Turtle-1 (see Well Folio, sections 4 & 5, plates 36 & 37) is interpreted as an older sequence restricted to the Turtle-Barnett High. Sequences Mill A1-8 can reasonably confidently be correlated between wells in the western Carlton Sub-basin and northward to Pelican Island-1 and the Turtle-Barnett High (Well Folio, section 5, plate 37). Recognition and correlation of these sequences in the central and eastern Carlton Sub-basin (Keep River-1, Skull-1, Weaber-2A, Spirit Hill-1) is less certain (Well Folio, section 6, plate 38), and is very tentative in the Keep Inlet Sub-basin and Kulshill Terrace areas (Kingfisher-1, Sunbird-1, Kulshill-1). Sub-division and correlation of the Milligans Supersequence remains an ongoing problem; improved resolution must await detailed sequence stratigraphic integration of well and newly acquired onshore seismic data, and continued revision and improvement of established and informal biostratigraphic zonations.

Seismic data indicate that the Milligans Supersequence extends throughout the Cambridge Trough and Keep Inlet Sub-Basin, across parts of the Cambridge and Turtle-Barnett Highs and Lacrosse Terrace, and extends as a discrete 45 km wide lobe northward of the Turtle-Barnett High (Map & Seismic Folio, plate 10).

The *Grandispora sp. cf. G. praecipua* interval in Barnett-2 and Turtle-1 is interpreted as the oldest sequence of the Milligans Supersequence, and unconformably overlies dipping beds of the Bonaparte Megasequence (see Fig. 4-1; Map & Seismic Folio, section C of enclosure 9). It comprises interbedded sandstone, siltstone and claystone, and is interpreted as a near shore, shallow-marine deposit incorporating upward-coarsening bars and upward-fining channel fills (Faehrmann, 1990). The palynomorphs are indicative of marginal marine and marsh-like environments (Foster, pers. comm., this study). This basal Milligans sequence is interpreted as a second-order lowstand deposit that developed around the margins of an offshore island formed by late Tournaisian uplift and exposure of the Turtle-Barnett High (Fig. 4-2). Lowstand basin fans within the Cambridge Trough (Fig. 4-3) were probably deposited at this time.

In the western Carlton Sub-Basin, the Milligans Supersequence unconformably overlies and progressively onlaps westward onto the eroded Ningbing Supersequence (Amity Oil, 1994, 1995, seismic lines BWA81-206 & BWA87-303, respectively). It comprises a 1500 m thick transgressive succession which is characterised by an upward-fining gamma log pattern (Sequences Mill A1-6, and the transgressive systems tract of Sequence Mill A7), that culminates in a second-order maximum flooding surface within Sequence Mill A7 (see Well Folio, Section 5, Plate 37). The second-order highstand is represented by the highstand systems tract of Sequence Mill A7 and all of Sequence Mill A8 (total thickness about 300 m). These transgressive and highstand sequences are dominated by turbidite deposits, probably deposited on a low angle, and locally distally steepened, ramp.

A similar westward and southward onlapping relationship of the lower transgressive Milligans sequences onto the eroded Bonaparte Megasequence is evident in the Cambridge Trough (Fig. 4-4), and against the Cambridge and Turtle-Barnett Highs to the north (Fig. 4-1; Mory, 1991, figs. 4, 6). Prominent NNE-prograding highstand sequences are evident in the upper portion of the supersequence in much of the Cambridge Trough (Fig. 4-3). Based on the assumption that subsidence of the Carlton Sub-Basin and Cambridge Trough was probably essentially contemporaneous, these

LINE CB80-21M

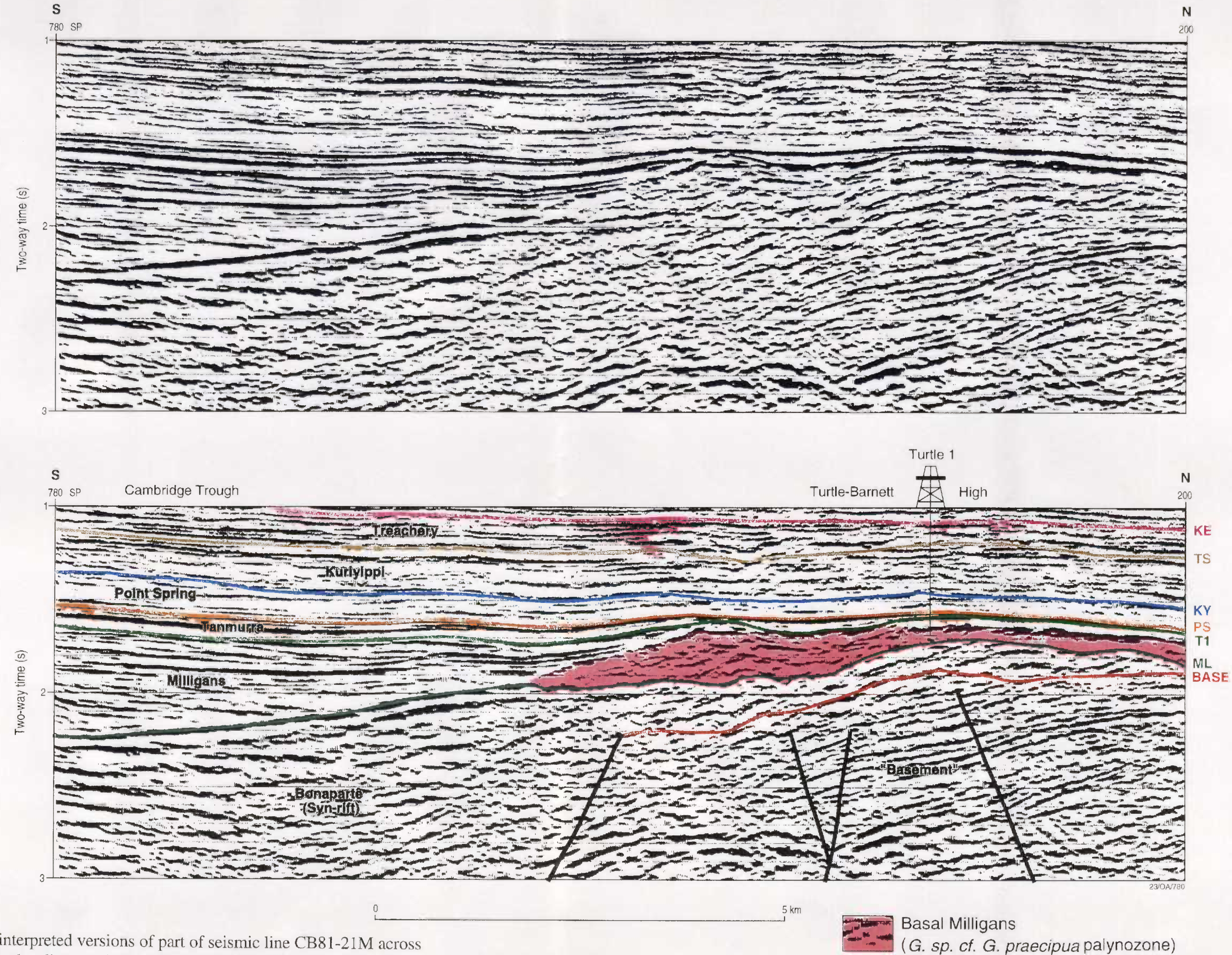
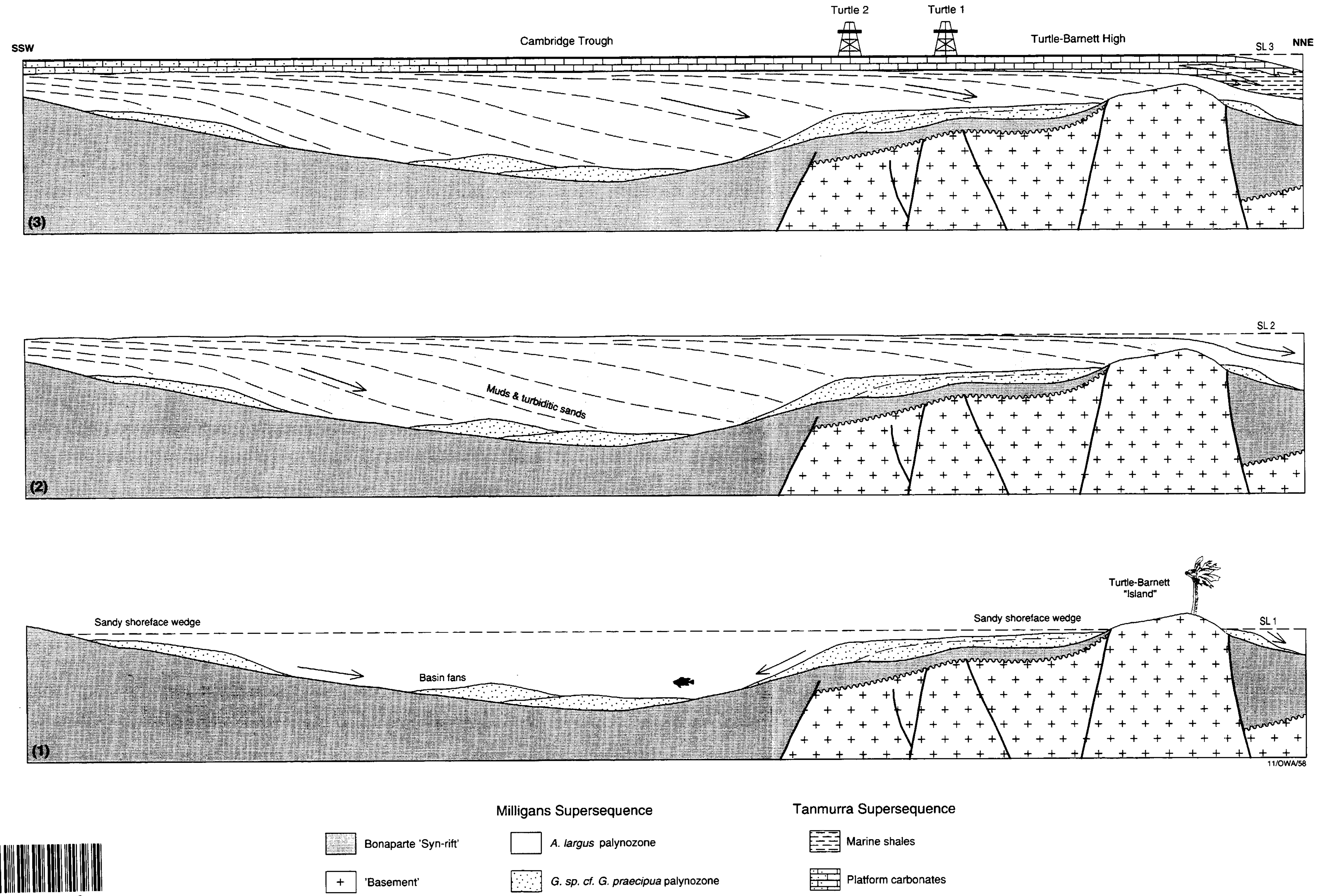


Fig. 4-1. Uninterpreted and interpreted versions of part of seismic line CB81-21M across the Turtle-Barnett High and adjacent flank of the Cambridge Trough showing stratigraphic relationships. Note the basal Milligans seismic facies.



R9604018

Figure 4-2. Schematic diagram showing the deposition of Milligans sequences on the Turtle-Barnett High and in the adjacent Cambridge Trough.

LINE CB81-11M

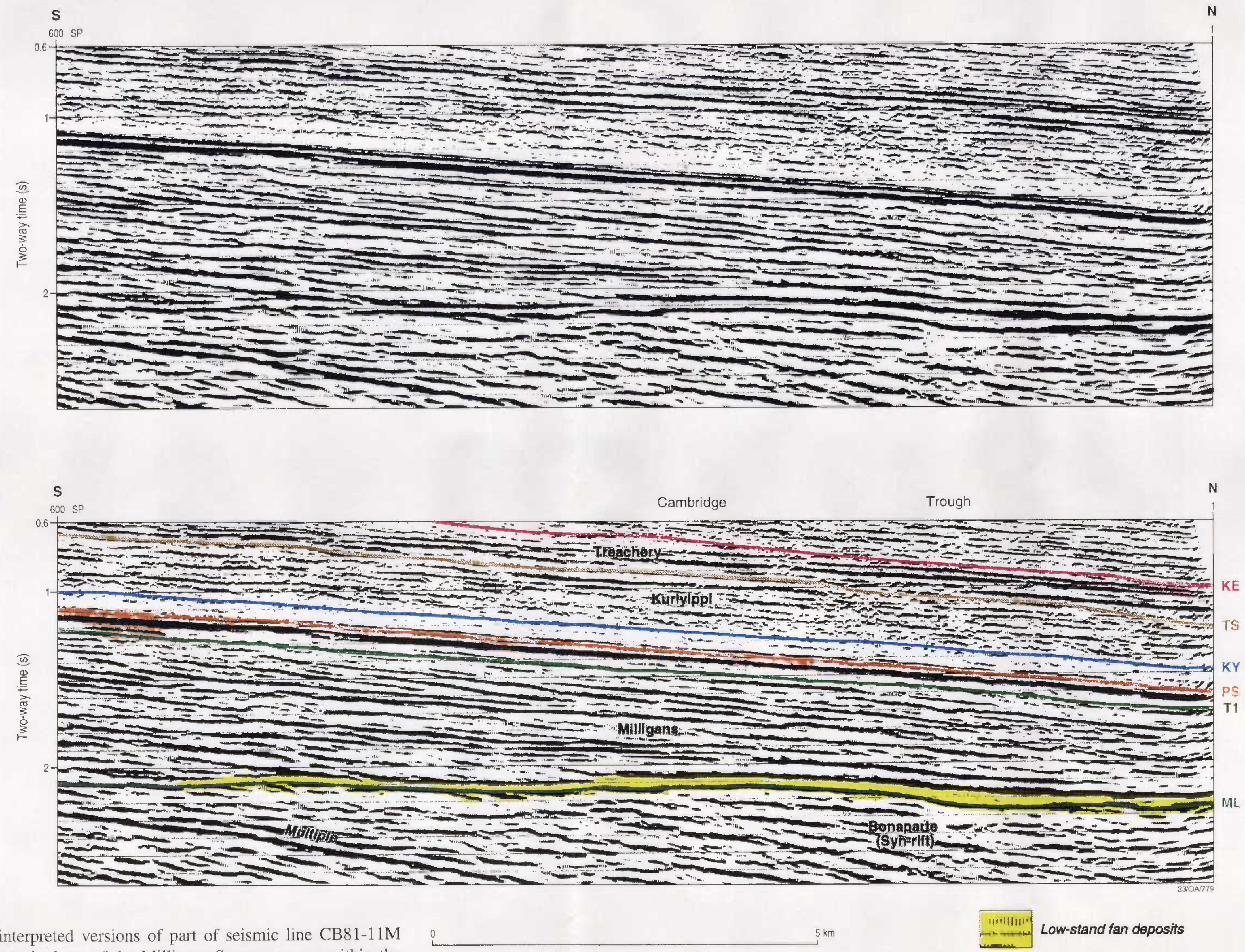


Figure 4-3. Uninterpreted and interpreted versions of part of seismic line CB81-11M showing low-stand fan deposits at the base of the Milligans Supersequence within the Cambridge Trough.

LINE CB81-03M

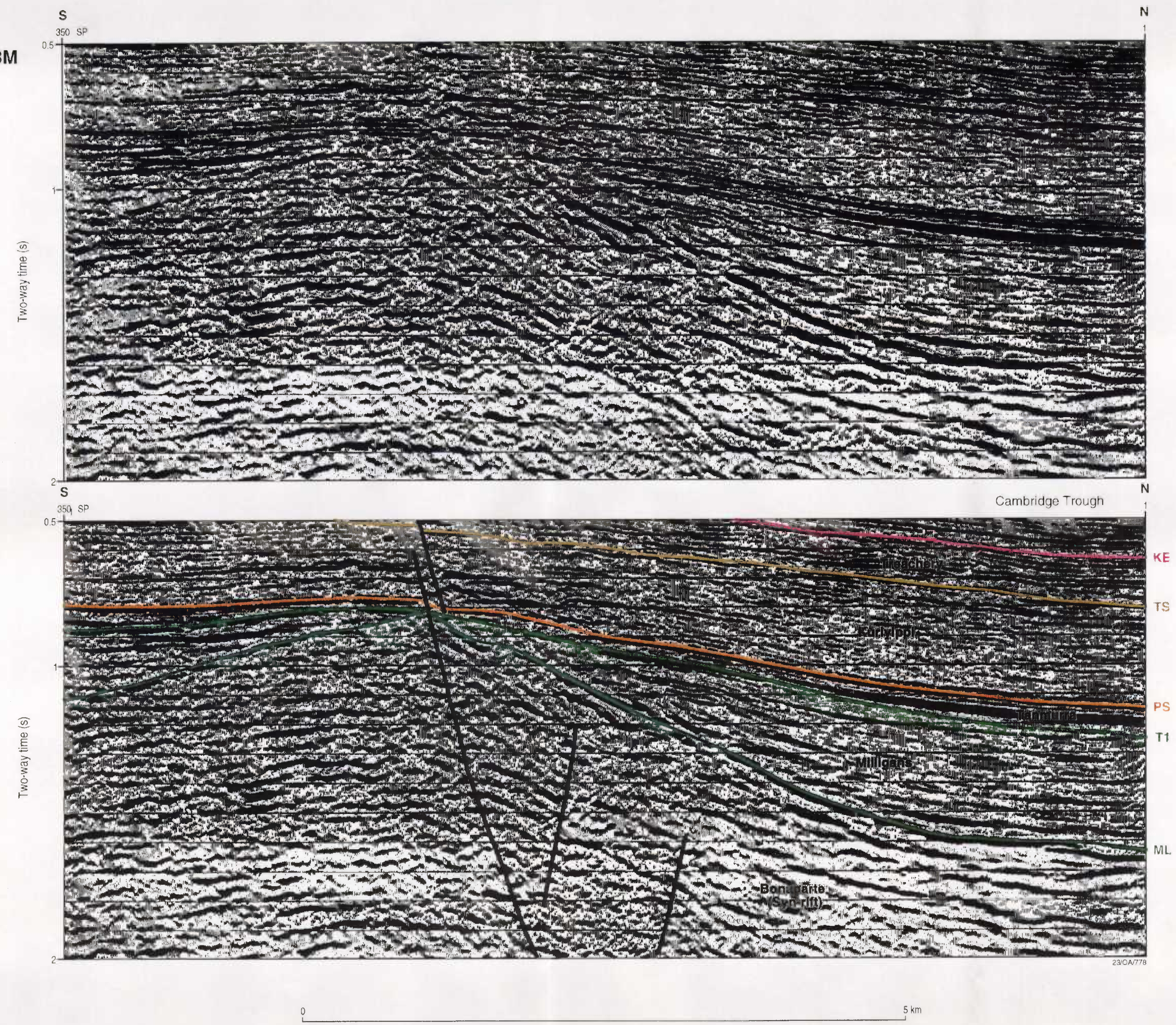


Figure 4-4. Uninterpreted and interpreted versions of part of seismic line CB81-03M showing onlapping relationship of lower transgressive Milligans sequences onto the underlying Bonaparte Megasequence.

upper prograding sequences probably correlate with Sequences Mill A7 and A8 identified in onshore wells. Continued northward progradation of these highstand sequences filled the Cambridge Trough and spilled across the now submerged Cambridge and Turtle-Barnett Highs (and the capping, lowstand, *Grandispora sp. cf. G. praecipua* Sequence), and extended out onto the Lacrosse Terrace and into the incipient Petrel Deep (Fig. 4-2).

TANMURRA SUPERSEQUENCE

This supersequence is based on the type section of the Tanmurra Formation in Bonaparte-1 (Le Blanc, 1964; ARCO, 1969, named the equivalent unit in Lacrosse-1 the 'Medusa Beds'). It comprises a thin basal, very fine- to fine-grained, sandy peloidal limestone, overlain by very fine to medium grained sandstone with interbedded limestone, bioclastic sandy dolostone and siltstone, and an upper sandy ooid grainstone. The basal sequence boundary is defined by a marked sonic log shift, and a regressive peak on the gamma log (this boundary is picked at 484 m KB in Bonaparte-1).

The Tanmurra Supersequence forms a 200-400 m thick succession of mixed clastic and carbonate shallow shelf facies throughout the Carlton Sub-basins, Keep Inlet Sub-basin and Cambridge Trough. It thins across the Cambridge and Turtle-Barnett Highs (100-300 m thick) where shallow shelf carbonates predominate, and then thickens to over 500 m of mixed carbonate-sandstone shallow shelf facies on the Lacrosse Terrace, and about 5-6 km (up to 1.8 seconds TWT) of presumed basinal clastic facies in the Petrel Deep (Map & Seismic Folio, plate 11).

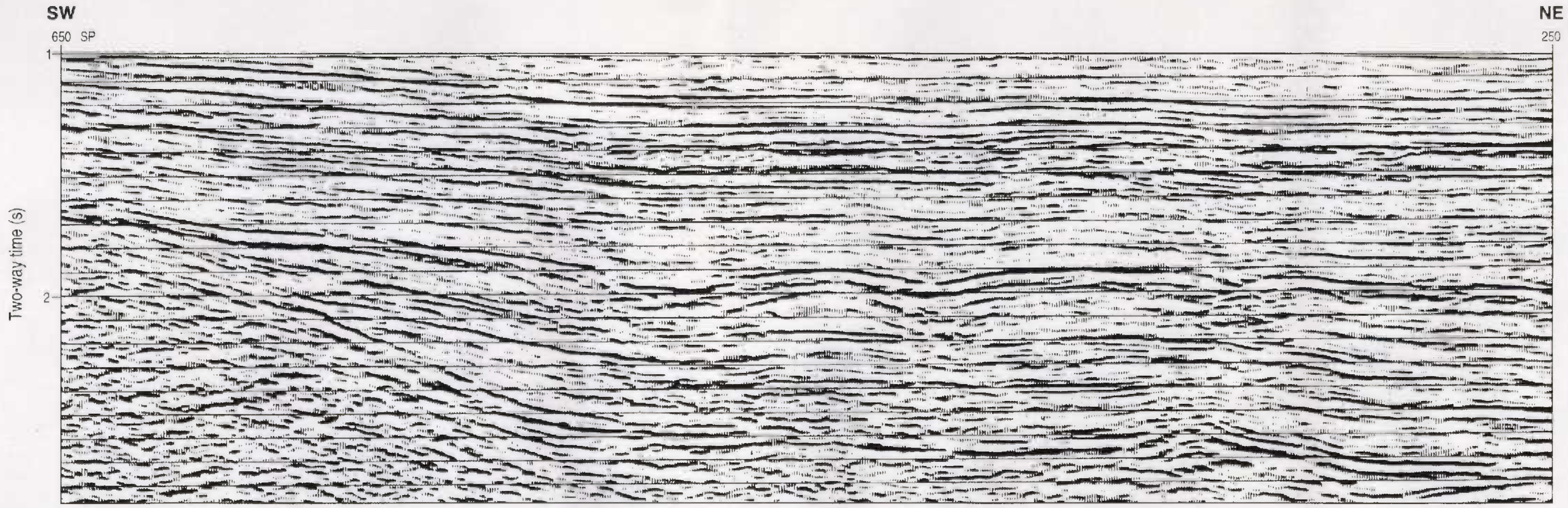
Palynoflora and fauna in Barnett-1, 2, Bonaparte-1, 2, Cambridge-1, Lacrosse-1, Lesueur-1, Matilda-1, Pelican Island-1, Skull-1 and Turtle-1 indicate a latest Visean age for the Tanmurra Supersequence (incorporating Mamet foraminiferal zones 15, 16s, 17; *A. largus* palynozone; *E. gradatus* brachiopod fauna; *Amphissetes sp. B* ostracod assemblage).

In the Turtle and Barnett wells, this supersequence comprises two upward-shoaling sequences (Sequences Tan 1, Tan 2; incorporating the so called 'Upper Milligans Turtle' in Barnett-2). These sequences thicken rapidly into the Petrel Deep, and record the successive basinward progradation of a mixed carbonate-clastic shelf. Thick basinal shale sections are postulated within this depocentre, and upper-slope carbonate buildups are identified north of the Turtle-Barnett High (Fig. 4-5). The supersequence thins westward along the Cambridge High where ooid shoals predominate. The basal 12 m thick unit of fine to very coarse sandstone penetrated in Cambridge-1 (?Tan 1) is interpreted as an incised valley fill deposit. In parts of the Cambridge Trough, the base of the supersequence is marked by a prominent truncation surface on seismic data.

