Geohistory modelling of hydrocarbon migration and trap formation in the Arafura Sea

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Abstract

Exploration for hydrocarbons in the Arafura Sea to the north and east of Darwin has been concentrated in the Goulburn Graben. Nine wells have been drilled without finding a commercial accumulation. Therefore, exploration ceased in this area which was conventionally given the highest rating for prospectivity. Geohistory studies show that prospective Lower Palaeozoic successions in the graben were buried deeply, heated to advanced maturity, then uplifted and cooled. Oil generation was halted after a period of early migration. These episodes pre-date the Late Triassic events that created the Goulburn Graben. Significant structures were not in existence when the oil migrated. This explains the failure of exploration in the graben.

The area north of the Goulburn Graben has been widely considered to be a platform area with shallow basement. AGSO reconnaissance seismic acquired in 1990 and 1991 shows a thick sedimentary basin north of the graben. We believe that the Palaeozoic Arafura Basin continues northward, covering a huge area of the northern Australian shelf and extending into Indonesian waters. Oils found in Arafura-1 well had a marine, Cambrian age source. That source should be present in the northern Arafura Sea. Three synthetic well sites in the northern Arafura Sea were analysed. The results suggest that hydrocarbon generation in this area could have occurred much later than in the Goulburn Graben, with migration post-dating the structuring. Traps outside and flanking the graben would have been in a position to accumulate hydrocarbons migrating from the northern basinal areas. On the grounds of timing, the areas to the north might be more prospective than those within the Goulburn Graben, the only site of drilling to date.