POINT SPRING SUPERSEQUENCE

The Point Spring Supersequence encompasses the Point Spring Sandstone and Border Creek Member (formerly 'Formation') as defined in outcrop sections by Mory & Beere (1988). In outcrop, the formation consists of sandstone, pebbly sandstone and minor

LINE B92-29



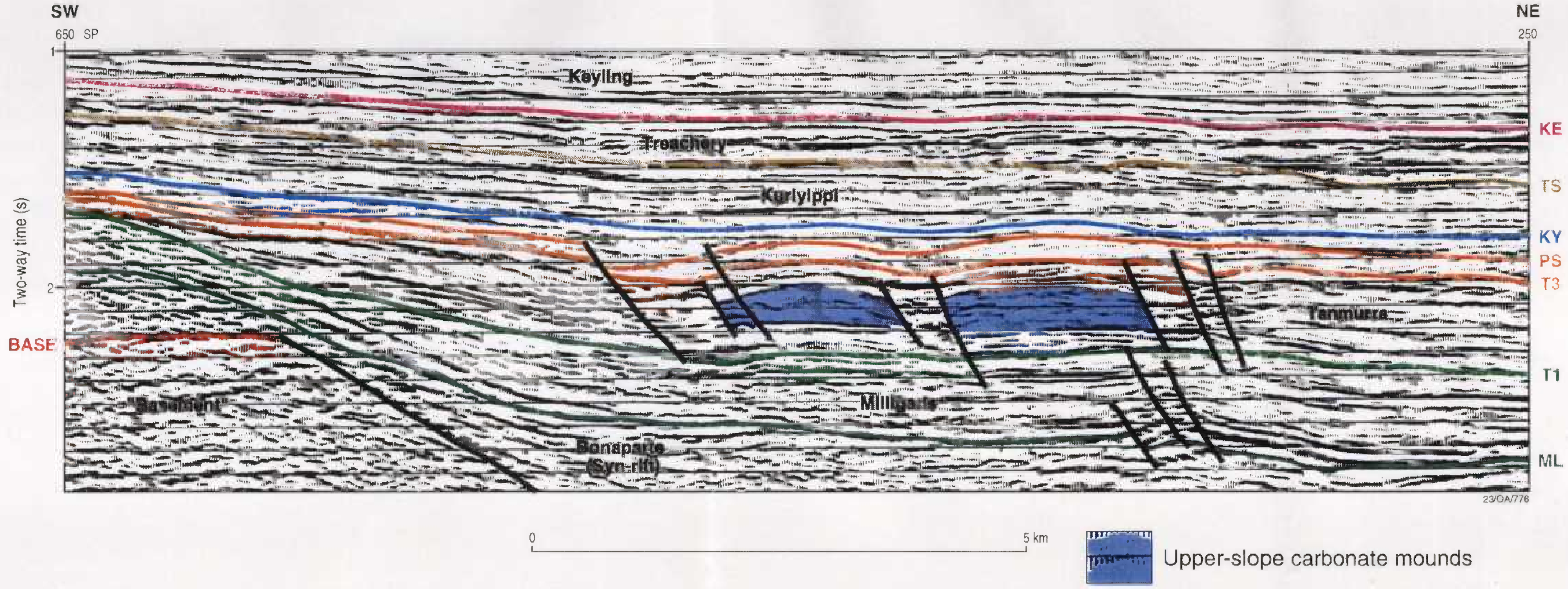


Figure 4-5. Uninterpreted and interpreted versions of part of seismic line B92-29 showing upper-slope carbonate mounds within the Tanmurra Supersequence.

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siltstone, arranged in fining-upward and coarsening-upward cycles generally less than 20 m thick (Mory, 1991). In the subsurface the unit contains more shale and includes minor amounts of calcareous sandstone and limestone. Some prominent thin limestone marker beds occur near the top of the supersequence. Fluviatile to shoreface, delta plain facies are present in outcrop and onshore wells, whereas prodelta and distal distributary deposits predominate in offshore wells (Mory, 1991).

The Point Spring Supersequence extends throughout the Carlton Sub-basin, Cambridge Trough, Cambridge and Turtle-Barnett Highs, Lacrosse Terrace and Keep Inlet Sub-basin (generally 200-400 m thick), thickens locally on the Kulshill Terrace (870 m in Kulshill-1), and thickens regionally into the Petrel Deep (0.65 seconds TWT or 1500+ m northwest of Bougainville-1; Map & Seismic Folio, plate 12). Brachiopods, ostracods and palynoflora indicate a mid Carboniferous Namurian age (*G. maculosa* and *S. ybertii* palynozones).

The basal sequence boundary is marked by a prominent shift to slow sonic log values above the carbonates of the Tanmurra supersequence. The onshore well sections are dominated by fluviatile highstand deposits, but possible basal lowstand fluvial and shoreface sandstones occur in Bonaparte-1 and 2, Keep River-1 and Skull-1. In offshore wells, the basal sequence boundary is overlain by transgressive marine shales and carbonates which display a prominent back-stepping ('retrogradational') gamma log motif. In these wells the early highstand deposits generally comprise one or two upward-coarsening deltaic or barrier bar cycles (probably third-order sequences), overlain by shoreface and fluvial facies with blocky and upward-fining gamma log cycles. Upward-fining fluvial sequences are particularly well defined in Lacrosse-1. The unusually thick Kulshill-1 section is atypical of other wells; here the supersequence comprises a thick, upward-fining, transgressive marine shelf facies (siltstone, shale and minor sandstone and bioclastic limestone, about 420 m thick), overlain by four upward-coarsening sequences of shale, siltstone, minor bioclastic limestone and fine sandstone (second order highstand). This supersequence incorporates units originally assigned to the 'Milligans Beds' (members 1, 2), 'Tanmurra Formation', 'unnamed Formation' and basal portion of the 'Kullshill Formation' (Duchemin & Creevey, 1966). Following Foster's (1986) recognition of microflora from the *G. maculosa* and *S. ybertii* palynozones within this succession, Mory (1991) similarly correlated this interval with the Point Spring Formation. This thick marine shelf succession indicates local rapid subsidence and marine incursion across the Kulshill Terrace at this time. An equivalent progradational highstand shelf deposit is evident on seismic data in the Petrel Deep (see AGSO Line 100/5, Map & Seismic Folio, enclosure 5).

KURIYIPPI SUPERSEQUENCE

This supersequences comprises the Kuriyippi Formation as defined by Mory (1991), except that the uppermost 30 m thick sandstone in the Lesueur-1 type section is interpreted as a basal transgressive unit of the overlying Treachery Sequence. The supersequence comprises a thick succession of braid-plain sandstone, shale and minor coal, overlain by glacial sandstone and conglomerate. It is correlated with the lower 'sandstone-dominated' unit of the Keep Inlet Formation in the onshore portion of the basin, which Mory & Beere (1988) interpreted as a series of fan-deltas shed from uplifted fault blocks. Diamictites and tillites intersected in Cambridge-1, Kinmore-1 and Kulshill-1 are here interpreted as the basal unit of the overlying Treachery Sequence.

The Kuriyippi Supersequence has been intersected in the central Carlton Sub-basin, Cambridge and Turtle-Barnett Highs, Lacrosse Terrace, Keep Inlet Sub-basin, Kulshill Terrace and Eastern Ramp margin of the Petrel Deep, and generally ranges from 500-1000 m thick in offshore areas; it is thinner in the onshore part of the basin. Seismic data indicates that it also extends throughout the Cambridge Trough (Map & Seismic Folio, plate 13), and pinches out against Proterozoic basement to the southwest on the Berkley Platform (absent in Berkley-1), and to the northeast on the Eastern Ramp (176 m in Flat Top-1). A thin eroded remnant of the supersequence is interpreted to be present in Bonaparte-1 and Bonaparte-2, and thermal maturation modelling indicates that it (and younger sequences) were probably widespread across the Carlton Sub-basin prior to erosion during the Fitzroy Movement (see Geohistory Modelling Report - Kennard, 1996b). The supersequence thickens to over 3 seconds TWT (8+ km) in the outer Petrel Deep where it forms the thickest sequence mapped in Petrel Sub-basin (Map & Seismic Folio, plate 13).

The Kuriyippi Supersequence contains diagnostic palynoflora of the *D. birkheadensis, M. tentula* and *G. confluens* palynozones, and spans the Late Carboniferous (Westphalian-Stephanian) and earliest Permian (Asselian-?Sakmarian; C.B. Foster, AGSO, pers. comm., September 1996).

The base of the supersequence is marked by a thick erosional-base sandstone which generally has faster sonic log velocities than sandstones of the underlying Point Spring Supersequence. In some wells this basal sandstone may be difficult to differentiate from erosional-base sandstones within the underlying supersequence, but the presence of microflora belonging to the younger *D. birkheadensis* palynozone is diagnostic of the Kuriyippi Supersequence. The supersequence is characterised by numerous 30-100 m thick blocky and upward-fining sandstone-shale cycles. The section intersected in Kulshill-1 is again atypical in that it comprises several 40-60 m thick upward-coarsening ?deltaic cycles with common marine and marginal-marine indicators (glauconite, brackish water *Botryoccus* algae). The marine embayment initiated during deposition of the underlying Point Spring Supersequence in the Kulshill area thus persisted throughout the deposition of the Kuriyippi Supersequence.

TREACHERY SEQUENCE

This sequence encompasses the Treachery Shale, and comprises tillite, carbonaceous shale, siltstone, sandstone and minor limestone and coal. In Kulshill-1, the type section of the Treachery Shale, the sequence comprises a basal 12 m thick conglomeratic sandstone (previously assigned to the underlying Kuriyippi Formation; Mory, 1991) overlain by an upward-coarsening siltstone-sandstone unit (30 m thick) and sandy-conglomeratic tillite (100 m thick). Striated pebbles, varved shale, minor glauconite and the lack of marine faunas, together with the presence of the green alga *Botryococcus* and rare Tasmanitid algae in Moyle-1 (Brophy, 1966), suggest glacial outwash deposits within lacustrine and marginal marine (lagoonal and estuarine) environments. The characteristic high gamma log values of the sequence are probably in part due to abundant exotic rock components, notably feldspars and micas.

The Treachery Sequence has been intersected on the Berkley Platform, Cambridge and Turtle-Barnett Highs, Keep Inlet Sub-basin, Kulshill Terrace and the Eastern Ramp. It is 150-200 m thick in these well intersections, and eroded remnants are intersected in the southern Cambridge Trough (Pelican Island-1) and central Carlton Sub-basin (Keep River-1). Seismic data indicate that it forms two lobes over 0.5 seconds TWT (1000 m) thick in the Petrel Deep, one beneath the Petrel Anticline and the other southwest of Gull-1 (Map & Seismic Folio, Plate 15). A third equally thick lobe may occur in the Keep Inlet Sub-basin west of Kulshill-1, but seismic interpretation is poorly constrained in this area.

Palynomorphs indicate an Early Permian (Asselian-?Sakmarian) age for the sequence (*M. tentula* and *G. confluens* palynozones; C.B. Foster, AGSO, pers. comm., September 1996).

The Treachery Sequence comprises a basal tillite (100-200 m thick in Berkley-1, Cambridge-1, Kinmore-1, Kulshill-1 and Moyle-1), interpreted as a lowstand systems tract restricted to the flanks of the sub-basin, overlain by two to four upward-fining and backstepping (retrogradational) conglomeratic sandstone and shale-sandstone parasequences which culminate in a shaly or coaly condensed section (50-100 m thick transgressive systems tract). This condensed section is overlain by one or two upward-coarsening shale-sandstone cycles with minor carbonates and coal seams (each cycle about 50-100 m thick), interpreted as progradational shoreface and coastal plain deposits (highstand systems tract). Numerous channels are evident at the base of the sequence on seismic data, which are interpreted as glacial scours.

KEYLING SUPERSEQUENCE

This supersequences encompasses the Keyling Formation as defined at the type section in Kulshill-1 (Mory, 1991). It consists of very fine to medium and coarse grained sandstone, and interbedded siltstone, shale and minor coal and limestone. Upward-fining and upward-coarsening cycles (each 30-80 m thick) occur throughout the sequence, with a predominance of coarser grained upward-fining cycles in the lower part of the supersequence. Coal seams tend to be more prevalent in the basal and upper portions, whereas limestone is generally restricted to the central portion. Fluviatile and shallow marine deltaic environments are indicated by coal seams, plant remains, green algae (*Botryococcus*), rare marine fossils, limestones and minor glauconite.

The supersequence has been intersected in most offshore wells, where it is 300-750 m thick. Onshore it has only been intersected in Kulshill-1 (836 m), but thermal maturation data (see Geohistory Modelling Report) suggests that it was probably originally deposited throughout most of the Carlton Sub-basin prior to erosion associated with the Fitzroy Movement. Seismic data indicates that it thickens to 0.4-0.6 seconds TWT (~1500 m) in the central axis of the Petrel Deep (Map & Seismic Folio, plate 16).

The Keyling Supersequence contains microfloras of the *Granulatisporites confluens* Oppel-zone, *Pseudoreticularspora pseudoticulata* zone (i.e., Stages 2 and 3a), indicating an early Early Permian (late Asselian - early Sakmarian) age. Stage 3b microfloras have been recovered throughout the upper 450 m of the supersequence in Lesueur-1 (Foster, 1986, 1990b); in all other wells Stage 3b microfloras are restricted to sequences in the overlying Fossil Head Supersequence. Marine faunas are impoverished throughout the Keyling Supersequence.

The basal sequence boundary is marked by a sharp erosional contact with the underlying Treachery Sequence, and marks the upper limit of glacial facies. This boundary may have been enhanced by isostatic rebound following glacial retreat. In most wells (e.g., Kinmore-1, Lacrosse-1, Lesueur-1, Turtle-1 and 2), a three-fold sub-division of the supersequence is possible: a lower thick fluvial dominated, coarse-grained sandstone, shale and coaly succession (lowstand deposits); a middle marine shale, sandstone and interbedded limestones unit, the top of which is marked by maximum gamma log values at or just below the middle of the supersequence (transgressive deposits); and a thick upper, thinly interbedded, fine-medium grained sandstone, shale and coaly succession of mixed fluvial and marine facies (highstand deposits). The supersequence is thus interpreted as an aggradational-transgressive-regressive coastal plain succession.

FOSSIL HEAD - HYLAND BAY SUPERSEQUENCE

This supersequence forms a major T-R cycle comprising sequences of the Fossil Head Formation (transgressive half-cycle), and Hyland Bay Formation (regressive half-cycle). It occurs throughout the Petrel Deep and Eastern Ramp margin, and has a maximum thickness of 0.95 seconds (~2300 m) to the southwest of Gull-1 (Map & Seismic Folio, plate 17).

Fossil Head Transgressive Half-Cycle

This transgressive half-cycle encompasses the Fossil Head Formation and a thin basal transgressive sandstone (or locally sandstone/limestone; generally less than 20-40 m thick) which has previously been assigned to the underlying Keyling Formation. Mory (1988) nominated the interval 2993 to 3569 m in Tern-1 as the type section of the Fossil Head Formation, whereas the basal sequence boundary is here picked at 3572 m to include these basal transgressive sandstones. The Fossil Head Formation comprises carbonaceous siltstone and mudstone, fine to medium sandstone and biomicritic limestone. An abundant marine fauna (bryozoa, echinoderms, brachiopods, corals, gastropods and ostracods) indicates an open shelf environment, with local carbonate shoals developed on the flanks of the basin (e.g., Flat Top-1; this limestone was previously assigned to the Hyland Bay Formation by Hughes, 1978).

The Fossil Head half-cycle has a maximum penetrated thickness of 700 m in Petrel-2 (basal sequence boundary at or near TD), and thins to 120-300 m on the flanks of the basin (Flat Top-1, Kulshill-1, Cambridge-1). It thickens to 0.6 seconds TWT (~ 1500 m) near Gull-1 (see AGSO Lines 100/5 & 7, Map & Seismic Folio, enclosures 5 & 7). Six or seven smaller-scale cycles (probably third-order sequences) are present in several wells (e.g., Cambridge-1, Lacrosse-1, Lesueur-1, Petrel-2, Tern-1, Turtle-1), the upper two cycles culminating in relatively thicker sandstones.

Palynomorphs (*G. trisinus* Stage 3b, *P. cicatricosa* and *M. villosus* assemblages) indicate an Early Permian (Sakmarian to early Kungurian) age. Stage 3a palynomorphs occur within the thin basal transgressive sandstone, the Stage 3a/3b boundary generally coinciding with the maximum flooding surface of this basal sequence (e.g., Cambridge-1 and Turtle-1, Well Folio, plates 8 & 30; palynological determinations by Foster, 1984).

Hyland Bay Regressive Half-Cycle

This regressive half-cycle comprises open-marine shelf and deltaic deposits of the Hyland Bay Formation. Mory (1988) nominated Petrel-2 as a reference section since Petrel-1, the type section, did not intersect the base of the formation. The formation contains five sub-units (Bhatia et al., 1984; Mory, 1988, 1991): 1) an unnamed basal shale, sandstone and minor bryozoan-crinoidal limestone unit (12-70 m thick), 2) biomicritic and bioclastic bryozoan-crinoidal limestone ('H5' or Pearce Member, 5-60 m thick), 3) mudstone, siltstone and sandstone with minor coal, generally forming two coarsening-upward cycles (Cape Hay Member, 200-450 m thick), which forms the main reservoir at the Petrel Field, 4) biomicritic and bioclastic bryozoan-crinoidal limestone ('H4' or Dombey Member, 5-30 m thick), and 5) a coarsening-upward cycle of mudstone and sandstone (Tern Member, 30-70 m thick) which forms the reservoir at the Tern Gas Field. Limestones of the Pearce and Dombey Members were deposited on an open-marine, temperate-water shelf. The intervening Cape Hay Member represents progradational pro-delta, delta-front, and lower to upper delta-plain facies, and the upper Tern Member represents progradational shoreface and barrier bar and shoreface facies (Bhatia et al., 1984). The thin unnamed basal unit probably represents estuarine and shallow marine facies.

The Hyland Bay half-cycle is 400-560 m thick in wells in the Petrel Deep, and gradually thins to less than 300 m on the flanks of the basin (145 m in Flat Top-1, 280 m in Lesueur-1). It has not been intersected in onshore exploration wells, but occurs in outcrops and coal bores in the Port Keats and Cliff Heads area (Drummond, 1963; Dickins et al., 1972). Seismic data indicates that it thickens in the outer portion of the Petrel Deep to a maximum of about 0.3 seconds TWT (~800 m; AGSO Line 100/5, Map & Seismic Folio, enclosure 5).

Three third-order sequences are generally evident within the Hyland Bay half-cycle. The basal sequence boundary is a prominent erosion surface overlain by a thin transgressive sandstone lag or bryozoan limestone; in many wells this basal sandstone has been previously assigned to the underlying Fossil Head Formation (e.g., Barnett-1, 2, Bougainville-1, Kinmore-1, Lacrosse-1, Turtle-1, 2). This basal unit and the overlying open shelf limestone of the Pearce Member represent a transgressive systems tract, and the progradational delta and delta-plain succession of the overlying Cape Hay Member forms the highstand systems tract. A second transgressive-regressive delta-plain sequence is recognised in the upper part of the Cape Hay Member in most wells (see Sections 1, 2 and 3, Well Folio, plates 33-35). The third sequence comprises transgressive open shelf limestones of the Dombey Member, and progradational barrier bar and shoreface sandstones of the Tern Member (highstand systems tract).

McConachie et al. (1996) refer to 'reefs' within the Pearce and Dombey Members. However, these carbonates form thin sheet-like deposits, and although they may gradually thicken on the flanks of the basin (e.g. 45 m thick basal limestone in Flat Top-1), local thickening or reefal buildups are not evident on seismic data. These carbonates are invariably tight, and do not offer reefal or drape targets. McConachie et al. (1996) also suggest that the limestones of the Pearce and Dombey Members coalesce 'to the northwest'; however, our data indicate that within the Petrel Sub-Basin these carbonate units are always separated by a substantial thickness of clastic deltaic deposits (Cape Hay Member).

Microflora indicate a Late Permian (Ufimian-Dzhulfian) age for this half-cycle, incorporating the *D. dulhuntyi* and *D. parvithola* palynozones. The absence of *D. granulata* and *D. ericainus* microflora (Stage 5a-b) suggests a significant hiatus between the Fossil Head and Hyland Bay half-cycles. This hiatus probably records an initial compressive pulse prior to the onset of the main Fitzroy Movement.

MOUNT GOODWIN - CAPE LONDONDERRY SUPERSEQUENCE

This supersequence forms a major T-R cycle comprising sequences of the Mount Goodwin Formation (transgressive half-cycle), and Cape Londonderry Formation (regressive half-cycle).

Mount Goodwin Transgressive Half-Cycle

This half-cycle encompasses the Mount Goodwin Formation, and a very thin basal transgressive sandstone lag that is generally assigned to the underlying Tern Member of the Hyland Bay Formation. It consists predominantly of shale, with minor amounts of glauconitic siltstone and thin fine-grained sandstone interbeds (Mory, 1991). These sediments were deposited in a low energy, possibly partially restricted, shelf environment, shallowing to the margins of the basin in the Port Keats area where conchostracans indicate brackish marginal-marine environments (Tasch & Jones, 1979).

The Mount Goodwin half-cycle is 450-610 m thick in wells in the Petrel Deep, thinning to 200 m on the northeast flank of the basin (Flat Top-1). Seismic data indicate that it thickens slightly towards the northwest (AGSO Line 100/5, Map Folio, enclosure 5). It formerly extended across the Cambridge and Turtle-Barnett Highs, Keep Inlet Sub-Basin, Cambridge Trough and probably the Carlton Sub-basin, but was subsequently eroded from these areas during the Fitzroy Movement. It extends onshore in the Port Keats area where it is now less than 20 m thick (Dickins et al., 1972; Mory, 1991).

As many as eight 50-150 m thick smaller scale (?third order) sequences are evident in the Mount Goodwin half-cycle (e.g., Penguin-1, Petrel-1A, 2). A regionally correlatable sequence boundary is evident near the middle of the half-cycle, and several thin progradational sand units overlie this boundary (e.g., Bougainville-1, Kinmore-1, Penguin-1, Petrel-1A, 2 and Tern-1; see Well Folio, sections 1 and 2, plates 33-34). In

Flat Top-1, the succession above this sequence boundary comprises interbedded fine-coarse grained sandstone and shale deposited in (?)marginal marine environments.

Microflora indicate a Late Permian - Early Triassic age for the Mount Goodwin half-cycle (late Dzhulfian to Nammalian Stages; *P. microcorpus, K. saeptatus* and equivalent *P. samoilovichii* zones).

Cape Londonderry Regressive Half-Cycle

This half-cycle consists of a lower interbedded sandstone, siltstone and shale unit (100-150 m thick, lower Cape Londonderry Formation), and a thick fine-coarse grained sandstone and pebbly sandstone unit (170-280 m thick, upper Cape Londonderry Formation). The lower unit contains both upward-coarsening and upward-fining cycles, each about 10-25 m thick, and the presence of glauconite together with the lack of marine fauna suggests a paralic, marginal marine environment. The upper unit is extensively cross-bedded, contains minor shale and coal partings, is devoid of both flora and fauna, and represents a fluviatile coastal braid-plain deposit.

The Cape Londonderry half-cycle is 200-430 m thick and is restricted to the Petrel Deep. It thins on the northeastern and southwestern flanks of the basin (e.g., Flat Top-1 and Fishburn-1), largely as a result of erosional truncation during the Fitzroy Movement, and was also eroded from the Cambridge and Turtle-Barnett Highs, Keep Inlet Sub-basin, Cambridge Trough and probably the Carlton Sub-basin at that time.

The sequence boundary at the base of the half-cycle is marked by a prominent gamma and sonic log shift which represents an abrupt basinward facies shift. The contact with the overlying braid-plain deposit is generally equally abrupt (e.g., Petrel-1A, 2 and Tern-1), and may also represent a sequence boundary.

The lower unit of the Cape Londonderry half-cycle contains microflora of the *T. playfordii* zone, which indicates a late Early to early Middle Triassic age (late Nammalian to early Anisian Stages). The thick upper braid-plain deposit is undated, and probably extends throughout the Middle Triassic.

MALITA SUPERSEQUENCE

This supersequences comprises the multicoloured 'redbeds' of the Malita Formation, consisting of siltstone, shale and minor fine- to coarse-grained sandstone. Whilst the abrupt change from coarse sandstone to multicoloured finer-grained 'redbeds' clearly marks the lithostratigraphic contact between the Cape Londonderry and the Malita Formations, the basal sequence boundary is generally more difficult to pick. In the type section of the Malita Formation (2229-2471 m in Petrel-1, Helby 1974a), the basal sequence boundary is picked at a prominent gamma and sonic log peak at 2485 m (correlated to 2494 m in Petrel-1A), such that the supersequence includes a basal 9-15 m thick (?)lowstand/transgressive sandstone at the top of the Cape Londonderry Formation.

The Malita Supersequence represents syntectonic deposits formed during the phase of compression and inversion associated with the Fitzroy Movement. The 'redbeds' are fluvial deposits, probably deposited within essentially land-locked drainage basins that formed during the compressive Fitzroy Movement; marine deposits were probably restricted to more outboard areas (e.g., Malita Graben) at this time. The Malita Supersequence has a maximum intersected thickness of 325 m in Petrel-2. Seismic data clearly indicates that it onlaps the Tern and Petrel Anticlines within the Petrel Deep, and pinches out against the flanks of the Petrel Deep immediately west of Sandpiper-1, and outboard of Lesueur-1 and Flat Top-1 (see AGSO Lines 100/2, 3 & 5, Map & Seismic Folio, enclosures 2, 3 & 5). It thickens to about 0.7 seconds TWT (~1600 m) on the western side of the Curlew-1 salt diapir (Map & Seismic Folio, plate 19).

The Malita Supersequence contains microflora of the *S. speciosus, M. crenulata* and *A. reducta* zones. In Plover-1 and Plover-3 (west of the present study area) the supersequence extends into the younger *C. torosa* zone. The supersequence is thus dated as Late Triassic to Early Jurassic (late Carnian, Norian, Rhaetian, Hettangian & ?Sinemurian Stages). The older *S. quadrifudus* palynozone is not represented in wells in the Petrel Sub-Basin (Helby's 1974b original determination of this zone in Gull-1 has since been revised following new sampling by Morgan, 1991, and further review by R.J. Helby for the APIRA Australian Petroleum Systems Projec;see McConachie et al., 1995). Thus the major unconformity between the Malita Supersequence and the underlying sequences of the Mount Goodwin Formation spans the late Anisian, Ladinian and early Carnian Stages of the Middle and Late Triassic. This interpretation is different to that of McConachie et al. (1996) who assigned a substantially younger Carnian-Norian boundary age to the Fitzroy Movement unconformity. McConachie et al. based their age on the occurrence of microflora of the *S. speciosus* zone below the original lithostratigraphically defined base of the Malita Formation ('Non-marine A Red Beds'; ARCO, 1971) at 3345 m KB in Gull-1. However, sequence stratigraphic analysis suggests that the basal sequence boundary of the Malita Supersequence occurs at or below 3400 m KB in Gull-1, and that the overlying upward-fining sandstone parasequences that contain the *S. speciosus* microflora represent basal lowstand or transgressive deposits of that sequence. The *S. speciosus* microflora zone also occurs within the overlying 'redbed' succession at the Petrel-1/1A type section.

PLOVER SUPERSEQUENCE

The Plover Supersequence comprises fine-coarse grained sandstone and minor shale, coal and limestone of the Plover Formation (type section Petrel-1, Hughes 1978, Mory 1991). The sequence represents an extensive fluvial-deltaic coastal-plain deposit, and marine shales, dinoflagellates, rare faunal fragments, glauconite and limestone in the upper part of the supersequence indicate shallow-marine (estuarine, interdistributary bay and delta slope) environments.

The supersequence is restricted to the Petrel Deep northwest of Kinmore-1 (Map & Seismic Folio, plate 20). It is 390-400 m thick at the Petrel Field, thins to about 200-300 m on the flanks of the Petrel Deep, and has a maximum penetrated thickness of 670 m in Gull-1. Seismic data indicate a major depocentre southwest of Gull-1 near the margin of the Malita Graben (Map & Seismic Folio, plate 20).

The *C. torosa, I. turbatus, D. complex, C. cooksoniae* and *M. florida* palynozones have been identified in the lower fluvial-dominated part of the supersequence, and the *W. digitata, R. aemula, W. spectablis* dinocyst zones in the upper marine portion. A prominent erosion surface is evident on both seismic and well log data at the base of the supersequence (e.g., Map & Seismic Folio, AGSO Lines 100/3 &118/18, enclosures 3 & 4). Microflora of the *C. torosa* zone occur both above (Gull-1, Penguin-1) and below (Plover-1, 3) this basal sequence boundary; in most wells, however, this zone is absent due to erosion. An Early-Late Jurassic (Pliensbachian - early Oxfordian) age is thus assigned to the supersequence.

The bulk of the supersequence comprises coarse coastal-plain deposits with minor coals, but a distinctive finer-grained marine sequence with abundant dinoflagellates (of the *W. digitata, R. aemula, W. spectablis* zones) and minor limestone (e.g., Petrel-2) can be identified at the top of the supersequence in most wells (see Well Folio, sections 1 & 2, plates 33 & 34). Messent et al. (1994, fig 12) assigned this sequence to their 'Lower Flamingo cycle' (supersequence) in Petrel-2, and considered it absent due to erosion in Gull-1. However, the *W. digitata, R. aemula,* and *W. spectablis* dinocysts zones are also present within a distinct marine sequence in Gull-1 (2400-2580 m KB), which is here correlated with the upper marine sequence of the Flamingo Supersequence in the Petrel-1/1A type section (see Well Folio, section 1, plate 33). Furthermore, Messent et al. considered their 'Lower Flamingo cycle' to comprise only the transgressive system tract of one third order sequence, and concluded that highstand deposits were absent due to erosion associated with a 'Kimmeridgian to Tithonian' tectonic event. However, well defined transgressive and highstand systems tracts are present in this sequence in several wells (e.g., Gull-1, Petrel-1/1a, Petrel-2, Penguin-1, Flat Top-1, Sandpiper-1 and Tern-1); the lack of highstand deposits in the wells analysed by Messent et al. in the southwestern portion of the Petrel Sub-Basin (e.g., Fishburn-1, Frigate-1 and Billabong -1) is more likely due to distal offlap in this area (that is, condensed or starved highstand), rather than erosion.

FLAMINGO SUPERSEQUENCE

This supersequence forms the well defined T-R cycle of the Flamingo Group. The basal sequence boundary is picked at 1826 m KB in the Petrel-1 type section, at the base of a 7 m thick transgressive sandstone lag which Hughes (1978) and Mory (1991) assigned to the underlying Plover Formation. The remainder of the transgressive cycle consists of shale, siltstone and minor fine sandstone and limestone (lower part of the 'Frigate'), the maximum flooding surface occurring near the middle of the Frigate Shale. The overlying regressive half-cycle consists of upward-coarsening shale-siltstone-sandstone (upper part of the 'Frigate Shale'), and a thick fine to coarse grained sandstone ('Sandpiper Sandstone'). The transgressive and early highstand shales represent a low energy open shelf environment, and the overlying highstand represents a progradation coastal plain succession; minor glauconite and marine microfauna within the upper sandstone interval indicate shallow marginal marine conditions, probably within a wave-dominated delta complex (Messent et al., 1994).

The Flamingo supersequence has a maximum penetrated thickness of 495 m in Petrel-1A; elsewhere in the central and outer Petrel Deep it is generally 200-300 m thick, thinning to less than 100 m on the flanks of the Petrel Deep. Seismic data indicates that it thickens into a WNW-trending depocentre outboard of the Petrel area (Map & Seismic Folio, plate 21; Messent et al., 1994, fig. 17) and has a maximum thickness of 0.45 seconds TWT (~650 m) northwest of Billabong-1. The supersequence encompasses the *W. clathrata* to *C. delicata* dinocyst zones, and is thus dated as Late Jurassic (late Oxfordian) to earliest Cretaceous (early Berriasian).

A detailed sequence stratigraphic study of the Flamingo Group in the central and outer Petrel Sub-Basin was undertaken by Messent et al. (1994); Robinson et al. (1994) analysed equivalent sequences in the Sahul Syncline. Messent et al. divided the Flamingo Group into two second-order cycles (supersequences) separated by a major 'Kimmeridgian to Tithonian' tectonic event: 1) their 'Lower Flamingo cycle' comprises only the transgressive systems tract of one third-order sequence, and 2) their 'Upper Flamingo cycle' comprises seven third-order sequences. However, as stated earlier, their 'Lower Flamingo cycle' in Petrel-1/1A (the type section of the Plover Formation), Petrel-2, Fishburn-1, Frigate-1 and Penguin-1 is here assigned to the uppermost third-order sequence of the underlying Plover Supersequence, and is characterised by dinoflagellates of the *W. digitata, R. aemula*, and *W. spectablis* zones. These zones also occur within the upper part of the Plover Supersequence in Gull-1, although Messent et al. considered their 'Lower Flamingo cycle' absent in this well. Their 'Kimmeridgian to Tithonian' tectonic event that separates the Lower and Upper Flamingo cycles was dated on the basis of the apparent absence of the *W. clathra, D. swanense* and *C. perforans* dinoflagellate zones in wells studied by Messent et al. (1994). However new and substantially revised biostratigraphic data undertaken by Helby (1994, AGSO STRATDAT database) indicates that all or some of these zones are represented in the lower transgressive portion of the Flamingo Supersequence in several wells, but are absent in Gull-1. The unconformity between the Flamingo Supersequence and the underlying Plover Supersequence is thus bracketed by the *W. spectabilis* zone below, and the *W. clathrata* or *D. swanense* zone above; that is, mid to late Oxfordian, rather than the 'Kimmeridgian to Tithonian' event proposed by Messent et al. (1994).

Messent et al. (1994) recognised seven third-order sequences within the Plover Supersequence (their 'Upper Flamingo cycle'); the second-order maximum flooding surface occurs within their basal UF1 sequence (lower *D. jurassicum* zone), and sequences UF2-UF7 represent the second-order highstand. These highstand sequences form a series of successively offlapping, basinward advancing, progradational deposits that were generally sourced from the southwest and south, and that downlap the underlying Plover supersequence between the Petrel wells and Gull-1 (see AGSO Line 100/5, Map & Seismic Folio, enclosure 5; compare with Messent et al., fig 5). The major hiatus evident at the base of the Flamingo Supersequence in Gull-1 (spanning the *W. clathrata* to *D. jurassicum* zones) thus represents a starved downlap surface on the northern flank of the Flamingo depocentre.

BATHURST ISLAND SUPERSEQUENCE

This supersequence encompasses the Bathurst Island Group and consists of a thin basal transgressive glauconitic sandstone, claystone and radiolarian claystone (Darwin Formation), overlain by a very thick highstand section of micaceous mudstone with minor marl and limestone, and upward-coarsening siltstone and fine sandstone (undifferentiated Wangarlu Formation and ?Moonkinu sandstone). The transgressive deposits of the Darwin Formation represent an extremely condensed shallow-marine shelf deposit; these few tens of metres of sediment span almost the entire Early Cretaceous (*E. torynum* to *C. denticulata* dinocyst zones; late Berriasian to mid Albian Stages), a period of some 30-35 million years. In contrast, the overlying upward-fining highstand succession is over 1400 m thick in Gull-1, and ranges from late Albian to late Maastrichtian (*P. ludbrookiae* to *A. circumtabulata* zones). These highstand deposits represent a progradational, distal to inner shelf succession.

The Bathurst Island Supersequence thickens rapidly towards the northwest along the axis of the Petrel Deep, reaching a maximum thickness of 1.7 seconds TWT (1600+ m) between Gull-1 and Curlew-1 (Map & Seismic Folio, plate 22). Thinning on the flanks of the Petrel Deep has been accentuated by Early Tertiary erosion, and the supersequence most probably originally extended throughout the present offshore portion of the Petrel Sub-basin.

TERTIARY SEDIMENTS

Up to 500 m of Tertiary clastics and carbonates have been intersected in wells in the offshore portion of the Petrel Sub-basin. These sediments are Miocene to Pliocene in age, but age control is limited to Curlew-1 and Fishburn-1. Seismic data suggests that older Tertiary sediments occur in the depocentres adjacent to the Curlew-1 and Gull-1 structures.

CHAPTER 5

BASIN DEVELOPMENT

A number of techniques have been applied in the Petrel Sub-basin Study to investigate aspects of the basin's development. These techniques include tectonic subsidence analysis, flexural-isostatic modelling, and analogue (sandbox) modelling. Each provide somewhat different insights, partly based upon different inherent starting-point assumptions.

Results of the different analytical and modelling techniques are given below; a preliminary synthesis of the basin's development is given at the end of the chapter.

TECTONIC SUBSIDENCE ANALYSIS by J.M. Kennard

The following summary of the tectonic subsidence history of the Petrel Sub-basin is based on a broader geohistory analysis that incorporates subsidence, thermal and source rock maturation models of the basin's stratigraphic succession (see Geohistory Report, Kennard, 1996b for full details). Twenty wells and six pseudo-wells sites (locations based on seismic interpretations) were analysed using the WinBury V2 burial and thermal geohistory modelling package for Windows™ produced by Paltech Pty Ltd. These wells/pseudo-wells represent all major structural provinces recognised in the basin, and were modelled on the basis of sequence stratigraphic units interpreted from well-logs (see Well Folio; Kennard, 1996a). All wells were modelled to basement below TD based on seismic stratigraphic interpretations (see Map & Seismic Folio; Colwell et al., 1996).

Tectonic subsidence models indicate that the Petrel Sub-basin has undergone a complex, multi-phase, tectonic history (Fig. 5-1). Nine distinct subsidence phases are evident in most wells/pseudo-wells (Phases B to J), although Phase E is evident only in the outer portion of the basin (e.g., Petrel-1A, -2, Fishburn-1, Tern-1 and Penguin-1). Several of these phases are characterised by an initial rapid subsidence or uplift stage followed by a more prolonged stage of waning subsidence, a pattern consistent with extension and subsequent thermal sag (McKenzie, 1978). Some of these extension-sag cycles were interrupted by subsequent events, such that the initial rapid mechanical subsidence stage of a new extension-sag cycle has been superimposed on, and thereby masks, the slow thermal sag stage of the preceding phase.

Total tectonic subsidence ranges from 7-9 km for wells in the outer and central Petrel Deep (Petrel-1A, 2, pseudo-well site AGSO Line 7-s.p.1100), to about 5 km in the inner Petrel Deep (Fishburn-1, Tern-1, Penguin-1), about 2-3 km in the Carlton Sub-basin, Cambridge Trough, Keep Inlet Sub-basin, Kulshill and Lacrosse Terraces, and less than 2 km on the Turtle-Barnett and Cambridge Highs and Eastern Ramp margin. Given that the maximum thermal subsidence of the present ocean basins is about 6 km, a single rift event and subsequent thermal sag cannot explain the observed amount

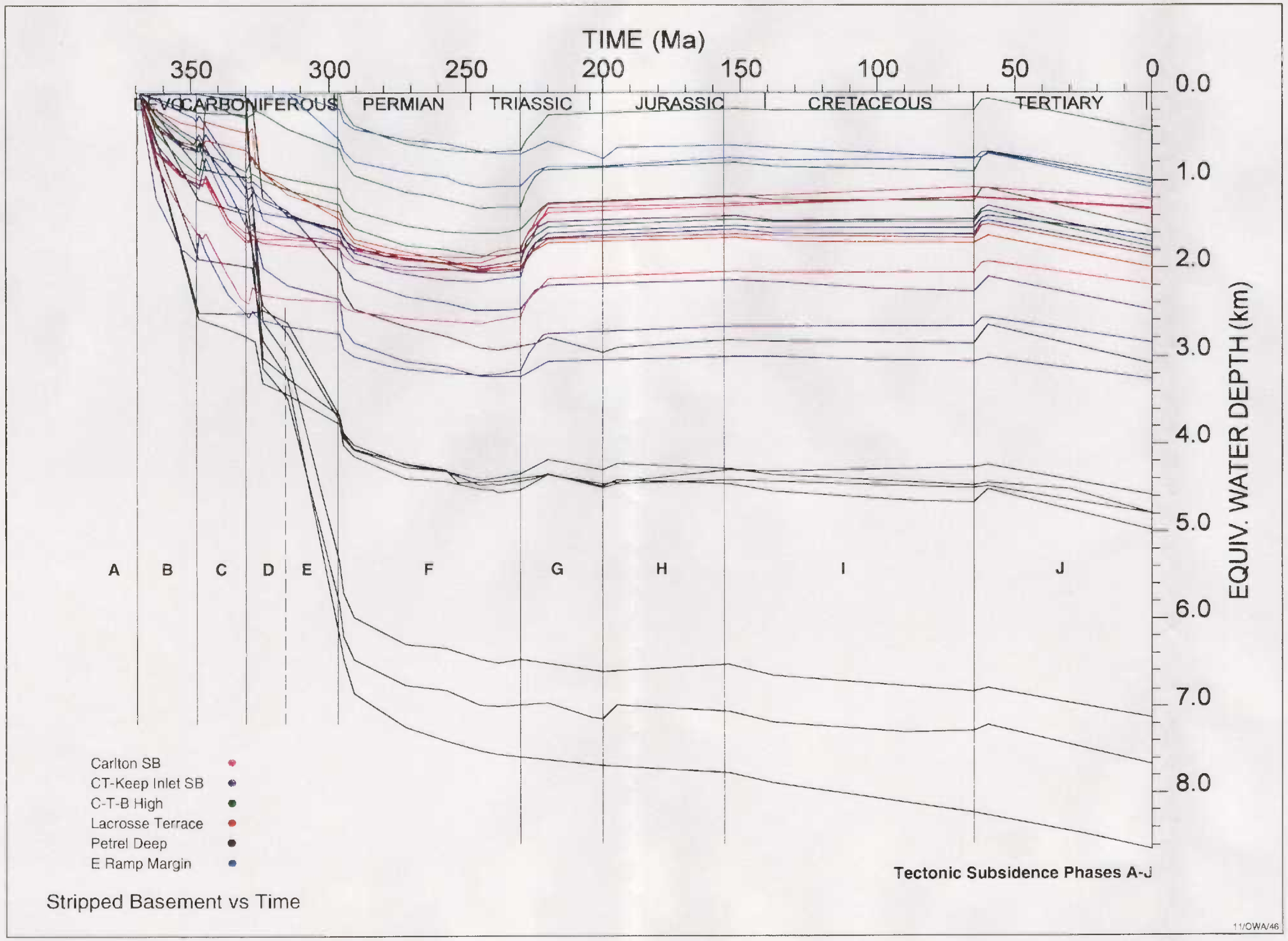

Figure 5-1. Tectonic subsidence curves for all wells/pseudo-wells modelled in the Petrel Sub-basin, showing tectonic subsidence phases A - J. SB = Sub-basin; CT = Cambridge Trough; C-T-B High = Cambridge & Turtle-Barnett Highs. (Kulshill-1 included in Keep Inlet SB).

of tectonic subsidence in the Petrel Sub-basin. A full discussion of other possible subsidence mechanisms is presented by Baxter (1996, see following section).

Phase A: Cambrian-?Silurian

An initial, 'pre-rift' Cambrian-?Silurian tectonic phase is thought to represent initial subsidence of the basin following extension and extrusion of tholeiitic basalts of the Antrim Plateau Volcanics in the Early Cambrian. However, these sediments have not been intersected in exploration wells, and the subsidence pattern during this phase has not been modelled in this study. This phase was terminated by gentle folding, regional uplift and erosion prior to initiation of the Late Devonian Petrel rift.

Phase B: Frasnian - Tournaisian

This phase is characterised by rapid subsidence following the initiation of the Petrel rift at the end of the Givetian. More detailed characterisation of this phase is only possible in wells in the onshore Carlton Sub-basin, and to a lesser extent Kulshill-1, where tectonic subsidence curves indicate very rapid initial subsidence during deposition of the Cockatoo Supersequence, and decreasing subsidence rates during deposition of the Ningbing and Langfield Supersequences (Fig. 5-1). Seismic data show clear evidence of large growth faults and rotated fault blocks during this phase (see AGSO Lines 100/1, 2 & 3, Seismic and Map Folio, enclosures 1-3). Similarly, the thickening of coarse clastic facies of the Cockatoo Supersequence against the eastern fault margin of the Carlton Sub-basin (Mory & Beere, 1988, fig. 52) indicates active fault movement at the beginning of this phase. Up to 2.5 km of tectonic subsidence occurred during this phase which appears to have affected all areas of the Petrel Sub-basin.

This 'syn-rift' extensional phase was terminated by widespread uplift and erosion in the mid Tournaisian, especially across the Cambridge and Turtle-Barnett Highs. Although the amount of uplift and erosion is difficult to gauge in most wells, clear evidence of about 1500 m of tilting, uplift and erosion of the Bonaparte Megasequence beneath the Milligans Supersequence is apparent on seismic data near Cambridge-1 (Fig. 3-8). Maturation modelling of this well is also consistent with about 1500 m erosion at the base Milligans unconformity (Maturation Modelling Report - Kennard, 1996b, Cambridge-1 maturity plot).

Phase C: late Tournaisian - mid Visean

This subsidence phase corresponds to deposition of the Milligans Supersequence, and is characterised by rapid subsidence of the Carlton Sub-basin, Cambridge Trough, Keep Inlet Sub-basin and Kulshill Terrace (Fig. 5-1). In these areas, modelling indicates about 500-1000 m tectonic subsidence during this phase, whereas subsidence was more limited across the Cambridge and Turtle Barnett Highs (about 200-300 m), and was even less on the Lacrosse Terrace and Petrel Deep.

Owing to poor chronostratigraphic subdivision of the Milligans Supersequence, it is difficult to determine the style (and hence the origin) of subsidence during this phase. However, the fact that the Milligans Supersequence comprises a major transgressive-

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regressive cycle suggests initial rapid subsidence (transgressive half-cycle) followed by slower subsidence (regressive half-cycle). Isopachs of the Milligans Supersequence (Map & Seismic Folio, plate 10) indicate that deposition of these sediments was greatest towards the centre of the Carlton Sub-basin and Cambridge Trough, and within lobes in the southern Petrel Deep. The sediments thin towards the faulted margins of the depocentres suggesting little or no fault movement during Milligans deposition. This subsidence phase is probably largely controlled by thermal sag following crustal extension during Phase B.

Phase D: late Visean - late Namurian
Phase E: latest Namurian - early Asselian

In all areas except the Petrel Deep, a typical extension-sag phase (Phase D plus E; Fig. 5-1) is recognised for the late Visean - early Asselian succession which incorporates the Tanmurra, Point Spring and Kuriyippi Supersequences. An initial stage of rapid subsidence during deposition of the Tanmurra Supersequence was controlled by renewed upper-crustal extension as indicated by (?oblique or strike-slip) faulting along the southwest margin of the Petrel Deep (see AGSO Lines 1, 2, and 3, Map & Seismic Folio). This initial extension phase was followed by a prolonged sag stage characterised by exponentially-waning subsidence.

Tectonic subsidence during this phase was greatest in the Petrel Deep (1200-2400 m tectonic subsidence during Phase D), and progressively decreases in more inboard areas (800-1000 m during Phase D-E on the Lacrosse and Kulshill Terraces, 300-500 m on the northeastern flank, Cambridge-Turtle-Barnett Highs and Cambridge Trough, and less than 200 m in the Carlton sub-basin).

Subsidence Phase E is only recognised in the Petrel Deep (e.g., Petrel-1A, -2, Fishburn-1, Tern-1 and Penguin-1, and pseudo-well sites AGSO/5-sp2800, AGSO/7-sp1100; Fig. 5-1), and corresponds to deposition of the Kuriyippi Supersequence. In these wells this phase is marked by a rapid increase in tectonic subsidence, especially in more outboard positions (e.g., Petrel-1A, -2, and pseudo-well sites AGSO/7-sp1100). This phase may be controlled by Late Carboniferous (latest Namurian) NW-SE extension in the Malita Graben which may signal the initiation of the Westralian Superbasin (Etheridge & O'Brien, 1994a,b). Flexural isostatic modelling indicates that NW-SE extension centred on an inferred major NE-SW fault in the vicinity of Gull-1 may have controlled the rapid increase in subsidence in the Petrel Deep during this phase (Baxter, 1996; this report), but any such fault is poorly imaged on existing deep seismic data. Mory & Beere (1988) also recognised local active faulting in the onshore portion of the basin at this time, based on the recognition of fan-delta facies within outcrops of the Keep Inlet Formation adjacent to uplifted fault blocks.

Phase F: late Asselian - Anisian

This phase incorporates the Treachery, Keyling, Fossil Head - Hyland Bay and Mount Goodwin - Cape Londonderry Supersequences. It is characterised by rapid early subsidence during deposition of the Treachery Sequence followed by a relatively prolonged stage (about 50 Ma.) of waning subsidence (Fig. 5-1). Tectonic subsidence during this phase ranges from 800-1200 m in the Petrel Deep, decreasing to about 400-

800 m in more inboard areas. In the Carlton Sub-basin, virtually all of the sediments deposited during this phase were subsequently stripped during the Fitzroy Movement, but modelling of maturation profiles for wells in this area suggest about 200 m tectonic subsidence during this phase.

Tectonic subsidence decreases to zero near the end of this phase, and many wells show minor uplift (less than 100 m) at the end of this phase. This apparent uplift probably indicates the first pulses of the Fitzroy Movement, but since much of the younger sediments of this phase was subsequently stripped during the Fitzroy Movement, the thickness of these eroded sediments may have been underestimated (the modelled thicknesses of eroded sediments are based on the minimal amount required to match observed maturity profiles).

The rapid and then waning subsidence pattern of this phase is consistent with renewed extension and thermal sag, but there is no clear seismic evidence of significant upper-crustal fault movement during this phase. Extension during this phase may thus have been partitioned within the lower crust beneath the Petrel Sub-basin.

This phase was terminated by uplift and erosion associated with the Fitzroy Movement, the peak of which occurred during the late Middle Triassic (Ladinian).

Phase G: Ladinian-Sinemurian (Fitzroy Movement and basin inversion)

This phase incorporates uplift and erosion during the Fitzroy Movement, and deposition of the 'syn-tectonic' Malita Supersequence (Fig. 5-1). This compressive movement affected all areas of the Petrel Sub-basin, and a substantial thickness of Permian and Early Triassic sediment was eroded from the southern and southwestern flanks of the sub-basin at this time (400-800 m on the Berkley Platform, Cambridge and Turtle-Barnett Highs, Cambridge Trough and Keep Inlet Sub-basin, and about 1000 m on the western flank of the Carlton Sub-basin). Large-scale inversion anticlines developed within the Petrel Deep at this time, and form traps for the Petrel and Tern Gas Fields.

Phase H: Sinemurian-Oxfordian

This phase of minimal net tectonic subsidence incorporates the Plover Supersequence, and appears to be uniformly expressed throughout all provinces of the Petrel Sub-basin (Fig. 5-1).

Phase I: late Oxfordian-Maastrichtian

This phase incorporates the Flamingo and Bathurst Island Supersequences, and is characterised by a moderate net increase in tectonic subsidence during the late Oxfordian to late Berriasian, followed by net minimal subsidence throughout the remainder of the Cretaceous (generally less than 100 m total net tectonic subsidence; Fig. 5-1). Detailed analysis of the subsidence history during this phase was not attempted during this study. Nevertheless, sequence stratigraphic concepts suggest two distinct pulses of rapid subsidence: the first in the late Oxfordian-Kimmeridgian corresponding to widespread transgression at the base of the Frigate Shale, and the second in the Valanginian corresponding to widespread transgression at the base of the very condensed Darwin Shale section. These pulses are correlated with the Argo and Gascoyne break-up events. This phase was terminated by regional uplift and channel incision at the base of the Tertiary Supersequence (e.g., AGSO Line 5, Map and Seismic Folio).

Phase J: Tertiary

The pattern of subsidence during this phase is not known due to inadequate chronostratigraphic subdivision of Tertiary strata in the basin. About 100-200m tectonic subsidence occurred in all areas during this phase (Fig. 5-1).

FLEXURAL ISOSTATIC MODELLING by K. Baxter (AGCRC)

Summary

As a contribution to the Petrel Sub-basin Study, models incorporating the flexural response to lithosphere extension have been applied to the sub-basin to determine the driving mechanism for the late Palaeozoic subsidence history and the development of basin geometry. Flexural isostatic modelling allows the development of basin accommodation space to be assessed using quantitative models of the loads developed during continental extensional tectonics and the associated isostatic response.

Previous workers in the Petrel Sub-basin (Gunn, 1988; O'Brien et al., 1996) have described the development of late Palaeozoic basin accommodation space as the result of massive thermal subsidence following 'Late Devonian - Early Carboniferous' rifting. Following both one- and two-dimensional thermal modelling of the basin, as well as isostatic modelling of the geometric and flexural isostatic response of the basin to deformation, this study concludes that a thermal subsidence mechanism is insufficient to describe the extreme sediment thicknesses and subsidence rates in the late Palaeozoic. An alternative model is proposed in which the Late Devonian - Early Carboniferous basin geometry is the result of the flexural response to upper crustal deformation. This includes a component of sub-resolution faulting within the basin axis allowing the stepping down of the basin flanks and the development of a 'sag' geometry. The development of small-scale deformation in the basin axis is considered to be the result of an oblique extension direction associated with a velocity discontinuity in the basin axis. It is proposed that in the Late Carboniferous, the development of NW-SE extension associated with the development of the Westralian Superbasin allowed the evolution of a large NE-SW trending normal fault at the northern extremity of the Petrel Sub-basin in the vicinity of Gull-1, and that the SE throw on this fault allowed the development of basin accommodation space. From these models, the NE-SW trending seismic lines across the basin are considered to represent oblique dip lines to Late Devonian - Early Carboniferous oblique extension and strike lines to Late Carboniferous extension, as opposed to representing pure dip lines as originally supposed.

Methodology

The methodologies employed during this study include both one- and two-dimensional modelling. The principles and methodology behind the computations used in the study are described in detail by Baxter (1996). One-dimensional models assume that loading is supported by local isostasy and as such represent the maximum isostatic response to lithospheric loading. These represent the extreme end-member models to two-dimensional models which include consideration of the flexural isostatic response. These allow loads to be supported by a lateral component of lithosphere flexural strength, reducing the vertical response to loading.

The flexural response of the continental lithosphere during extension is known to control the geometry of sedimentary basins. Mechanical unloading during upper crustal extension generates basin accommodation space and the associated buoyancy force from this unloading generates the characteristic uplift of footwall blocks (e.g. Weissel & Karner, 1989). Additional isostatic effects due to lower crust and lithospheric mantle thinning may generate a less significant loading on the syn-rift basin development, with the longer term re-equilibration of the thermal lithosphere driving post-rift basin subsidence. Basin geometry may be amplified by loading due to sediment infill, compaction of underlying sediment units, post-rift thermal subsidence, and rises in sea-level; and can be destroyed by effects of erosion and the associated isostatic rebound, and falls in sea-level. The forward model incorporates these effects in order to build a two-dimensional model over time of the development of basin accommodation space and the associated sediment infill to generate the observed basin geometry.

Two-dimensional forward models are used to model the observed deformation on AGSO seismic Lines 100/3 and 100/5 and the associated flexural response to upper crustal faulting and lower crustal and lithospheric mantle pure-shear stretching. The models are applied to backstripped and decompacted two-dimensional sections of the original seismic interpretation 'rewound' to particular time intervals. This allows the model to assess the mechanisms responsible for the development of sediment accommodation space within the time intervals for stratigraphic units. One-dimensional thermal models are also applied as these represent simple and computational time efficient models to test the end-member flexural response (i.e. local isostasy) and hypotheses of thermal subsidence.

Results

A full description of the results of this work is given by Baxter (1996). This summary represents the main results from this study relating to the development of Late Devonian to Late Carboniferous basin geometry and subsidence history, and does not discuss in detail the methodology and derivation of the final models. The models are applied to line 100/03 to define the Late Devonian - Early Carboniferous basin geometry, and to line 100/05 to define the Late Carboniferous basin geometry.

Late Devonian (Frasnian) - Early Carboniferous (Tournaisian) rifting (line 100/3)

Figure 5-2a shows a 'default' model for the Late Devonian - Early Carboniferous rift geometry in which faults observed from seismic data are input into the model. The upper crustal extension is balanced in the lower crust and lithospheric mantle by pure-shear stretching, which also controls the degree of syn-rift perturbation of the thermal lithosphere and drives post-rift thermal subsidence as the thermal perturbation re-equilibrates over time. This model generates a half graben geometry in which the area of maximum basin thickness is associated with the location of basement faults. The amount of lithosphere stretching in the model is controlled by the amount of upper crustal extension and has a maximum of $\beta=1.15$. This model does not describe the development of the 'sag' offset from the faulted SW basin flank. However, applying an additional component of pure-shear deformation in the lower crust and lithospheric mantle and offsetting this beneath the main basin axis may allow the development of the observed basin geometry up to the base Kuriyippi Supersequence (Figure 5-2b). It should be stressed here that the development of this 'sag' geometry is not a direct consequence of thermal subsidence. The principle lithospheric load to generate this basin space is driven by lower crustal thinning and the replacement of lower crustal rocks by denser lithospheric mantle rocks. This model also necessitates a relatively low flexural rigidity (Te < 5.0 km) in order to allow the lower crustal loading to dominate over the flexural response to unloading generated by normal faulting on the SW flanks of the basin.

The model in Figure 5-2b represents a low flexural strength model (Te = 5.0 km) in which Late Devonian to Early Carboniferous basin space is developed during rifting as a consequence of increased lower crustal thinning (pure-shear) relative to the amount of extension in the upper crust (simple-shear). This generates a large discrepancy between upper crustal faulting as interpreted from seismic data which has an extension of ~15 % and the required degree of lower crustal stretching which has an extension of ~270 %. Although depth dependant stretching models have been proposed for continental extension by previous workers (e.g. Royden & Keen, 1980), the discrepancy described above is considered extreme.

Carboniferous thermal subsidence

Both one- and two-dimensional models have been applied to seismic line 100/3 in order to test whether the 'sag' basin geometry may be a consequence of Late Devonian - Early Carboniferous extension followed by thermal subsidence as previously proposed. This modelling has demonstrated that the observed sediment units cannot be generated with either flexural or local isostatic models for a range of crust and lithosphere thicknesses and thermal structures. One-dimensional modelling has also shown that multiple stretching events, which allow an increase in the thermal perturbation generated during rifting and an associated increase in the rate of post-rift thermal subsidence, cannot generate the amount of observed basin space. This process becomes even more difficult when flexural isostasy is included which acts to reduce the vertical response to loads generated by thermal re-equilibration. Therefore, a model of Late Devonian - Early Carboniferous rifting followed by thermal subsidence is not considered valid in the light of this work.

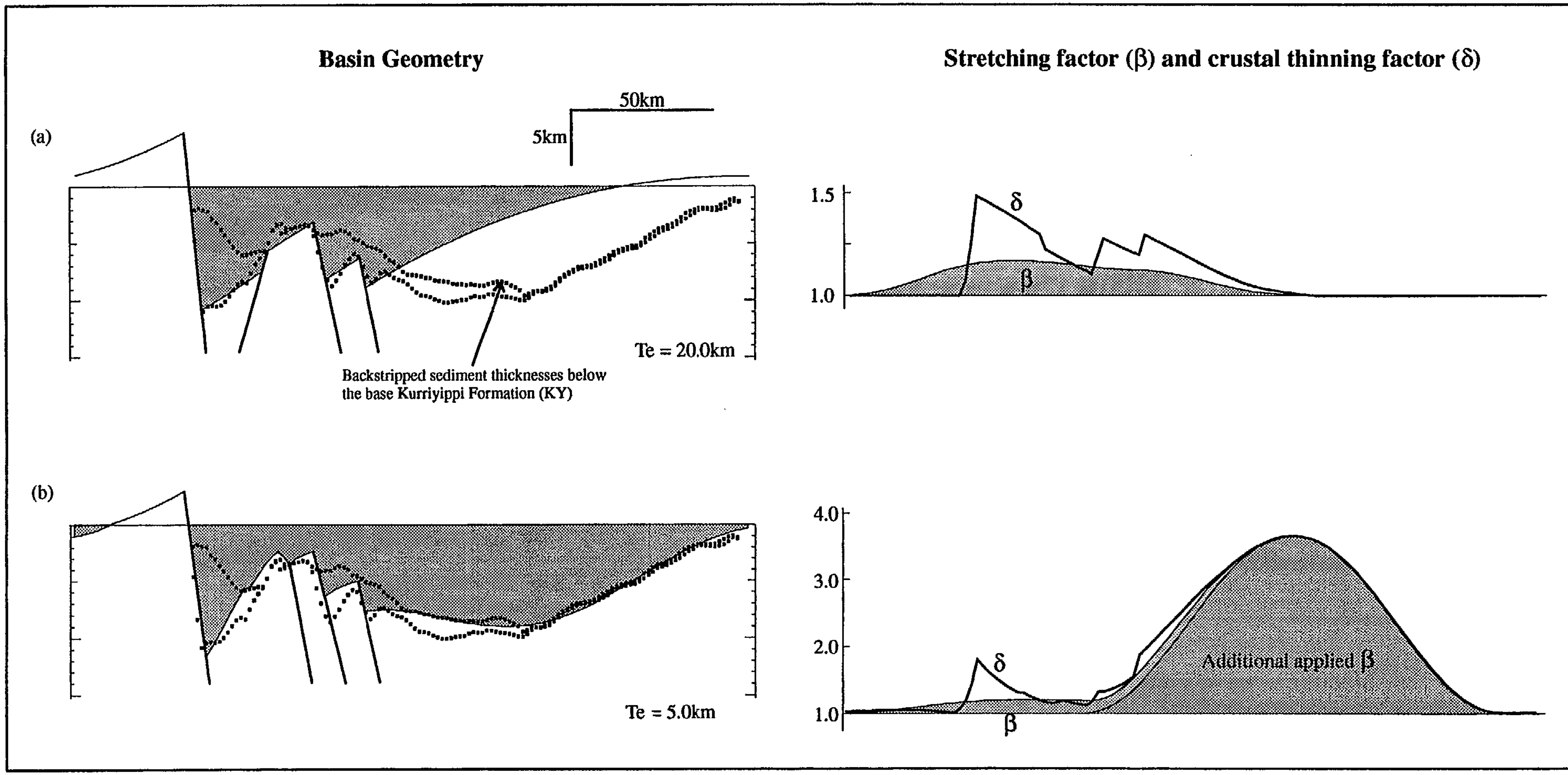

Figure 5-2. Forward model of the development of Late Devonian-Early Carboniferous basin geometry on line 100/3. Dashed line represents the backstripped and decompacted basin geometry at the base Kuriyippi Supersequence seismic horizon obtained from the AGSO seismic interpretation.
(a) ‘Default’ basin model. Extension in the upper crust is input from faults interpreted from seismic data and this is balanced by a similar amount of extension in the lower crust and lithospheric mantle. Note the development of a classic half graben geometry which does not describe the prominent basin ‘sag’ and which is developed irrespective of lithosphere flexural strength.
(b) Applying an additional component of pure-shear stretching in the lower crust and lithospheric mantle allows the development of the sag geometry if this additional stretching component is offset to the NE from the faulted basin flank. This model requires a relatively low flexural strength (in the model shown the effective elastic thickness = 5.0 km) and implies a high discrepancy between upper and lower crustal extension.

Revised Late Devonian -Early Carboniferous rift model (line 100/3)

An alternative model is proposed here in which the development of the Late Devonian to Early Carboniferous basin geometry is developed by a structural mechanism as opposed to thermal or depth dependant stretching mechanisms. Lithosphere with a high flexural strength may allow the development of increased basin space following faulting due to the longer wavelength, reduced amplitude response to unloading during faulting. This regional effect may allow the development of a 'sag' basin in the Petrel Sub-basin, laterally offset from the main rifted flank, by the down stepping of the basement on a number of low displacement faults within the basin axis and on the NE flank of the basin (Figure 5-3a). This generates an increase in the amount of crustal thinning (δ) which is known to generate basin space. If this deformation is assumed to be below the resolution of the deeper seismic data on line 100/3, then δ becomes a smoother function reflecting this and similarly also generates a smoother basin profile (Figure 5-3b). This model does not generate the high discrepancy between upper and lower crustal stretching, and as such allows extension to be balanced with depth. The small-scale faulting generates an additional 10 % extension across the basin with a total lithosphere stretching of β=1.25. However, due to the high flexural strength across the basin (Te~30 km) the amount of crustal thinning in the basin axis (δ=1.45) is increased relative to that on the faulted SW flank (δ=1.22).

Late Carboniferous subsidence (line 100/5)

The models described above for the development of the Late Devonian - Early Carboniferous rift geometry cannot predict the thickness of the Late Carboniferous Kuriyippi Supersequence as a result of post-rift thermal subsidence following rifting. Similarly, from one- and two-dimensional thermal modelling, the Kuriyippi Supersequence cannot be generated by thermal subsidence mechanisms resulting from either a single Late Devonian - Early Carboniferous rift, or by multiple lithosphere stretching during the late Palaeozoic. However, from the NW-SE seismic lines oriented along the axis of the basin, the Kuriyippi Supersequence shows a distinct thickening towards the NW. From isopachs (see Map & Seismic Folio - Colwell et al., 1996, plate 13), this thickening has a strongly elliptical profile which suggests the presence of at least one normal fault to the NW of the Petrel Sub-basin. Elliptical displacement gradients are well known from seismic faults (e.g. Walsh & Watterson, 1988) and when the flexural response is considered, produce elliptical 'saucer-shaped' basins. Figure 5-4 shows the application of the forward model to the Kuriyippi Supersequence on line 100/5. A good fit to the data is achieved by applying a large normal fault in the vicinity of Gull-1. Although the seismic quality in this region is poor, the presence of large diapirs of pre-Late Devonian salt near Gull-1, and also to the NE at Curlew-1, suggests the presence of structures which may have acted as a conduit for salt migration. On line 100/3, evidence of reflector disturbance on the NE flank of the basin in the Kuriyippi Supersequence may suggest some continuation of earlier low displacement faulting on the NE flank and this may have developed additional basin space and hence the misfit on the line 100/5 model in this area. Alternatively, this misfit may be related to: increased compaction of locally thicker pre-Kuriyippi units in the 100/3 area (see Map & Seismic folio); may reflect the

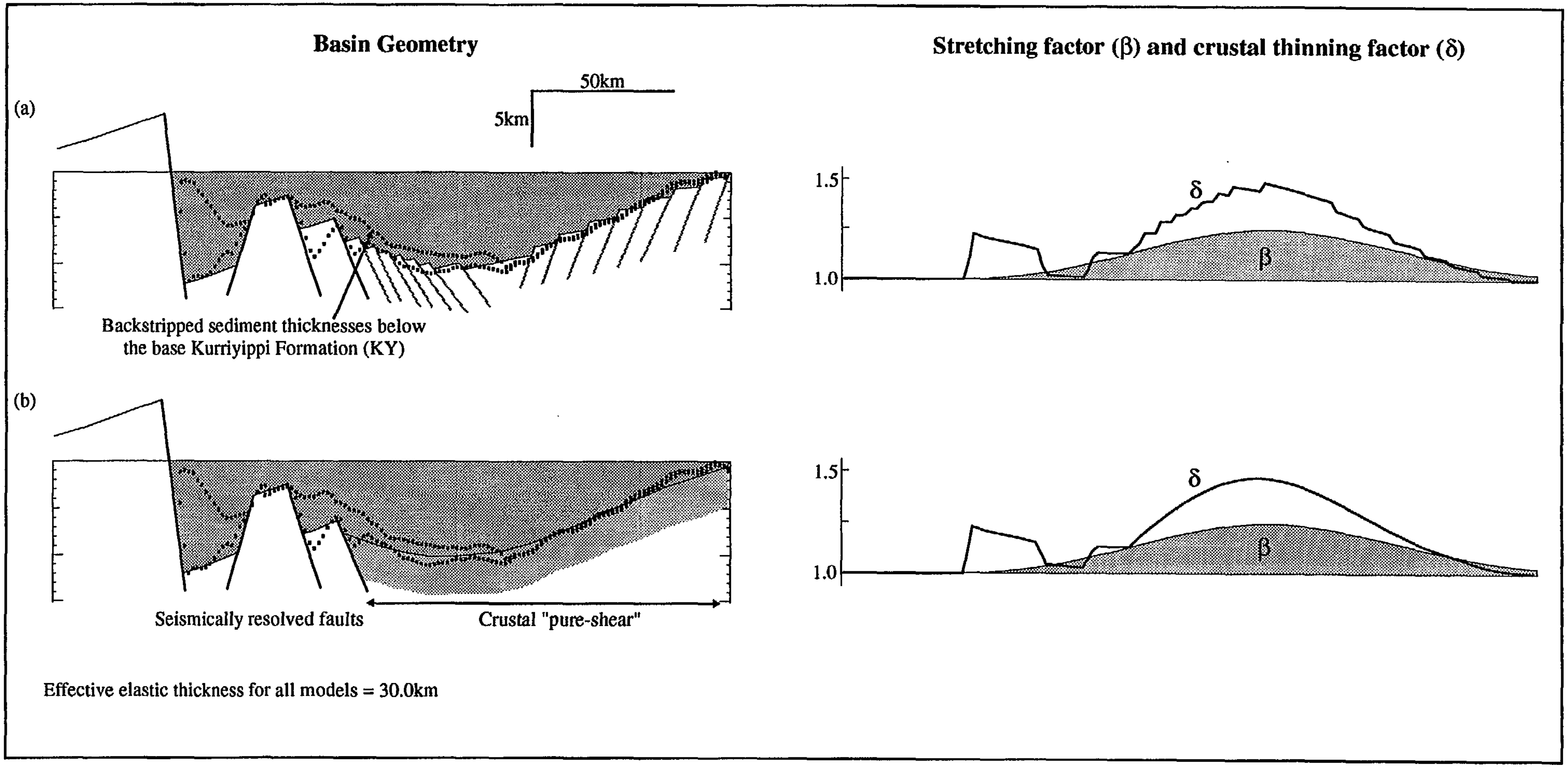

Figure 5-3. Forward model of the development of Late Devonian-Early Carboniferous basin geometry on line 100/3 including an additional component of upper crustal faulting on low displacement normal faults. Dashed line represents the backstripped and decompacted basin geometry at the base Kuriyippi Supersequence seismic horizon obtained from the AGSO seismic interpretation.

(a) Using an additional component of low displacement normal faulting within the basin axis and on the NE flank of the basin allows the downstepping of the basin and the development of the 'sag' geometry if the flexural rigidity is relatively high (in this model the effective elastic thickness = 30.0 km).

(b) If the deformation in (a) is assumed to be below the resolution of the seismic reflection data, this results in a smoothing of the crustal thinning factor, δ, and an associated smoothing in the basin geometry.

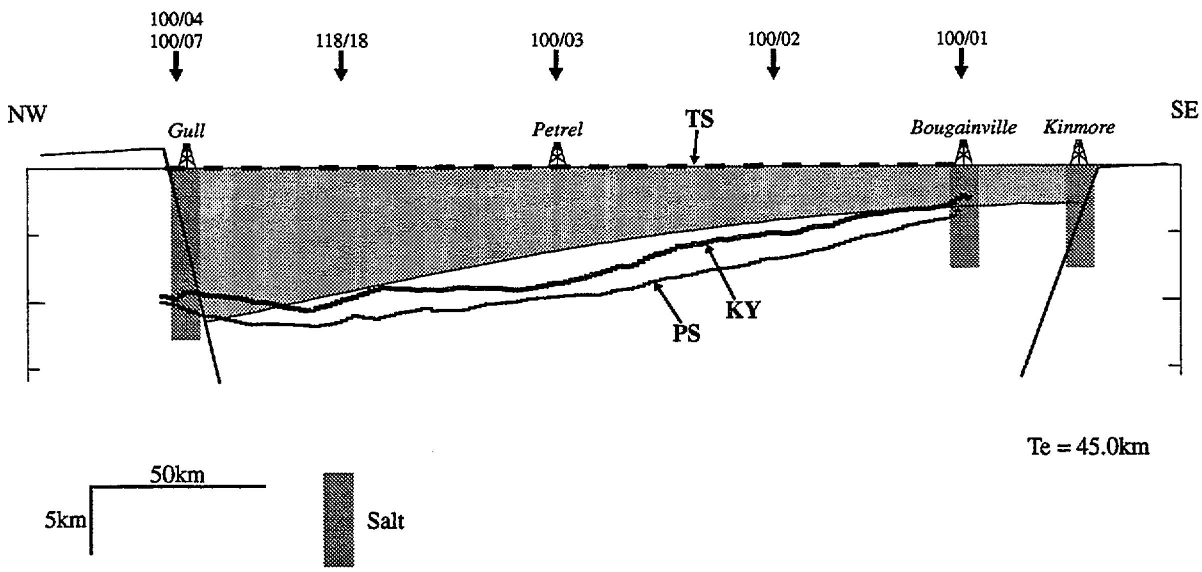

Figure 5-4. Forward model of the development of the Late Carboniferous (Kuriyippi Supersequence) basin geometry on line 100/5. Dashed line represents the backstripped and decompacted basin geometry at the base Treachery Shale seismic horizon obtained from the AGSO seismic interpretation. The basin geometry can be modelled by a large normal fault located in the region of Gull-1. An additional fault has been interpreted in the vicinity of Kinmore-1. The model necessitates a high flexural strength (model shown has an effective elastic thickness of 45.0 km). The misfit in the region of line 100/3 may be due to either some continued small-scale faulting (similar to that shown in Figure 5-3), or the result of compaction of thicker pre-Kuriyippi sediments in this region.

difficulty in interpreting deeper basin units which in some areas are poorly resolved; or may represent pre-existing basin space not totally infilled by earlier sediment units.

Additional subsidence mechanisms

Additional subsidence mechanisms can be considered for the development of basin space and include igneous intrusion and associated thermal effects, and movement within basement on the Halls Creek Mobile Zone. Although these cannot be ruled out due to the lack of evidence for or against either mechanism, some problems are apparent with these models.

Gravity modelling is often used in areas of continental extension to identify the amount of crustal thickening and potential underplating. However, these techniques are difficult to apply in areas which have undergone multiple rifting histories as the present day gravity signal is likely to include components of each rift event which cannot be identified individually by modelling. The Halls Creek Mobile Zone is known to be a pre-Cambrian feature which represents a structurally complex and highly intruded zone (see e.g. Plumb, 1990). Offshore gravity anomalies beneath the Petrel Sub-basin (Fig. 3-4) suggest the presence of intrusions which, if Late Devonian in age, may have generated a crustal load and therefore added to the subsidence history of the basin. However, similar gravity anomalies onshore relate to pre-Cambrian intrusions (Anfiloff, 1988; Plumb, 1990) and evidence for Late Devonian igneous activity is not immediately apparent. To generate the volume of melt in order to produce a crustal load, and subsequently the observed basin geometry, necessitates a melting scheme to be active over a considerable period of time - from the Late Devonian to at least the Late Carboniferous to Early Permian - and similarly evidence for this is not immediate.

Reactivation along an extension of the Halls Creek Mobile Zone during Late Devonian - Early Carboniferous rifting will not generate significant accommodation space unless a component of normal extension is also present. Although this may give the extensional structures observed on seismic data (similar to that modelled in Figure 5-2a), it does not immediately describe a mechanism in which small-scale deformation in the basin axis is laterally offset from larger-scale extensional faulting on the SW flank of the basin as necessary to generate the 'sag' geometry by a structural mechanism. It is not immediately apparent that the reactivation of a basement structure will generate either significant lower crustal thinning or thermal perturbations and therefore this model also fails to describe a mechanism for the continued subsidence of the Kuriyippi Supersequence.

Discussion and tectonic model

As discussed above, a number of subsidence mechanisms may be active associated with the development of the Petrel rift. However, a number of problems are associated with some of these models. The development of the Late Devonian - Early Carboniferous basin geometry may be described by a low flexural rigidity lithosphere in which deformation has a high discrepancy between upper crustal extension and lower crustal stretching (as in Figure 5-2b). However, a preferred model in which basin space is developed as a result of low displacement faulting within a high flexural rigidity lithosphere allows a lithospheric model which does not include high discrepancies in the amount of deformation with depth (Figure 5-3). From the modelling described above and in Baxter (1996), continued subsidence is not considered to be due to post-rift thermal subsidence and a model describing the development of the Upper Carboniferous Kuriyippi Supersequence as a consequence of NW-SE directed extension, coincident with a regional 'Visean' (dated in this report as latest Namurian) event described by previous workers (e.g. Etheridge & O'Brien, 1994b; AGSO North West Shelf Study Group, 1994) as initiating the Westralian Superbasin, is preferred.

The development of the Late Devonian - Early Carboniferous rift in which small-scale deformation is located within the basin axis may be described by a NE-SW extension direction. However, a comparison with the physical models of Withjack & Jamieson (1986) and Tron & Brun (1991) suggests that the localisation of smaller-scale deformation within the basin axis is associated with an oblique rift mechanism and the location of a basement velocity discontinuity. As described elsewhere in this report, gravity anomalies suggest that an extension of the Halls Creek Mobile Zone may exist beneath the Petrel Sub-basin axis, and this may have influenced the evolving structural style of the Petrel rift. This model does not necessarily infer a reactivation of the Halls Creek structures but rather suggests that the intrusions are associated with a weakened upper mantle which may represent a critical component in partitioning deformation during the development of oblique rift basins. A comparison with physical models suggests a Late Devonian - Early Carboniferous extension direction of approximately NNW-SSE to N-S as opposed to the NE-SW direction previously proposed, followed by a change to NW-SE extension at about the Early/Late Carboniferous boundary, i.e. base Kuriyippi Supersequence.

Conclusions

- The Petrel Sub-basin is not a consequence of massive thermal subsidence and deep lithospheric thinning.
- The Late Devonian to Early Carboniferous basin accommodation space may be described by a structural mechanism which generated a laterally offset component of low displacement faulting within the basin axis within a high flexural strength lithosphere.
- The Late Carboniferous Kuriyippi Supersequence cannot be described by a thermal subsidence mechanism and a preferred model of NW-SE extension related to a late Namurian event may generate the observed basin geometry by a large normal fault located in the vicinity of Gull-1.
- Although additional subsidence mechanisms such as igneous intrusion cannot be ruled out, there is little evidence to suggest the presence of large igneous activity during the Late Devonian - Early Carboniferous and its continuation into the Late Carboniferous and Early Permian.
- The Late Devonian - Early Carboniferous structural evolution may be related to the presence of a velocity discontinuity within the basin axis and this may represent a weakened lithosphere structure which controls the development of oblique extension, rather than the reactivation of pre-Cambrian structures.

- The models suggest a Late Devonian - Early Carboniferous extension direction of NNW-SSE to N-S and a Late Carboniferous extension direction of NW-SE.

ANALOGUE MODELLING OF BASEMENT RIFT ARCHITECTURE AND REACTIVATION by G.W. O'Brien & R. Higgins

Several analogue modelling experiments were carried out to test concepts developed from the interpretation of the deep-crustal and conventional seismic, and aeromagnetic data, in the Petrel Sub-basin. In particular, these models were designed to investigate:

- The manner in which switches in polarity of the rift between adjacent compartments takes place.
- The nature and appearance of dip, strike and oblique sections across basement hard links.
- The presence or absence of transfer faults in the syn- rift phases of the models.
- The possible stress directions which were responsible for the formation of the inversion structures.
- The manner in which the rift structures and basement hard links have reactivated under compressional stress.

The methodologies for all of the Petrel Sub-basin models were similar and all of the experiments were carried out using the deformation rig and approach described in O'Brien et al. (1996). Basement blocks were represented by clay blocks, and hard links by zones of 'less viscous' putty separating slabs of 'normal' silicon putty.

Seven analogue modelling experiments were carried out in total -- full descriptions of all seven experiments will be available in upcoming AGSO Records.

Two of the experiments are described below (descriptions after O'Brien et al., 1996); these experiments involved:

1. NE extension; sectioning on a dip azimuth.
2. NE extension, followed by NNW inversion of ~2 per cent; sectioning along dip azimuth.

The observations from these experiments were as follows:

Experiment 1: Simple NE extension; sectioning on a dip azimuth

During the early stages of extension, synthetic and antithetic faults formed synchronously, adjacent to the margins of both clay blocks and extended into respective neighbouring compartments (Fig. 5-5A-C), right across the basement hard link. With continued extension, faults developed at a distance from the clay blocks, which linked and flipped the dip-direction between the adjacent compartments (Fig. 5-5D,E). The synthetic faults extended into the neighbouring compartments and

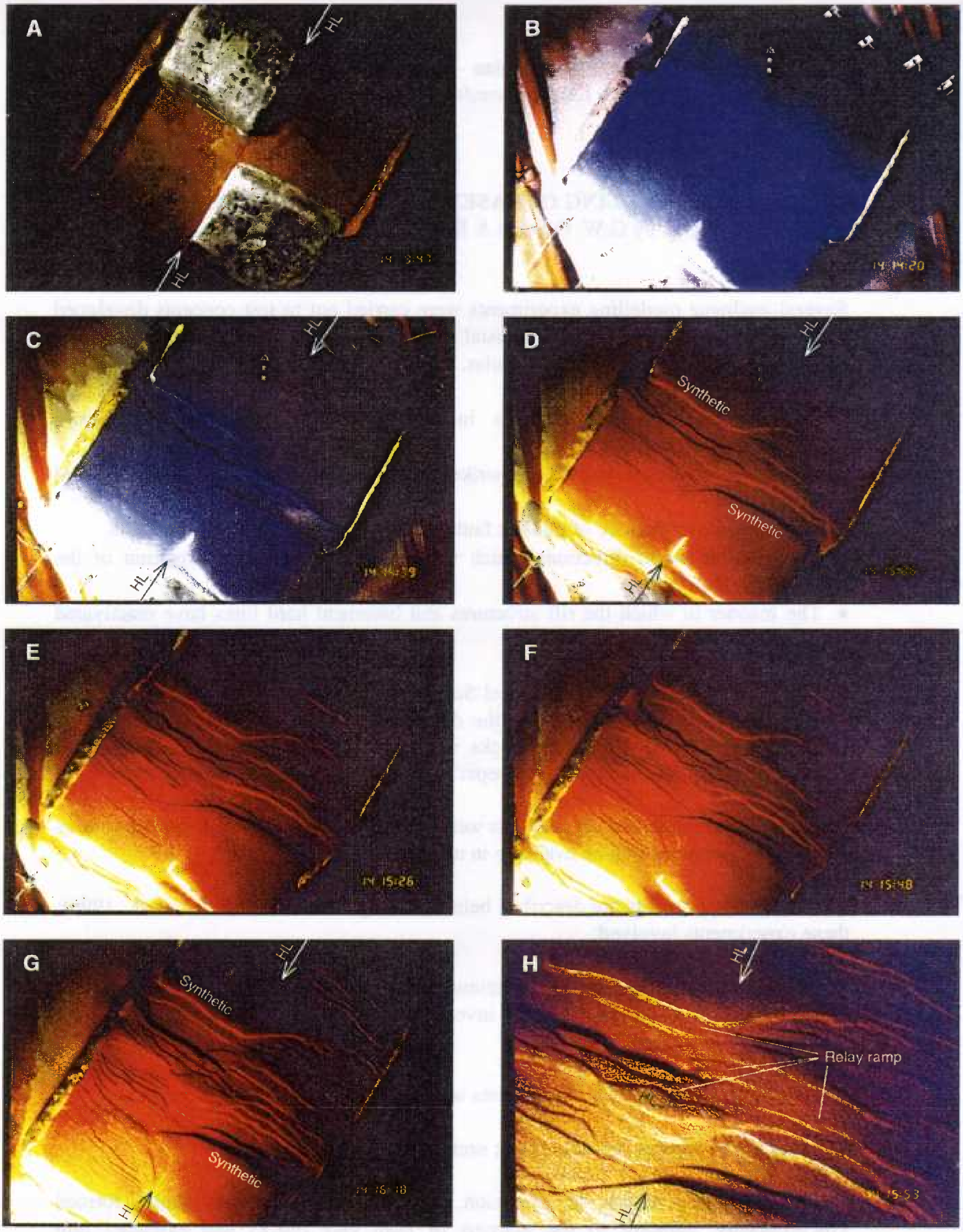

Figure 5-5. Plan views of the extensional phase of the Petrel Sub-basin model (after O'Brien et al., 1996). Position of hard link (HL) is indicated. Note the relay ramps and HLSR which extend across the hard link in view H.

typically showed a significant change of trend across the basement hard link (Fig. 5-5E-G). Faults on opposite sides of the basement hard link which had the same dip direction reduced offset as they approached each other, resulting in the formation of relay ramps between them, which transferred the strain from one fault to another. With continued extension, new faults formed adjacent to each clay block, with these new faults becoming dominant, thereby reducing movement on the originally formed graben-bounding faults (Fig 5-5F,G). Antithetic faulting dominated the area distal to the clay blocks in both compartments. Both the antithetic and synthetic faulting were characterised by a rapid decrease in throw as they trended across the hard link into the adjacent compartment.

With further extension, the hard link became relatively complex compared to the areas distal to the clay margins in each compartment. Secondary antithetics developed in the area close to the hard link in each extensional compartment, with a large overlap developing between the antithetics from each compartment (Fig. 5-5H). This fault overlap created a long, thin, sub-linear horst/ridge across (ie. perpendicular to) the accommodation zone (Fig. 5-5E-H). O'Brien et al. (1996) termed this feature a hard link strike ridge or HLSR.

There is no evidence in the models that the basement hard link forms a discrete, through-going structure during the syn-rift phase. The change of rift polarity in the adjacent compartments is simply accommodated by the progressive relaying of fault throws from one side of the 'rift' to the other. However, changes in strike of the synthetic (basin margin) faults did occur across the hard link, that is, they bent away from the opposing block across the hard link.

Using the same model as shown in Figure 5-5, sections were cut at 1-2 cm intervals parallel to the extension direction. In summary, the serial sections show that the flip in the polarity between adjacent compartments takes place progressively, via the rapid relaying of fault throws from one margin to the other. The rift simply 'rolls over' from one polarity to the other across the hard link, with the transition taking place rapidly and smoothly via fault relaying, with no through-going structures being required to achieve this (see Fig. 5-6a). The only distinctive structure which develops as a result of the polarity flip is the mid-basin horst/ridge (HLSR), which occurs when the rift is largely symmetrical (ie. where the fault throws on either side of the extensional system are almost equal), within the zone of fault overlap (Fig. 5-5H). This feature actually trends along the basin axis, almost perpendicular to the basement hard link. It would also be orthogonal to any 'transfer faults zones' that would be interpreted using a simple, orthogonal, Gibbs-type extensional model.

Experiment 2: NE extension, followed by NNW inversion of ~2 per cent; sectioning along dip azimuth.

The wrench-related anticlines in the Petrel Sub-basin are interpreted to have formed in the Late Triassic (O'Brien, 1993; O'Brien et al., 1993; Etheridge and O'Brien, 1994; O'Brien et al., 1996) or Middle Triassic (Ladininan)-Early Jurassic (Sinemurian) (this study), contemporaneous with the Fitzroy Movement in the Canning Basin (Forman & Wales, 1981; Horstman, 1984), with a probable shortening direction which ranged between NS to NNW (Etheridge et al., 1991). To test these ideas, analogue modelling

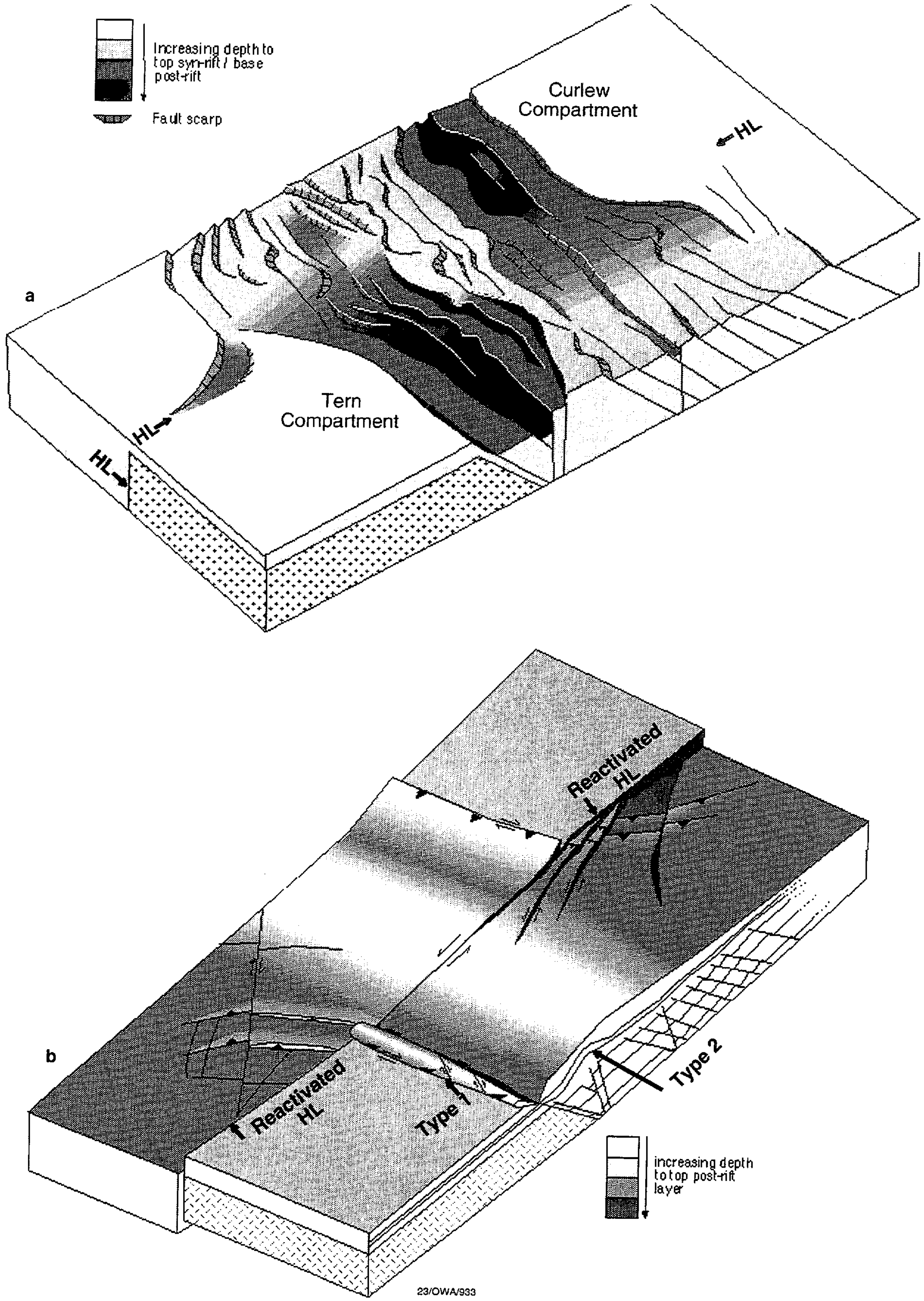

Figure 5-6. Oblique, three-dimensional views at the end of the extensional phase (a) and at the end of the inversional phase (b) (after O'Brien et al., 1996). Under extension, the intra-basinal hard link acts simply to relay the faults, resulting in the development of topographic highs along the hard link and in the centre of the basin (HLSR). Both are potential catchments for fluids migrating from the depocentres. Under inversion, the basement hard link is strongly reactivated and produces through-going structures which form both traps and facilitate vertical fluid migration. Such structures could be erroneously interpreted as transfer faults.

experiments were carried out which incorporated compression directions spanning from NNE to NNW. The NNW compression direction produced structures which were very consistent with those observed in the Petrel Sub-basin, whereas NE-NNE compression produced geometries at odds with those observed.

Following extension experiment 1, the model was shortened by about 1-2 per cent from the NNW, which resulted in the reverse and strike-slip reactivation of the large displacement faults. Subsequent snapping of the rubber sheet then resulted in very minor (<1 per cent) additional NS compression. This compression resulted in the formation of oblique-thrust faults that offset the earlier formed, reactivated structures.

Serial sectioning of the inverted model reveals the manner in which the assorted faults and compartments have reactivated. The simple large displacement fault/opposing ramp pair within the middle of the SSE compartment is largely unreactivated. However, reactivation progressively increases as the fault displacement is relayed to the opposing margin. Tight, Type 1 structures (compare with Lacrosse-1 and Lesueur-1) developed over the basin margin faults, whereas broader Type 2 anticlines (see Tern and Penguin) formed over the major antithetic faults.

The amplitude of these individual structures decreases into the basement hard link (where the fault displacement is largely equally distributed between both sides of the rift), although this region is one of broad uplift. This is consistent with the general lack of reactivation seen on line 118/18, and probably simply indicates that the parts of the faults with the greatest displacements reactivate the most. As the 'rift' polarity flips or rolls over into the NNW compartment, the reactivated structures are relayed from the left hand side of the model to the right.

Sectioning revealed that the basement hard link had deformed during inversion. In the centre of the model, the basement feature bent towards a higher intersection angle with the bulk compression direction. It is likely that the northern clay block forced the northern portion of the basement feature southwards and the southern clay block pushed the southern portion northwards. The middle portion of the basement feature would have been unaffected by the clay blocks, resulting in slight clockwise rotation. Sectioning also revealed that both clay blocks were rotated anti-clockwise by a few degrees during inversion.

Observations based upon both the extensional and inversional phases are summarised in Figure 5-6a & b respectively.

SUMMARY compiled by J.B. Colwell & J.M. Kennard

A summary of the main events that have controlled the development of the Petrel Sub-basin is presented in Table 5-1. Our current understanding of the major aspects of the basin development is summarised as follows:

- The Petrel sub-basin has undergone a complex structural and stratigraphic history spanning the Early Cambrian to the present. 10 distinct basin phases (A-J) are identified.
- The sub-basin was initiated by crustal extension and tholeiitic extrusion in the Early Cambrian, followed by crustal sag throughout the Cambrian and ?Ordovician-Silurian (Basin Phase A).
- Major rifting and upper-crustal extension occurred in the Late Devonian-earliest Carboniferous (Basin Phase B). The subsequent sag-dominated Carboniferous-Permian history was punctuated by a series of renewed upper and/or lower crustal extension-sag cycles (Phases C-F).
- Regional compression (Fitzroy Movement), dated in this study as Ladinian - Sinemurian, reactivated faults along the basin margins (mainly in the southwest) and produced a series of inversion anticlines and monoclines within the basin fill (commonly above basement blocks or fractures), including the traps of the Tern and Petrel gas/condensate fields. Following the Early Jurassic, the sub-basin mainly underwent slow sag.
- The Petrel sub-basin is underlain by complex crust. A high-density zone (possibly resulting from the intrusion of igneous material into the lower crust and Precambrian Kimberley Block) underlies much of the central part of the basin. This may reflect the offshore continuation of the Halls Creek Mobile Zone, which was probably re-activated throughout the Palaeozoic. This zone of weakened/brittle crust, together with a series of basement fractures ('hardlinks'), have exerted a significant control on the location within the sub-basin of major depocentres and basement highs.
- Thermal modelling of the basin, as well as modelling of the geometric and isostatic response of the basin to deformation, indicate that the previously accepted concept of a single phase of rifting followed by thermal sag cannot explain the extreme thickness and subsidence history of the late Palaeozoic sediments in the Petrel Deep. It is proposed that the Late Devonian - Early Carboniferous basin geometry is the result of the flexural response to upper-crustal deformation, including a component of sub-resolution faulting along the basin axis above the offshore Halls Creek Mobile Zone. Following this deformation, the Late Carboniferous basin accommodation space was largely created as a result of movement on a large NE-SW trending normal fault located at the northern extremity of the sub-basin in the vicinity of Gull-1. The development of this fault is attributed to initiation in the latest Namurian of NW-SE extension associated with the development of the Westralian Superbasin.

Table 5-1. Event History for the Petrel Sub-basin

AGE Ma*		EVENT	EVIDENCE
525-515	Early Cambrian	Extension, and sub-aerial extrusion of tholeiitic basalts of Antrim Plateau Volcanics.	• Widespread distribution of Antrim Plateau Volcanics in region (Bultitude, 1976;Veevers, 1984).
~508	Early Middle Cambrian	Transgression and initiation of crustal sag (proto Petrel sub-basin).	• Erosional contact between Antrim Plateau Volcanics and overlying shallow-marine Tarrara Fm (basal Carlton Gp.) in onshore basin (Mory & Beere, 1988).
508-487	Early Middle Cambrian - earliest Ordovician	Continued sag of proto-basin and accumulation of Carlton Group (Basin Subsidence Phase A). Possible minor rift basin development.	• Outcrop of Carlton Group on Carlton Shelf (Mory & Beere, 1988). • ?Pre-rift section within Lacrosse Terrace. • 'Old syn-rift' on Eastern Ramp margin (this report).
?487-?434	Ordovician - ?Silurian	Waning subsidence of proto-basin (Subsidence Phase A).	• Reworked Ordovician conodonts (Nicoll, 1995). • ?Ordovician salt in basin by analogy with Canning Basin (Kennard et al., 1994). • ?Pre-rift section within Lacrosse Terrace.
410-400	Early Devonian	Major compressional event resulting in uplift and erosion or non-deposition.	• Regional unconformity separating Proterozoic, Cambrian & Ordovician rocks from Upper Devonian in onshore areas (Mory & Beere, 1988). • Planation of pre-rift basement in offshore seismic (Colwell et al., 1996). • Analogy with Canning Basin ('Prices Creek Movement'; Kennard et al., 1994).
375-369	Middle-Late Devonian (late Givetian or early Frasnian)	Initiation of major phase of upper-crustal extension and development of Petrel rift. Possible major movement on Halls Creek Mobile Zone (Lasseter Shear Zone) offsetting Ord Basin to south (Nicoll, 1995).	• Horsts, (half) grabens, rotated fault blocks, and Bonaparte Megasequence syn-rift relationships on offshore seismic data (Colwell et al., 1996; this report). • Analogy with 'Pillara Extensional Event' of Canning Basin (see Kennard et al., 1994). Note that oldest dated syn-rift sediments in the Petrel Sub-basin are Frasnian (see Mory & Beere, 1988). • Palinspastic reconstruction of Ord Basin against southern Petrel Sub-basin (Nicoll, 1995).

369-347	Late Devonian (Frasnian) - earliest Carboniferous (Tournaisian).	Continued upper-crustal rifting and rapid to waning subsidence (Subsidence Phase B: Bonaparte Megasequence). Rift geometry largely controlled by pre-existing basement weaknesses associated with basement fractures ('hard links'), inc. offshore continuation of Halls Creek Mobile Zone (HCMZ). Possible salt deposition in early-formed rift basins. Initiation of reef buildups in Famennian (Ningbing Group).	• Onshore geology and dating of Bonaparte Megasequence (Cockatoo, Ningbing and Langfield Groups; see Mory & Beere, 1988). • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report). • Gravity and magnetic data, and analogue modelling indicating basement influence on rift development (O'Brien et al., 1993, 1996; this report). • Late Devonian palynomorphs in salt intersected in Sandpiper-1 well (ARCO, 1971).
347-345	Early Carbon. (late Tournaisian)	Widespread uplift and erosion; reactivation of major faults; local compression. Termination of syn-rift dominated phase of basin's development.	• Marked angular unconformity at top of Zimmermann Sandstone (top Langfield Gp.) central Burt Range (Mory & Beere, 1988). • Offshore seismic & wells: erosional unconformity at top of Bonaparte Megasequence; tilting, uplift and erosion of Bonaparte Megasequence across Cambridge and Turtle-Barnett Highs (e.g. lines CB80-8, -25); gentle folding of Bonaparte Megasequence adjacent to fault at eastern end of line 100/6 (Colwell et al., 1996; this report).
345	Early Carbon. (late Tournaisian)	Start of sag-dominated phase of basin's development. 'Sag' most-likely driven by a combination of post-rift thermal cool-down, sediment loading, probable movement on basement faults, and/or lower crustal thinning.	• Offshore seismic (Colwell et al., 1996). • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report). • Flexural isostatic modelling (Baxter, 1996; this report).
345-330	Early Carbon. (late Tourn. - late Visean)	Basin Subsidence Phase C: Milligans Supersequence.	• Offshore seismic (Colwell et al., 1996). • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report).
330-329	Late Early Carboniferous (late Visean)	Down-faulting of Lacrosse Terrace; minor uplift of inboard areas (Cambridge and Turtle-Barnett Highs, Cambridge Trough and Carlton Sub-basin)	• Erosion of top of Milligans sequence in inboard areas on seismic data (Colwell et al., 1996; this report). • Thickening of shallow-marine carbonates of Tanmurra Supersequence on Lacrosse Terrace, e.g. in Lacrosse-1 (Kennard, 1996a).
329-315	Late Early Carboniferous (late Visean-Namurian)	Basin Subsidence Phase D: Tanmurra and Point Spring Supersequences. Termination of warm-water carbonates.	• Offshore seismic (Colwell et al., 1996). • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report).

			• Wells (Kennard, 1996a) and onshore geology (Mory & Beere, 1988).
315	Late Carboniferous (latest Namurian)	Possible uplift of hinterland related to ?peak of Alice Springs Orogeny. Initiation of Westralian Superbasin (Yeates et al., 1987).	• Fan-deltas shed from up-lifted fault blocks (Mory & Beere, 1988). • Interpreted regional unconformity at base Kuriyippi in onshore geology (Jones et al., 1996). • Regional geology (e.g. AGSO NW Shelf Study Group, 1994; Etheridge & O'Brien, 1994).
315-296	Late Carboniferous (latest Namurian)-earliest Permian (Asselian)	Basin Subsidence Phase E: Kuriyippi Supersequence. Rapid subsidence to NW partly due to movement on a postulated major NE-SW trending normal fault in the vicinity of Gull-1 at the northern extremity of the Petrel Sub-basin.	• Offshore seismic (Colwell et al., 1996) • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report). • Flexural isostatic modelling (Baxter, 1996; this report).
~305-296	Late Carboniferous (Stephanian)-Early Permian (Asselian)	Onset of glaciation	• Diamictites and tillites in the Treachery Sequence in Cambridge-1, Kinmore-1 and Kulshill-1 (Kennard, 1996a). • Gondwanan evidence (e.g. Frakes, 1979).
296-239	Early Permian (Asselian) - Middle Triassic (Anisian)	Basin Subsidence Phase F: Treachery - Cape Londonderry sequences.	• Offshore seismic (Colwell et al., 1996) • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report).
~265	Late Permian - ?Early Triassic	First (?localised) compressional pulses leading up to Fitzroy Movement. Deposition of temperate-water carbonates.	• Initial growth of Tern and Petrel structures at the beginning of or during Hyland Bay times on seismic line 100/3 (Colwell et al., 1996; this report) • Anticline development at end of Late Permian Hyland Bay or during Late Permian-Early Triassic Mount Goodwin times on seismic line 100/7pt 1 s.p. 1000-2200 (Colwell et al., 1996). • H4 and H5 bryozoal limestones in wells (Kennard, 1996a; this report).
~235-200	Middle Triassic (Ladinian) - Early Jurassic (Sinemurian)	Uplift, erosion, and basin inversion during the broadly N-S directed compressional Fitzroy Movement. Deposition of the 'syn-tectonic' Malita Supersequence (Basin Subsidence Phase G).	• Offshore seismic showing inversion anticlines, onlap of Malita sediments against inversion anticlines, widespread erosion of basin margins, reactivation of faults etc. (Colwell et al., 1996; O'Brien et al., 1996; this report). • Dating of basal Malita unconformity (Kennard, 1996a; this report). • Analogue modelling (O'Brien et al., 1996; this report).

			• Analogy with Fitzroy Movement of Canning Basin (Forman & Wales, 1981; Kennard et al., 1994)
~200-195	Early Jurassic (Sinemurian)	Period of erosion.	• Erosion at base of Plover sequence on offshore seismic data, particularly over inversion anticlines, e.g. line 100/3 s.p. 2000-2200 (Colwell et al., 1996).
195-155	Early Jurassic (Sinemurian)-Late Jurassic (Oxfordian)	Basin Subsidence Phase H: Plover Supersequence.	• Offshore seismic (Colwell et al., 1996) • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report).
155-65	Late Jurassic (Oxfordian)-Late Cretaceous (Maastricht.)	Basin Subsidence Phase I: Flamingo and Bathurst Is Supersequences. Some evidence from sequence stratigraphic analyses and biostratigraphy of breaks in the stratigraphic record between Plover and Flamingo, and Flamingo and Bathurst Island sequences corresponding to continental breakup which formed Argo and Gascoyne Abyssal Plains to south. Renewed deposition of warm-water carbonates during Bathurst Island Group times.	• Offshore seismic (Colwell et al., 1996) • Subsidence modelling using wells and pseudo-wells (Kennard, 1996b; this report). • Sequence stratigraphic and biostratigraphic analyses of wells (Kennard, 1996a; this report). • Carbonates in Bathurst Island Group in, for example, Curlew-1 (Kennard, 1996a). • Regional geology (e.g. AGSO NW Shelf Study Group, 1994).
~65	Earliest Tertiary	?Uplift and erosion.	• Base Tertiary erosional down-cutting, e.g. seismic line 100/5pt 2 s.p. 1700-2500 (Colwell et al., 1996).
65-0	Tertiary-Quaternary	Basin Subsidence Phase J: Undifferentiated Tertiary and Quaternary deposits.	• Little known due to inadequate chronostratigraphic subdivision.

* All ages based on AGSO Phanerozoic Timescale 1995 (Young & Laurie, 1996).

CHAPTER 6

ORGANIC GEOCHEMISTRY

by D.S. Edwards & R.E. Summons

As part of the Petrel Study, isotopic and biomarker analyses were carried out on Late Devonian, Carboniferous and Permian-reservoired oils and their inferred source rocks. Full details of these analyses and their results are given in the Petrel Study Organic Geochemistry Report (Edwards & Summons, 1996); only a summary is presented here.

Three geochemically distinct oil families are recognised in the Petrel Sub-basin: Late Devonian marine oils, Early Carboniferous siliciclastic marine oils, and Permian deltaic condensate. These crudes are assigned to the Ningbing-Bonaparte (Larapintine 3), Milligans (Larapintine 4) and the Keyling - Hyland Bay (Gondwanan 1) Petroleum Systems, respectively (Fig. 6-1).

NINGBING-BONAPARTE OILS AND SOURCE ROCKS

Late Devonian-reservoired bitumens and oil-stains found within mineral holes and onshore petroleum wells in the Carlton Sub-basin are attributed to the Ningbing-Bonaparte Petroleum System. The isotopic signature of oil stains extracted from cores in Ningbing-1 (core 4, Cockatoo Supersequence) and an outcrop of Ningbing Limestone is depleted in ^{13}C (mean δ^{13}Csat = -29 ‰). From these limited samples, the biomarker signatures show some variability indicating localised generation, probably from the Late Devonian - earliest Carboniferous marine sediments of the Bonaparte Megasequence. The oil stained Ningbing Limestone outcrop sample has a typical carbonate signature (low abundance of diasteranes, absence of diahopanes, presence of 30-norhopanes). The oil stain from Ningbing-1 contains significant concentrations of diasteranes relative to steranes as well as abundant gammacerane and 28,30-dinorhopane, inferring derivation from anoxic hypersaline calcareous mudstones.

Few geochemical analyses exist for the Late Devonian sediments in the Petrel Sub-basin, although numerous mineral exploration holes around the southern margin of the basin (Fig. 3-1) penetrate these sediments. Biomarker and isotopic analyses exist for the petroleum wells Ningbing-1 and Spirit Hill-1. At Ningbing-1, organic-rich stylolites occur in carbonates of the Ningbing Supersequence (cores 1 and 2), which also show some oil-staining. The carbonates of the Cockatoo Supersequence have TOCs up to 0.7 % but again show oil-staining, making oil-source correlations unreliable for both sequences. At Spirit Hill-1, an organic-rich, oil-prone (TOC = 1.7 %; HI = 123 $mgS_2/gTOC$) calcareous mudstone unit was identified within the Ningbing Supersequence but could not be correlated to the oil stains in outcropping Ningbing Limestone and at Ningbing-1.

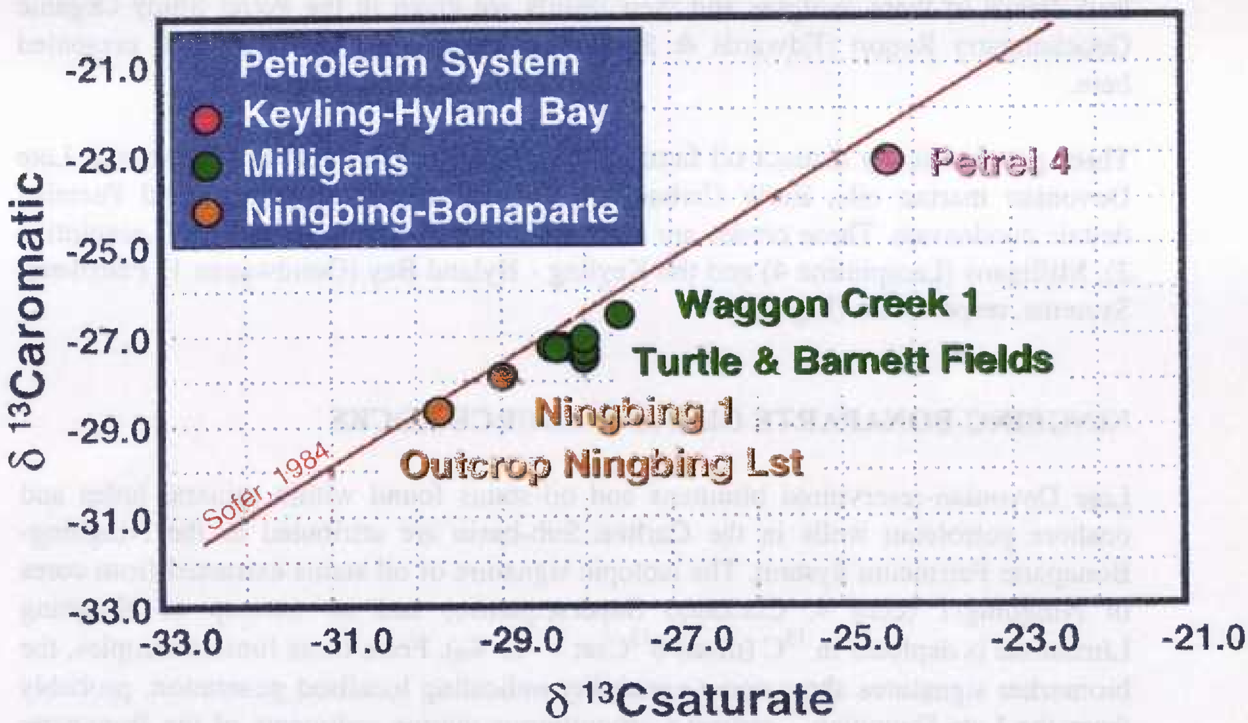

Figure 6-1. Carbon isotopic composition of Petrel Sub-basin petroleums.

MILLIGANS OILS AND SOURCE ROCKS

Oils of Early Carboniferous age have been recovered onshore at Waggon Creek-1 from the Milligans Supersequence, and offshore at Barnett-1, -2, Turtle-1 and -2 in the Milligans Supersequence and overlying Carboniferous-Permian reservoirs. These oils are characterised by light carbon isotopic signatures (mean δ^{13}Csat = -28 ‰), pristane/phytane and C_{27}/C_{29} steranes ratios approaching parity, an abundance of diasteranes and diahopanes with minor gammacerane and 28,30-dinorhopane. They also have a diagnostic tri- and tetracyclic terpane distribution, characterised by two unidentified compounds.

Severe biodegradation has altered the composition of many of these Carboniferous oils in the offshore wells, resulting in an overprint of 25-norhopanes. Gas chromatograms for some of the oils reservoired at Barnett and Turtle show both intact *n*-alkane profiles and abundant 25-norhopanes, indicating multiple phases of reservoir charging and biodegradation.

A good correlation to the Barnett, Turtle and Waggon Creek-1 oils has been made with some anoxic marine mudstones (containing Type II/III kerogen) in the Early Carboniferous Milligans Supersequence, mineral hole NBF1002 (mean TOC = 2.8 %; mean HI = 204 $mgS_2/gTOC$; location of hole shown in Fig. 3-1). However, this locality is the exception as the majority of Milligans mudstones intersected over structural highs are largely gas-prone, containing Type III/IV kerogen derived from degraded land-plants (lycopods and ferns). It therefore seems likely that the hydrocarbons reservoired at Barnett and Turtle are derived from Early Carboniferous mudstones located in the undrilled parts of the Milligans depocentres located to the north and south of the Turtle-Barnett High (see Map & Seismic Folio, plate 10; Chapter 7, Fig. 7-4).

KEYLING - HYLAND BAY OILS AND SOURCE ROCKS

Permian aged condensate is produced from the Hyland Bay sequence at Petrel-4. This condensate is isotopically enriched in ^{13}C (δ^{13}Csat = -24 ‰) and its biomarker assemblage is characterised by abundant rerranged steranes and rearranged hopanes indicating derivation from mature deltaic source rocks. This geochemical signature may allow the identification of Permian components in hydrocarbon occurrences elsewhere in the Timor Sea currently attributed to the Mesozoic Westralian Petroleum Supersystem.

Potential source rocks identified in the Keyling Supersequence and, to a lesser extent, the Hyland Bay sequence are deltaic in origin, containing predominantly terrestrial organic matter. The Early Permian Keyling Supersequence contains delta-plain coals and marginal marine shales which have good organic richness and good source quality (mean TOC = 35 %, mean HI = 230 $mgS_2/gTOC$; and mean TOC = 2.8 %, mean HI = 95 $mgS_2/gTOC$, respectively). The Late Permian pro-delta Hyland Bay sequence also has good organic richness but is largely gas-prone (mean TOC = 2 %, mean HI = 55 $mgS_2/gTOC$) and is isotopically similar to the Petrel-4 condensate.

CONCLUSIONS

This work has established likely oil-source rock correlation for the major hydrocarbon discoveries in the basin. The identification of a potential oil-prone, coaly source facies in the Keyling Supersequence warrants renewed exploration of the Gondwanan Petroleum Supersystem. Similarly, the recognition of oil-prone pods in the Milligans Supersequence at NBF1002, and the close correlation between these mudstones and the Barnett, Turtle and Waggon Creek oils implies that similar source rocks may be developed elsewhere in the sub-basin. Hence, depocentres in the central Carlton Sub-basin, Cambridge Trough and north of the Turtle-Barnett High should be considered in future exploration appraisals.

CHAPTER 7

PETROLEUM SYSTEMS

by J.M. Kennard, D.S. Edwards, J.B. Colwell, & J.E. Blevin

Three active petroleum systems are recognised in the Petrel Sub-basin, each named according to the mature source rock that underpins them:

- 'Ningbing-Bonaparte' Petroleum System (Larapintine 3)
- 'Milligans' Petroleum System (Larapintine 4)
- 'Keyling - Hyland Bay' Petroleum System (Gondwanan 1)

Liquid hydrocarbons of these systems can be readily differentiated by their carbon isotopic signature (Fig. 6-1) and biomarkers (see Organic Geochemistry Report, Edwards & Summons, 1996).

The delineation of these systems follows the concepts proposed by Bradshaw (1993) and Bradshaw et al. (1994) who defined a series of Australian-wide petroleum supersystems and systems (Larapintine, Gondwanan etc.). Detailed descriptions of these systems in the Petrel Sub-basin were originally presented by McConachie et al. (1995, 1996). The following analysis builds on these previous studies and integrates new carbon isotope and biomarker geochemical data (see Organic Geochemistry Report) and maturation models (see Geohistory Modelling report, Kennard, 1996b) with the structural, sequence stratigraphic and biostratigraphic framework defined during the 1995-1996 AGSO Petrel Sub-basin Study.

The Australian-wide supersystems and systems defined by Bradshaw (1993) and Bradshaw et al. (1994) are broader in scope than the original definition of a petroleum system proposed by Magoon & Dow (1991) and detailed by Magoon & Dow (1994); namely, a mature source rock pod and all its generated hydrocarbons. Instead, the Australian supersystems/systems are based on families of similar source rocks that extend across many basins. In addition to shared source family, unifying structural, climatic and palaeogeographic factors have been emphasised in the recognition of the Australian systems. Thus many of the systems are bounded by regional unconformities, and partly or fully equate with regional tectono-stratigraphic units (e.g., a particular mega- or supersequence). Consequently, in some cases Bradshaw et al. (1994) and McConachie et al. (1995, 1996) have attributed hydrocarbon occurrences within the Petrel Sub-basin to a particular petroleum system largely on the basis of the age and present tectono-stratigraphic setting of the hydrocarbon accumulation, rather than the generative source rock *per se*.

In the following analysis, emphasis has been re-focussed on the proven (or probable) source rock or source pod for each hydrocarbon occurrence, and the links between that source and the generated hydrocarbon accumulations (e.g., time of maturation and expulsion, migration pathway, entrapment, seal and subsequent alteration of hydrocarbon accumulations). In several cases, hydrocarbon occurrences within a single stratigraphic formation can be shown to have been generated from source rocks of markedly different age and character, and are thus attributed to different petroleum systems.

1. NINGBING-BONAPARTE PETROLEUM SYSTEM (Larapintine 3)

Definition

- Hydrocarbons generated from Late Devonian marine carbonates of the Ningbing Group and/or shales of the undifferentiated Bonaparte Formation (Fig. 7-1).
- Source rocks deposited within an equatorial epicontinental sea.
- Forms part of the Larapintine 3 Petroleum System defined by Bradshaw (1993) and Bradshaw et al. (1994).

Significant Shows

- Oil show in Ningbing-1: Good fluorescence and slight oil bleed from fractured core in the Ningbing Supersequence, and oil-stained core from the Cockatoo Supersequence. Oils derived from marine algal and bacterial enriched kerogen, probably from a marly source rock (see Organic Geochemistry Report).
- Oil shows in onshore mineral holes in Ningbing Limestone (Laws, 1981, fig. 4). Oils derived from marine algal and bacterial enriched kerogen, from a carbonate source rock (see Organic Geochemistry Report).
- Gas in Garimala-1: DST 2 recorded a gas flow of 0.75 MMCFD decreasing to 0.47 MMCFD over a 2 hour period from the Langfield Supersequence. Alternatively, this gas may have been sourced from the Milligans Formation, as suggested by Laws (1981).

Source Rock

Two possible source rock units:

- Late Devonian marine algal carbonates, probably inter-reef facies of the Ningbing Supersequence (cf. Pillara Limestone, Canning Basin). Organic-rich units (micritic shale, lignitic shale, biomicrite) reported in onshore mineral holes by Le Tran et al. (1980), but stratigraphic sequence uncertain.
- Late Devonian basinal marine shales of the Bonaparte Megasequence (Bonaparte Formation facies). Rare organic-rich shales identified in Spirit Hill-1 (TOC = 1.73%, HI = 123) which are marginally mature, with gas and minor liquid potential (however, mean TOC = 1%, mean HI = 53).

Distribution

- Distribution of potential source rocks and generated hydrocarbons poorly known, but the encompassing 'syn-rift'-dominated Bonaparte Megasequence occurs throughout the Carlton Sub-basin, Cambridge Trough, Keep Inlet Sub-basin, Kulshill Terrace, Cambridge and Turtle-Barnett Highs, Lacrosse Terrace and parts of the Petrel Deep (see Plate 9, Map & Seismic Folio). Source potential of possible 'older syn-rift' section on Eastern Ramp margin is unknown.

Reservoir

- Fluvial and fan-delta sandstones of the Cockatoo Supersequence (onshore outcrops; 16% porosity and 71 mD in Ningbing-1).

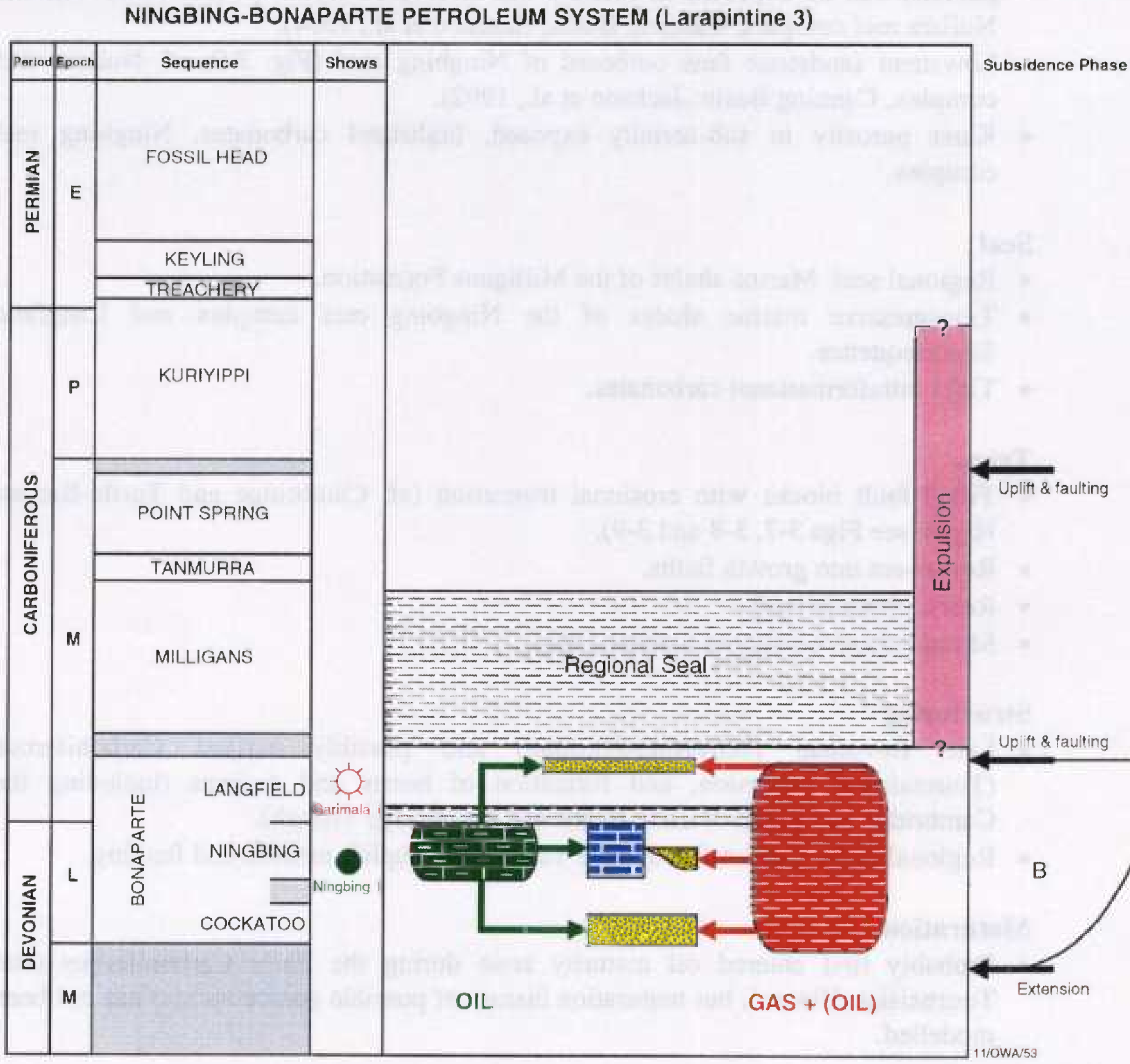

Figure 7-1. Schematic diagram of the Ningbing-Bonaparte Petroleum System.

- Shallow-marine sandstones of the Langfield Supersequence (gas flow in Garimala-1).
- Transgressive algal reefs and pinnacle reefs, Ningbing reef complex (Fig. 7-2). Poor primary porosity in reef-margin facies, but dolomitisation and secondary porosity can be expected in forereef and backreef carbonates (cf. Blina Oilfield, Nullara reef complex, Canning Basin; Kennard et al., 1994).
- Lowstand sandstone fans outboard of Ningbing reef (Fig. 7-2; cf. Nullara reef complex, Canning Basin; Jackson et al., 1992).
- Karst porosity in sub-aerially exposed, highstand carbonates, Ningbing reef complex.

Seal
- Regional seal: Marine shales of the Milligans Formation.
- Transgressive marine shales of the Ningbing reef complex and Langfield Supersequence.
- Tight intraformational carbonates.

Traps
- Tilted fault blocks with erosional truncation (cf. Cambridge and Turtle-Barnett Highs; see Figs 3-7, 3-8 and 3-9).
- Roll-overs into growth faults.
- Reefs, pinnacle reefs.
- Mounded and onlapping lowstand fans.

Structuring
- Late Devonian (?Givetian-Frasnian) and possibly earliest Carboniferous (Tournaisian) extension, and formation of horsts and grabens (including the Cambridge and Turtle-Barnett Highs and Cambridge Trough).
- Regional Early Carboniferous (late Tournaisian) uplift, erosion and faulting.

Maturation
- Probably first entered oil maturity zone during the Early Carboniferous (late Tournaisian-Visean), but maturation history of possible source rock(s) has not been modelled.

Expulsion & Migration
- Probably Early Carboniferous (Visean-Namurian), but expulsion history of possible source rock(s) has not been modelled.

Critical Success Factors:
- Adequate source rock has not been demonstrated.
- Poor, or poorly known, reservoir quality.
- Preservation of old (pre-Early Permian) hydrocarbon accumulations during Middle-Late Triassic Fitzroy Movement.

Failures
- Tight carbonates, Ningbing reef complex (Keep River-1, Ningbing-1, Weaber-1).

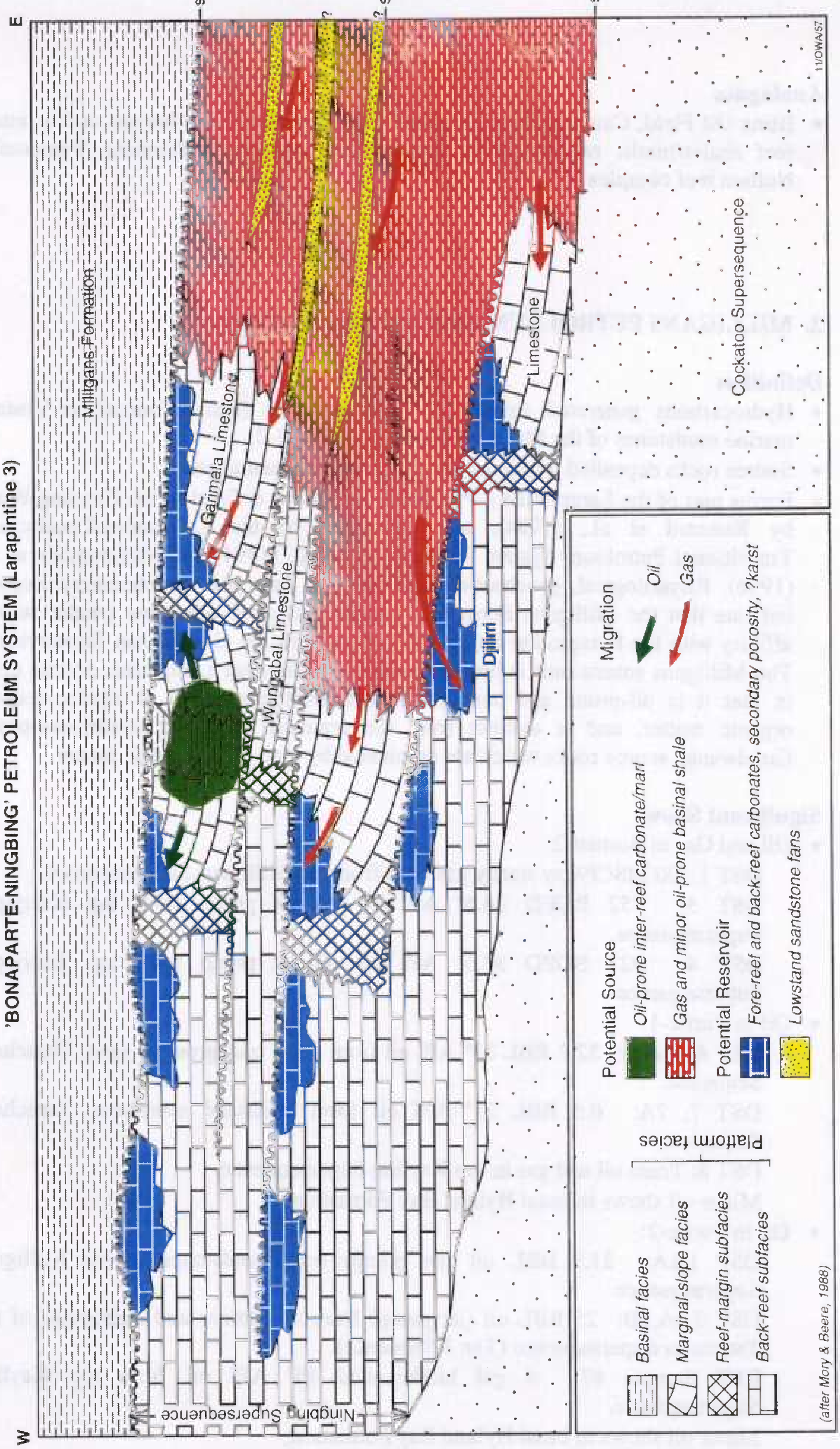

Figure 7-2. Ningbing reef plays (adapted from Mory & Beere, 1988).

Analogues

- Blina Oil Field, Canning Basin (sourced from Frasnian Gogo basinal and/or inter-reef shales/marls, reservoired in transgressive platform carbonates, Famennian Nullara reef complex).

2. MILLIGANS PETROLEUM SYSTEM (Larapintine 4)

Definition

- Hydrocarbons generated from Early Carboniferous (latest Tournaisian-Visean) marine mudstones of the Milligans Formation (Fig. 7-3).
- Source rocks deposited within an equatorial epicontinental sea.
- Forms part of the Larapintine 4 Petroleum System as defined in the Canning Basin by Kennard et al., (1994), and equivalent to the Larapintine/Gondwanan Transitional Petroleum System of Bradshaw et al. (1994) and McConachie et al. (1996). Palynological, geochemical and isotopic data (see Geochemistry Report) indicate that the Milligans Formation and its generated oils have greater source affinity with the Larapintine Supersystem than with the Gondwanan Supersystem. The Milligans source unit is broadly comparable to other Larapintine source units in that it is oil-prone and contains a significant proportion of marine-derived organic matter, and is distinct from the typically gas- and condensate-prone Gondwanan source rocks which are dominated by land-plant organic matter.

Significant Shows

- Oil and Gas in Barnett-2:
  - DST 1: 90 MSCF/day steady gas flow from top Milligans Supersequence.
  - DST 3: 752 BOPD 38.6° API oil on jet pump from top Kuriyippi Supersequence.
  - DST 4: 921 BOPD 38.6° API oil on jet pump from top Kuriyippi Supersequence.
- Oil in Turtle-1
  - DST 4, 5 & 6: 32.7 BBL 33° API oil from basal transgressive sand, Treachery Sequence.
  - DST 7, 7A: 0.5 BBL 31° API oil from highstand sandstone, Treachery Sequence.
  - DST 8: Trace oil and gas in top Keyling Supersequence.
  - Minor oil shows in basal Hyland Bay Formation
- Oil in Turtle-2:
  - DST 1,1A: 21.9 BBL oil (jet pump) from sandstones of the Milligans Supersequence.
  - DST 2,2A,2B: 25 BBL oil (jet pump) from sandstones and carbonates of the Tanmurra Supersequence (Tan 1 Sequence).
  - RFT Sample #7: 4 gal biodegraded 15° API oil from top Keyling Supersequence.
  - Minor oil shows in basal Hyland Bay Formation.

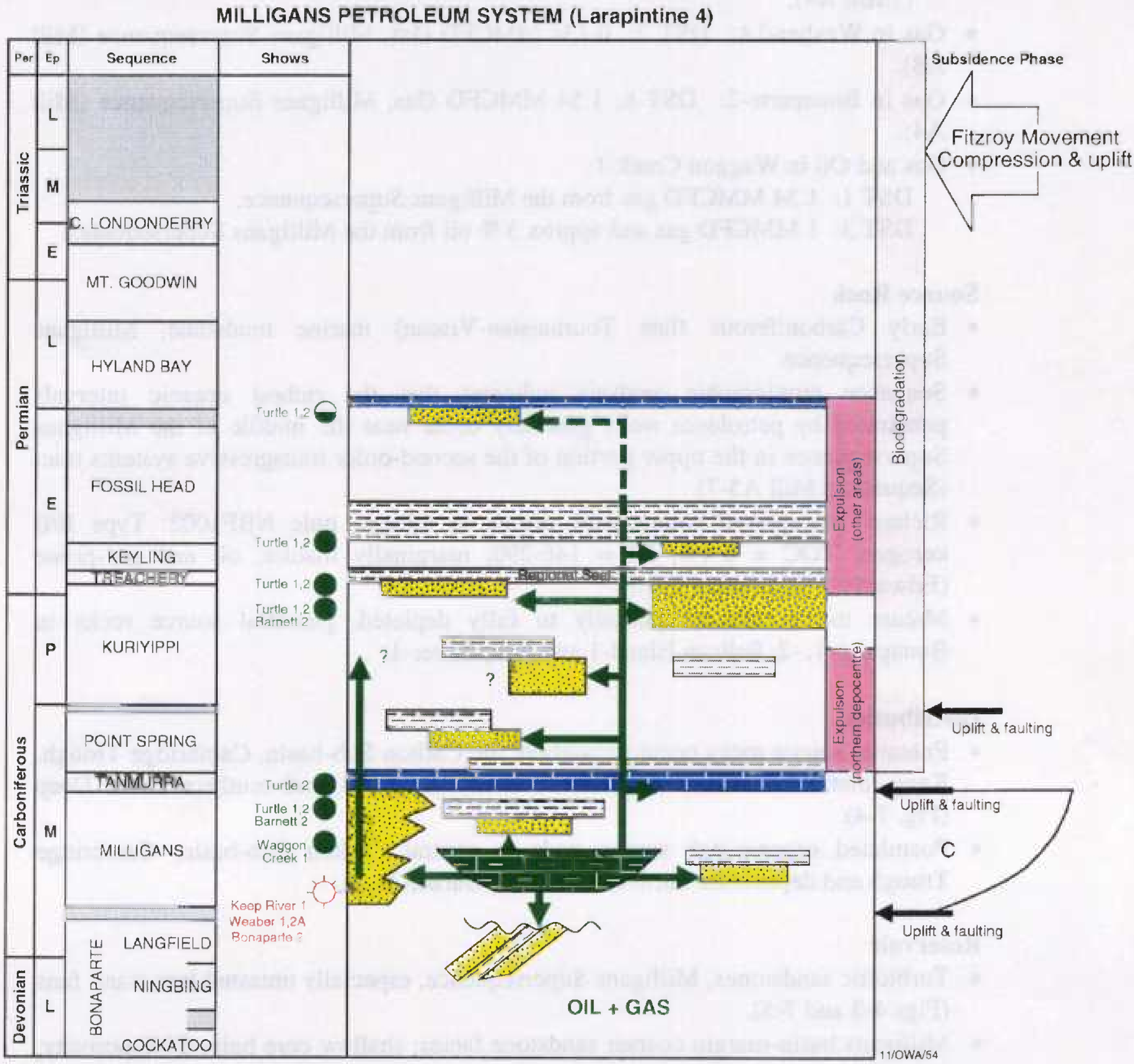

Figure 7-3. Schematic diagram of the Milligans Petroleum System.

- Gas in Keep River-1: DST 4; 3-0.2 MMCFD gas from the upper Langfield and lower Milligans Supersequences.
- Gas in Weaber-1 (re-entered 1985):
  DST-1: 2 MMCFD dry gas, 'Enga Sandstone', Milligans Supersequence (?Mill A4).
  DST-4: 3.6-4.5 MMCFD gas, 'Enga Sandstone', Milligans Supersequence (?Mill A4).
- Gas in Weaber-2A: DST 2; 0.134 MMCFD Gas, Milligans Supersequence (Mill A8).
- Gas in Bonaparte-2: DST 6; 1.54 MMCFD Gas, Milligans Supersequence (Mill A4).
- Gas and Oil in Waggon Creek-1:
  DST 1: 1.34 MMCFD gas from the Milligans Supersequence.
  DST 3: 1 MMCFD gas and approx 3 % oil from the Milligans Supersequence

Source Rock

- Early Carboniferous (late Tournaisian-Visean) marine mudstone, Milligans Supersequence.
- Sequence stratigraphic analysis indicates that the richest organic intervals penetrated by petroleum wells generally occur near the middle of the Milligans Supersequence in the upper portion of the second-order transgressive systems tract (Sequences Mill A5-7).
- Richest recognised source rock occurs in mineral hole NBF1002: Type II/II kerogen, TOC = 2-4%, HI = 146-290, marginally mature, oil and gas-prone (Edwards & Summons, 1996).
- Mature to overmature, partially to fully depleted, potential source rocks in Bonaparte-1, -2, Pelican Island-1 and Keep River-1.

Distribution

- Potential source rocks occur throughout the Carlton Sub-basin, Cambridge Trough, Keep Inlet Sub-basin, Kulshill and Lacrosse Terraces, and southern Petrel Deep (Fig. 7-4).
- Postulated organic-rich source pods in central Carlton Sub-basin, Cambridge Trough and depocentre north of the Turtle-Barnett High.

Reservoir

- Turbiditic sandstones, Milligans Supersequence, especially untested low-stand fans (Figs 4-3 and 7-5).
- Milligans basin-margin coarser sandstone facies; shallow core holes 25% porosity, 500 mD.
- Carbonates within the Tanmurra Supersequence; possible secondary porosity within ooid shoals and fractured carbonates; upper-slope carbonate mounds (Fig. 4-5).
- Fluvio-deltaic sandstones, Point Spring Supersequence.
- Highstand fluvial sandstones, near top Kuriyippi Supersequence.
- Basal transgressive shoreface sandstones, Treachery Sequence.
- Truncated 'syn-rift' Langfield/Bonaparte sandstones within tilted horst blocks.

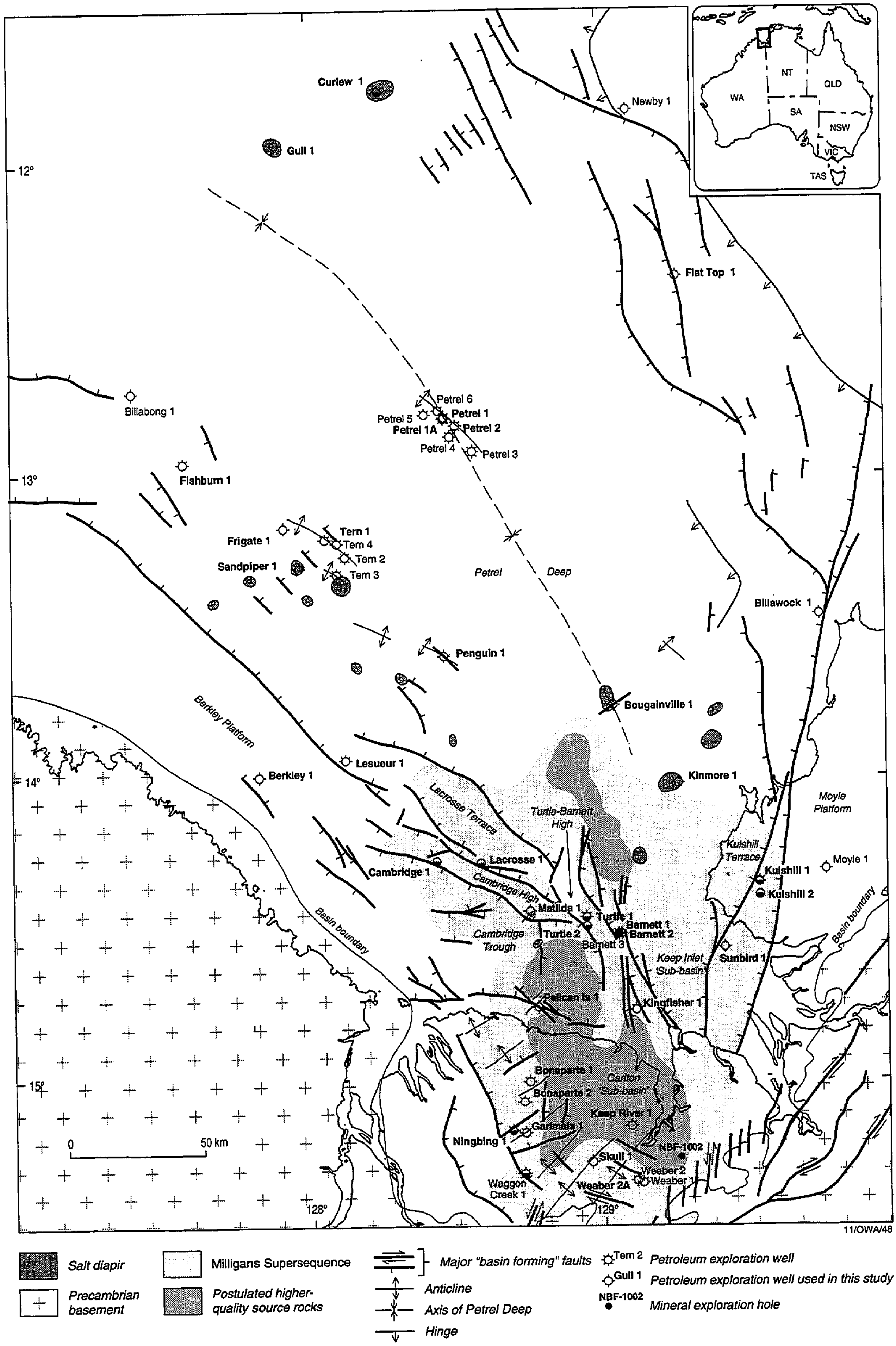

Figure 7-4. Distribution of source rocks of the Milligans Petroleum System.

- Truncated/karsted carbonate platform/reefs, Ningbing reef complex.

Seal
- Regional seal: Marginal marine glacial shales, Treachery Sequence (partially fault-breached across Turtle-Barnett High).
- Intraformational marine shales, Milligans Supersequence.
- Tight highstand carbonates (?micro-fracturing) and transgressive marine mudstones, Tanmurra Supersequence.
- Intraformational mudstones, Point Spring and Kuriyippi Supersequences.

Traps
- Faulted and drape anticlines/horsts (Turtle and Barnett structures; see Fig. 4-1). Stratigraphic onlap and downlap of turbiditic sands, Milligans Supersequence (Figs. 4-1, 4-4 and 7-6).
- Mounded low-stand fans, basal Milligans Supersequence (Figs. 4-3 and 7-5).
- Carbonate mounds, Tanmurra Supersequence (Fig. 4-5).
- Tilted and/or truncated Langfield and Ningbing reservoirs below basal Milligans Supersequence boundary, sourced and sealed by Milligans (e.g. deep play beneath Turtle-1, see Fig. 4-1; 'Crocodile' structure, Maung et al., 1994, fig. 9.15; Pincombe prospect, Amity Oil, 1994).

Structuring
- Regional Early Carboniferous (late Tournaisian) uplift, erosion and faulting at end of 'syn-rift' phase, and renewed uplift of Cambridge and Turtle-Barnett Highs.
- Late Early Carboniferous (late Visean) down-faulting of Lacrosse Terrace and Petrel Deep, and minor uplift of inboard areas (Cambridge and Turtle-Barnett Highs, Cambridge Trough and Carlton Sub-basin).
- Possible uplift and faulting at base of Kuriyippi Supersequence.

Maturation
- First entered the oil maturity zone during the mid Early Carboniferous (Visean; central Carlton Sub-basin, Cambridge Trough, Keep Inlet Sub-basin, Kulshill Terrace and depocentre north of Turtle-Barnett High), or Early Permian (western Carlton Sub-basin, Turtle-Barnett High and Lacrosse Terrace).
- Attained maximum maturity during Late Permian - Early Triassic prior to Fitzroy Movement.
- Presently mature in the western Carlton Sub-basin and on Turtle-Barnett High, and overmature in all other areas.

Expulsion
- Late Early Carboniferous (Namurian) expulsion from the depocentre north of the Turtle-Barnett High.
- Early Permian expulsion from the Keep Inlet Sub-basin, Cambridge Trough and central Carlton Sub-basin.
- Two phases of oil charge evident at Turtle-Barnett; first charge (probably from the northern depocentre) was biodegraded in shallow reservoirs; second charge (probably from the Cambridge Trough and/or Keep Inlet Sub-basin) was mixed with earlier biodegraded accumulation in more deeply buried reservoirs.

LINE 89BO-19

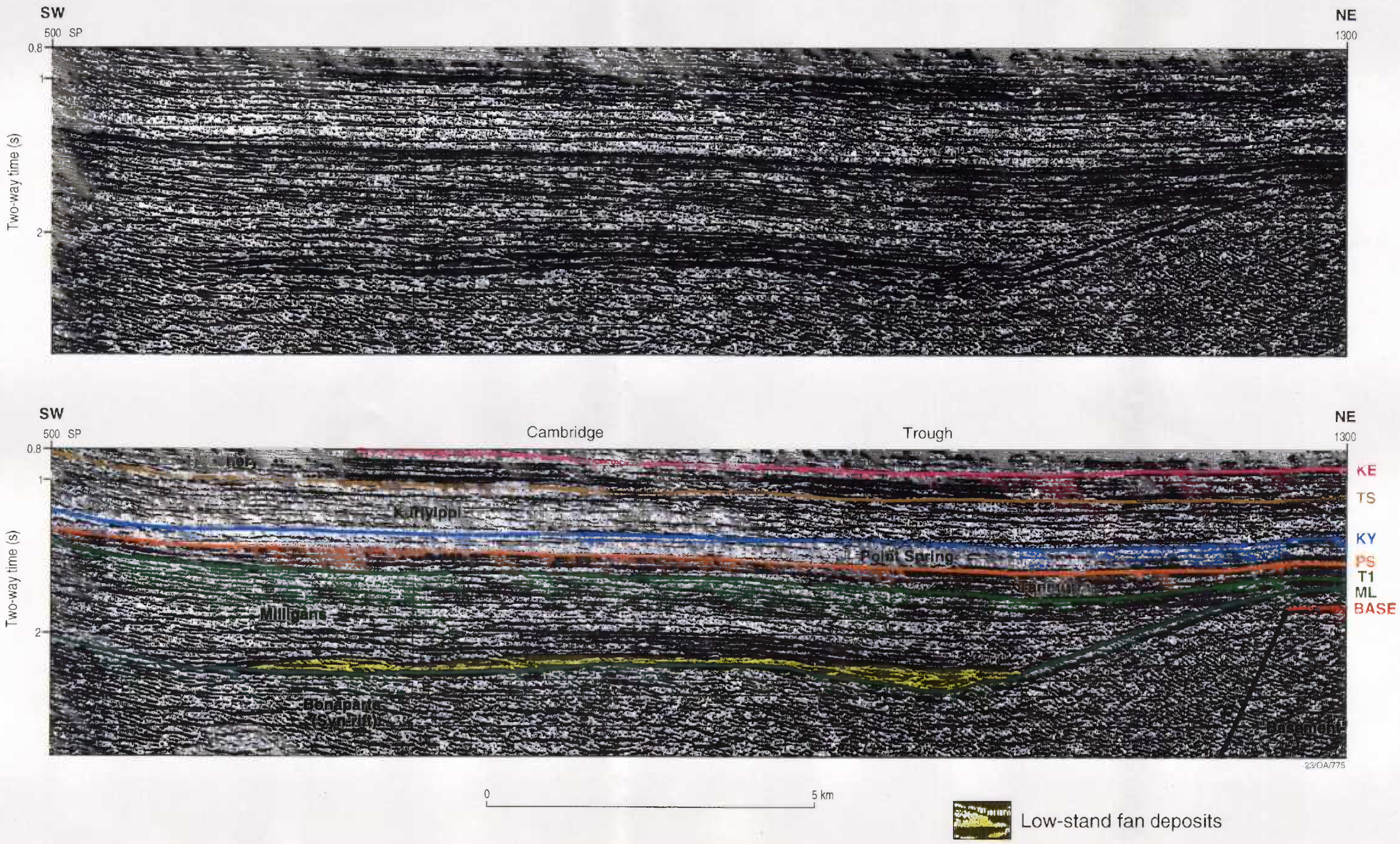

Figure 7-5. Uninterpreted and interpreted versions of part of seismic line 89BO-19 showing low-stand fan deposits at the base of the Milligans Supersequence.

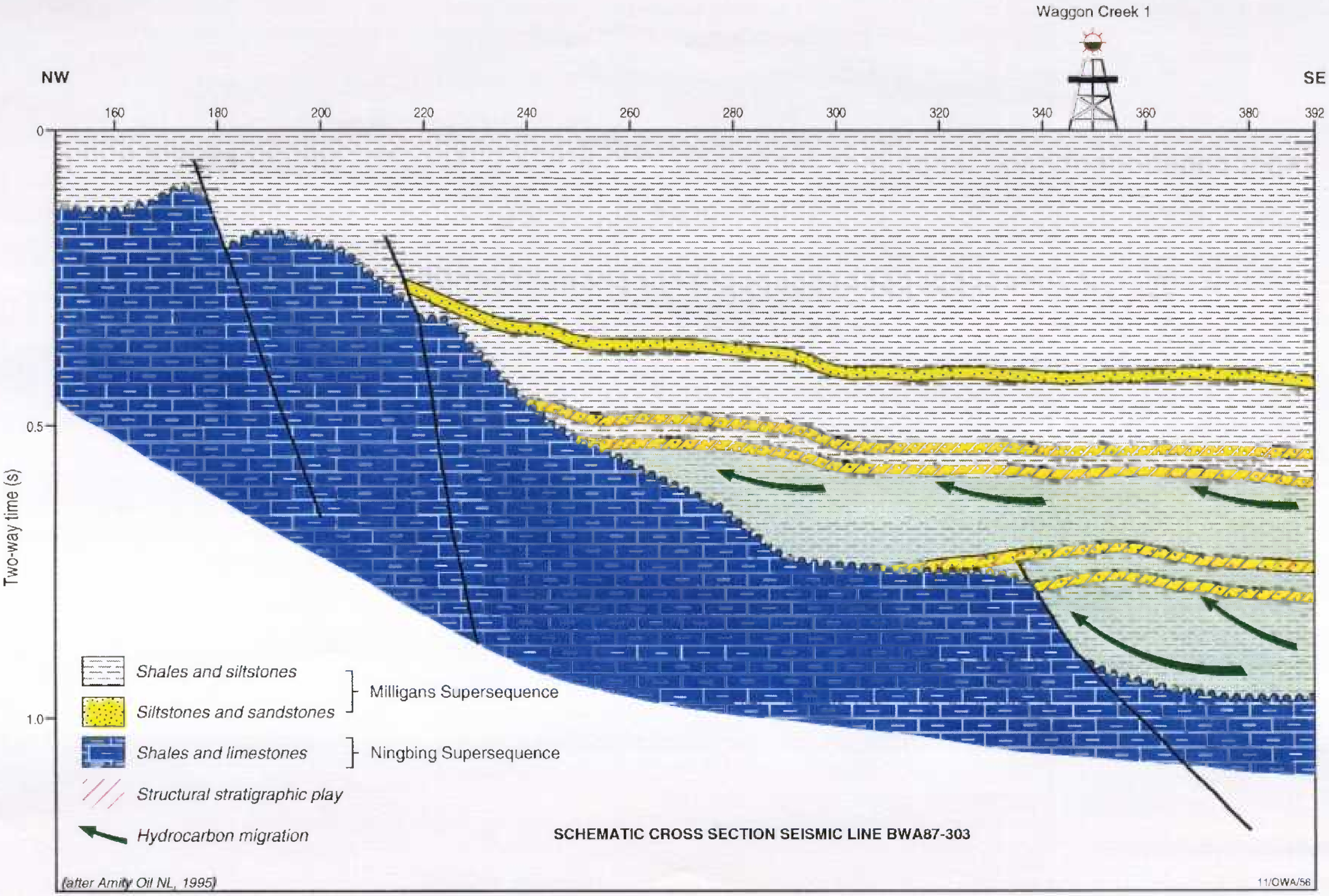

Figure 7-6. Waggon Creek play (after Amity Oil, 1995).

Migration

- Lateral migration through Milligans turbiditic sandstones to margins of sub-basins.
- Vertical along faults at margins of sub-basins and bounding horst blocks.

Critical Success Factors

- Adequacy of regional Treachery Shale seal (e.g., partially breached by fault re-activation, and consequent fresh-water flushing and biodegradation of shallow reservoirs in Turtle-Barnett area).
- Timing of expulsion/migration from different source pods (late Early Carboniferous and Early Permian) versus deposition of regional Treachery Shale seal (basal Permian)
- Reservoir development and quality.

Failures

- Late-formed salt structures (Pelican Island-1).
- Primary target (Ningbing limestone) not reached (Skull-1).
- Lack of closure (Spirit Hill-1).
- Poor reservoir quality, biodegradation and ?breached regional seal (Turtle, Barnett).

Analogues

- Lloyd and Sundown Oil Fields, and Point Torment Gas discovery, Canning Basin (sourced from Early Carboniferous Anderson Formation, reservoired in deltaic and marginal marine sandstones of the Anderson Formation).

3. KEYLING - HYLAND BAY PETROLEUM SYSTEM (Gondwanan 1)

Definition

- Hydrocarbons generated from Early Permian marginal marine shales and coaly shales of the Keyling Supersequence, and/or Late Permian marine shales of the Hyland Bay sequences (Fig. 7-7).
- Liquid hydrocarbons generated from these two sources cannot be distinguished on the basis of available geochemical data (see Edwards & Summons, 1996).
- Source rocks deposited within a mid-high latitude, epicontinental sea following a period of glaciation.
- Bradshaw et al. (1994) recognised two Gondwanan petroleum systems based on a tectonic separation between Permian and Triassic source intervals: Gondwanan 1 is characterised by Permian terrestrial source-facies in eastern Australia and in the Perth Basin, and unproven marine shale source rocks in several basins in Western Australia; Gondwanan 2 is characterised by oil-prone Lower Triassic marine shales in the Perth Basin. The Keyling - Hyland Bay petroleum system thus forms part of the Gondwanan 1 system, although Bradshaw et al. (1994) and McConachie et al., (1995, 1996) assigned the Hyland Bay source and the Tern and Petrel gas accumulations to Gondwanan 2. There are no recognised Triassic source rocks in the Petrel Sub-basin, and the heavy isotopic signature of the Petrel-4 condensate makes such a source unlikely.

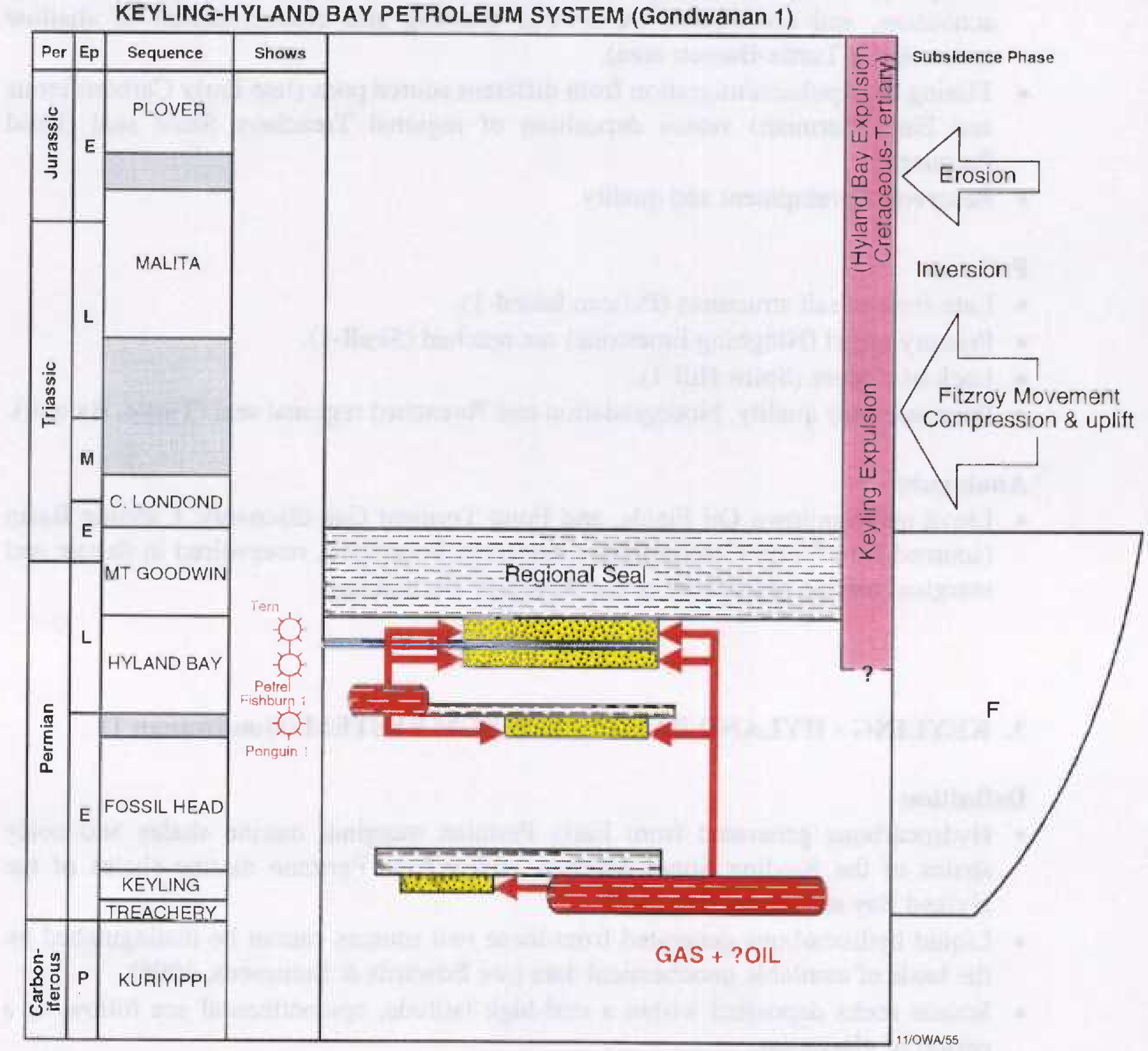

Figure 7-7. Schematic diagram of the Keyling-Hyland Bay Petroleum System.

Significant Shows

Petrel Gas and Condensate Field: 3.3-13.6 TCF gas-in-place.

Tern Gas Field: 1.3 TCF gas-in-place.

- Gas in Petrel-1, gas blow-out.
- Gas and condensate in Petrel-2:
  DST 6: 14.6 MMCFD gas and 19.7 BOPD of 39° API oil from the Cape Hay Member of the Hyland Bay Formation.
- Gas and condensate in Petrel-3: All from the Cape Hay Member, Hyland Bay Formation.
  DST-1: 22 MMCFD gas flow, 200 BOPD condensate.
  DST-2: 7.3 MMCFD gas flow, 58 BOPD condensate.
  DST-3: 10.7 MMCFD gas flow.
- Gas in Petrel-4: 28.7 MMCFD gas flow.
- Gas and condensate in Petrel-5: 34.6 MMCFD gas flow and ~17 BOPD condensate.
- Gas in Tern-1: Gas shows in Tern Member, Hyland Bay Formation.
- Gas in Tern-2: Gas flow from the Tern Member, Hyland Bay Formation.
- Gas in Tern-4: 5.37 MMCFD gas from the Tern Member, Hyland Bay Formation.
- Gas in Fishburn-1: Gas flow from the Tern-Cape Hay Members, Hyland Bay Formation.
- Gas in Penguin-1: Gas flow from basal sandstone of the Hyland Bay Formation.

Source Rocks

Two probable source rock units:

- Early Permian marginal marine-deltaic shales and coaly shales, Keyling Supersequence.
  - Shales: Mean TOC = 2.8 %, mean HI = 95, gas-prone Type III/IV kerogen and oil/condensate-prone Type II/III kerogen.
  - Coaly shales: Intersected in Flat Top-1 and Kinmore-1: mean TOC = 35.2 %, mean HI = 230; oil and gas-prone Type II/III kerogen.
- Late Permian marine shales, Hyland Bay Formation. Mean TOC = 2%, mean HI = 55, gas-prone Type III/IV kerogen.

Distribution

- Keyling and Hyland Bay source units occur throughout the Petrel Deep, and Keyling source unit also extends into the Lacrosse and Kulshill Terraces, Keep Inlet Sub-basin, Cambridge Trough and part of the Carlton Sub-basin (Figs. 7-8 and 7-9).
- Higher source-quality coaly shales in the Keyling Supersequence apparently restricted to Eastern Ramp margin (intersected in Flat Top-1 and Kinmore-1).
- Higher source-quality shales in the Hyland Bay Formation may occur below well intersections in the outer Petrel Deep.

Reservoir

- Highstand delta-front bars, tidal bars and shoreface sandstones, Cape Hay and Tern Members, Hyland Bay Formation.

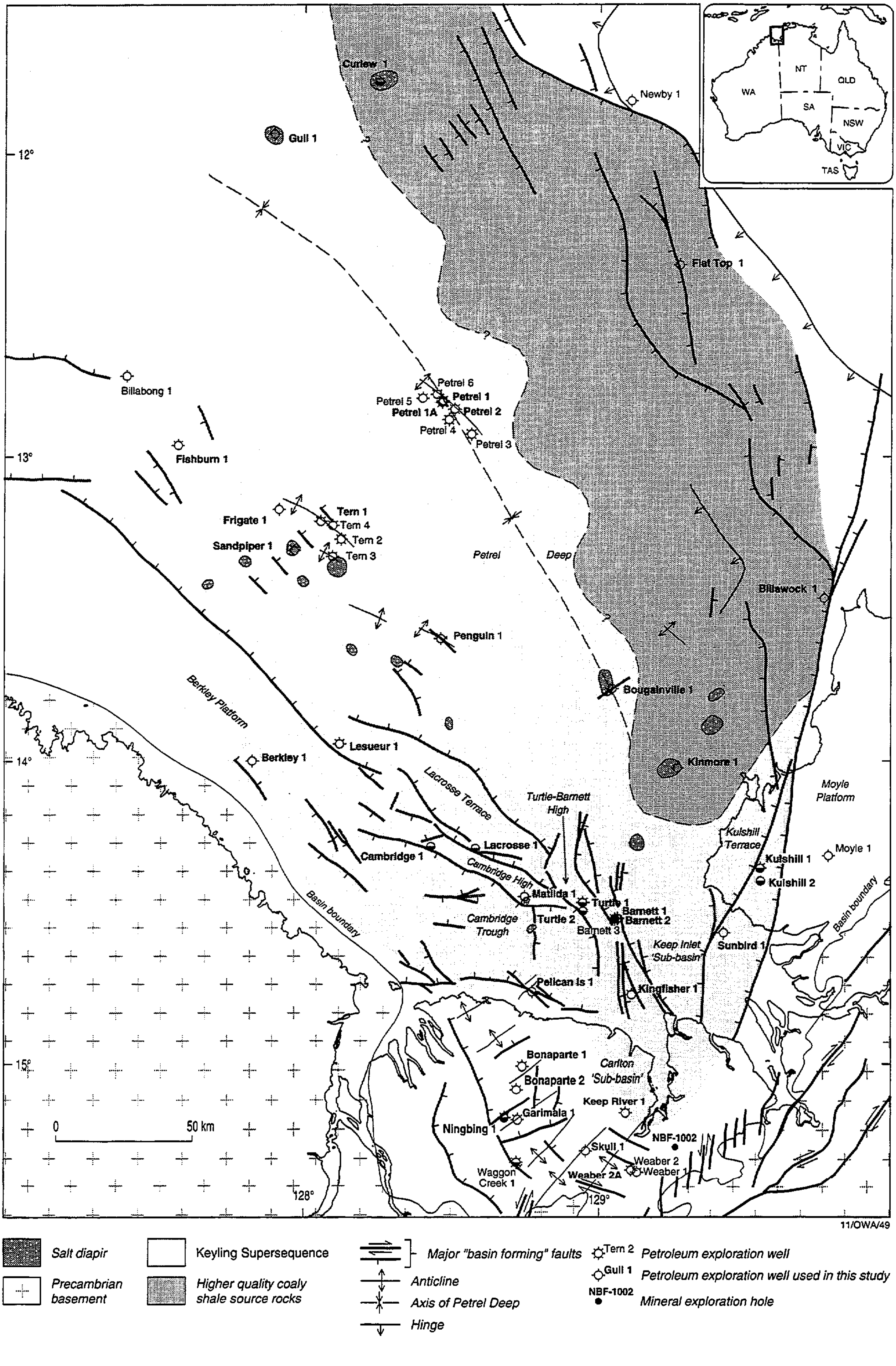

Figure 7-8. Distribution of Keyling source rocks.

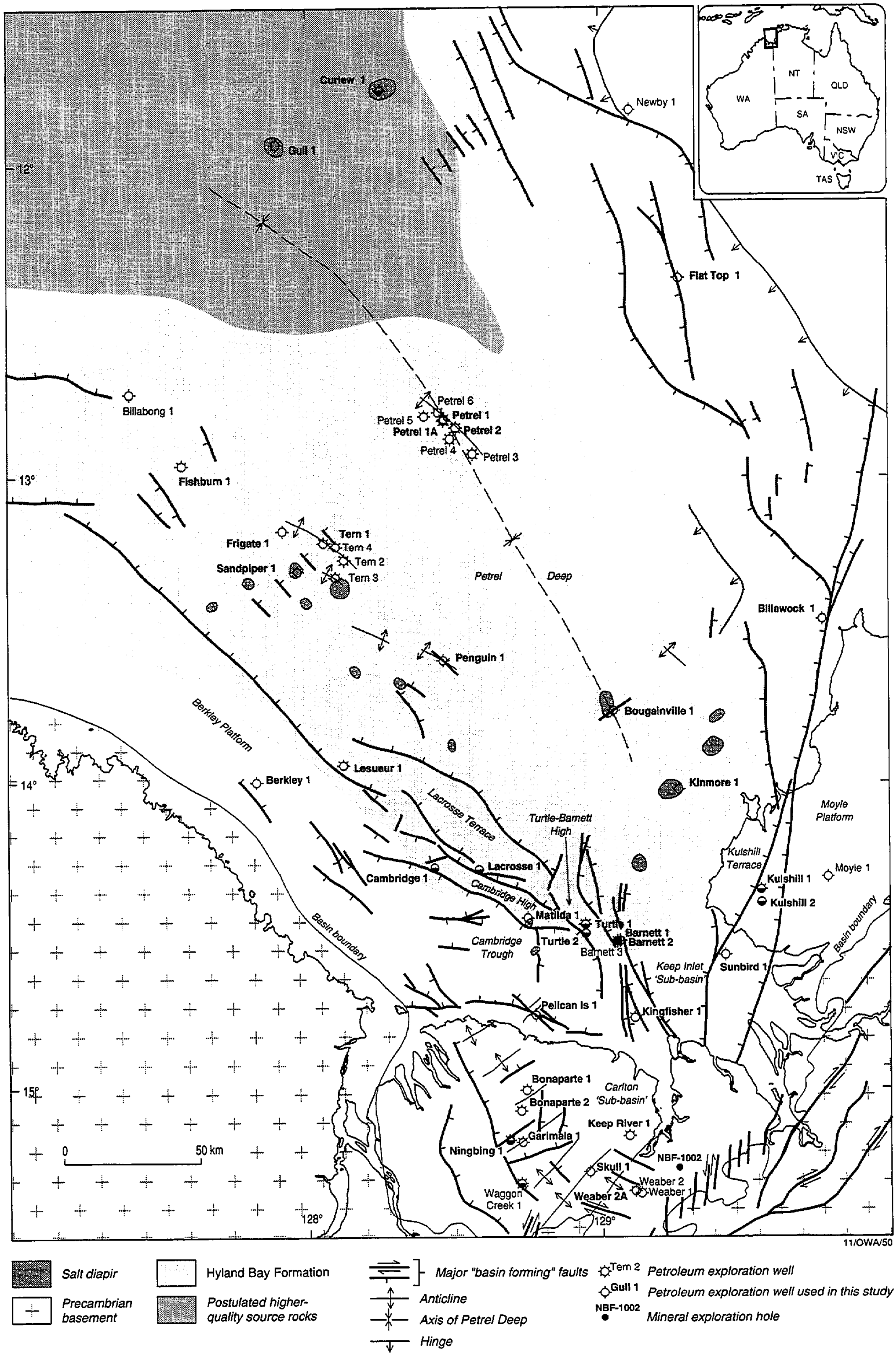

Figure 7-9. Distribution of Hyland Bay source rocks.

- Basal transgressive sandstone, Hyland Bay Formation.
- Fluvio-deltaic sandstones, Keyling Supersequence.

Seal
- Regional seal: Transgressive marine shale, Mount Goodwin Formation.
- Intraformational marine shales (Cape Hay Member) and biomicritic limestone (Dombey and Pearce Members), Hyland Bay Formation.

Traps
- Anticlines associated with fault reversals (e.g. Lacrosse-1, Lesueur-1) (Fitzroy Movement).
- Large-scale inversion anticlines (e.g. Tern-1, Petrel-1) (Fitzroy Movement).
- Faulted anticlines.
- Stratigraphic traps and pinchouts, Hyland Bay Formation.
- Early-formed salt diapirs.

Structuring
- Middle Triassic - Early Jurassic inversion (Fitzroy Movement), with some evidence of initial compressional pulses in the Late Permian during and after deposition of the Hyland Bay Formation (see Fig. 3-10).

Maturation
Keyling source unit:
- First entered the oil maturity zone during the Middle-Late Permian (Gull, Petrel, Tern) or Late Triassic - Early Jurassic (Fishburn, Penguin).
- Presently immature on Eastern Ramp margin, Lacrosse Terrace and Cambridge High.
- Presently at maximum attained maturity level in all other areas.

Hyland Bay source unit:
- First entered the oil maturity zone during the Middle Jurassic (Gull), Early Cretaceous (Petrel), or Late Cretaceous-Tertiary (Tern, Fishburn, Penguin).
- Presently immature in innermost Petrel Deep, Lacrosse and Kulshill Terraces, and Eastern Ramp margin.
- Presently at maximum attained maturity level in all other areas.

Expulsion
Keyling source unit:
- Outer Petrel Deep (Gull): Peak oil expulsion during Late Permian, gas expulsion throughout Late Permian - Early Jurassic.
- Central Petrel Deep (Petrel): Peak oil expulsion during Early Triassic if significant proportion of coaly shales (5-10 % of source unit), or during Middle-Late Triassic if less than 5 % coaly shales; i.e., pre or post Fitzroy Movement structuring depending on proportion of coaly shales. Peak gas expulsion during Early Triassic and Late Cretaceous.
- Inner Petrel Deep (Tern, Fishburn): Peak oil and gas expulsion during Late Cretaceous - Tertiary, but little or no hydrocarbon expulsion from shallow parts of the Petrel Deep (e.g., Penguin)

Hyland Bay source unit:

- Outer Petrel Deep (Gull): Minor gas expulsion during Cretaceous, peak gas expulsion during Tertiary.
- Central Petrel Deep (Petrel): Minor gas expulsion during Late Cretaceous.
- Flanks and inner Petrel Deep (Tern, Fishburn): Little or no hydrocarbon expulsion.

Migration

- From axis of Petrel Deep to surrounding flanks prior to Fitzroy Movement.
- From compressional synforms to adjacent antiforms and margins of Petrel Deep during and after Fitzroy Movement.

Critical Success Factors

- Net effective thickness of higher source-quality, oil-prone, Keyling coaly shales in the central and outer Petrel Deep.
- Timing of expulsion versus trap formation (Fitzroy Movement, salt movement). Expulsion occurs earlier with increasing proportion of higher source-quality Keyling coaly shales.

Failures

- Late-formed salt structures (Sandpiper-1, Tern-3).
- Fault-breached early-formed salt structures (Kinmore-1).
- ?Water-flushed early-formed salt structures (Bougainville-1).
- Lack of structural closure (Flat Top-1).

Analogues

- Dongara Gas Field, Perth Basin (Irwin River Coal Measures source and reservoir).

FUTURE EXPLORATION POTENTIAL

The Early Carboniferous Milligans and Permian Keyling-Hyland Bay petroleum systems are considered to offer significant future exploration potential in the Petrel Sub-basin.

The oil and gas-prone Milligans system has been proven by offshore oil discoveries at Barnett-2 and Turtle-1 and 2, and onshore gas flows at Keep River-1, Weaber-1,2A, Bonaparte-2 and, most recently, Waggon Creek-1. These hydrocarbons have been shown to be sourced from marine mudstones of the Milligans Supersequence, and the most organic-rich penetrated intervals occur in the upper portion of the second-order transgressive systems tract near the middle of the supersequence. However, no wells have penetrated what are probably the most promising source pods identified offshore on seismic data in the Cambridge Trough and north of the Turtle-Barnett Highs. These pods are believed to have sourced the Barnett and Turtle discoveries, which contain composite biodegraded and non-biodegraded oils, and record at least two phases of migration and accumulation. These source pods are ideally located to charge identified Milligans basin-floor fans and stratigraphic pinchouts in the Cambridge Trough, and

Tanmurra carbonate mounds north of the Turtle-Barnett High. Maturation modelling suggests that these untested plays in the Cambridge Trough were probably charged by hydrocarbons during the Early Permian. They are unlikely to have are suffered subsequenent biodegradation, as has occurred in the shallow reservoirs on the Turtle-Barnett High, since the regional Treachery Shale seal was deposited prior to hydrocarbon expulsion and migration in the Cambridge Trough. Similarly, potential oil accumulations within carbonate mounds north of the Turtle-Barnett High are also unlikely to be biodegraded since they were protected from oxidising meteoric groundwatwers by intraformational seals: these seals are either poorly developed, or breached by subsequent fault reactivation, across the Turtle-Barnett High.

The Keyling-Hyland Bay system has been proven by the giant Petrel gas-condensate and Tern gas fields, and gas discoveries at Fishburn-1 and Penguin-1. These hydrocarbons have been shown to be sourced by Permian sediments containing mixed land-plant and marine algal material; either from marginal marine shales and delta-plain coaly shales in the Keyling Supersequence, or pro-delta shales in the Hyland Bay sequences. Coaly shales within the Keyling Supersequence have also been shown to have significant oil potential. Geohistory modelling suggests that postulated source rocks of similar high quality in the central Petrel Deep would have expelled significant quantities of oil and gas immediately prior to the main phase of trap formation during the Middle Triassic - Early Jurassic Fitzroy Movement. Thus any stratigraphic or combined structural-stratigraphic traps of Permian-Early Triassic age on the flanks of the Petrel Deep may have been charged by these hydrocarbons. These findings suggest a new oil-prone Permian play along the northeast flank of the Petrel Sub-basin.

On the basis of current data, further exploration of the onshore Late Devonian Ningbing-Bonaparte petroleum systems is unwarranted.

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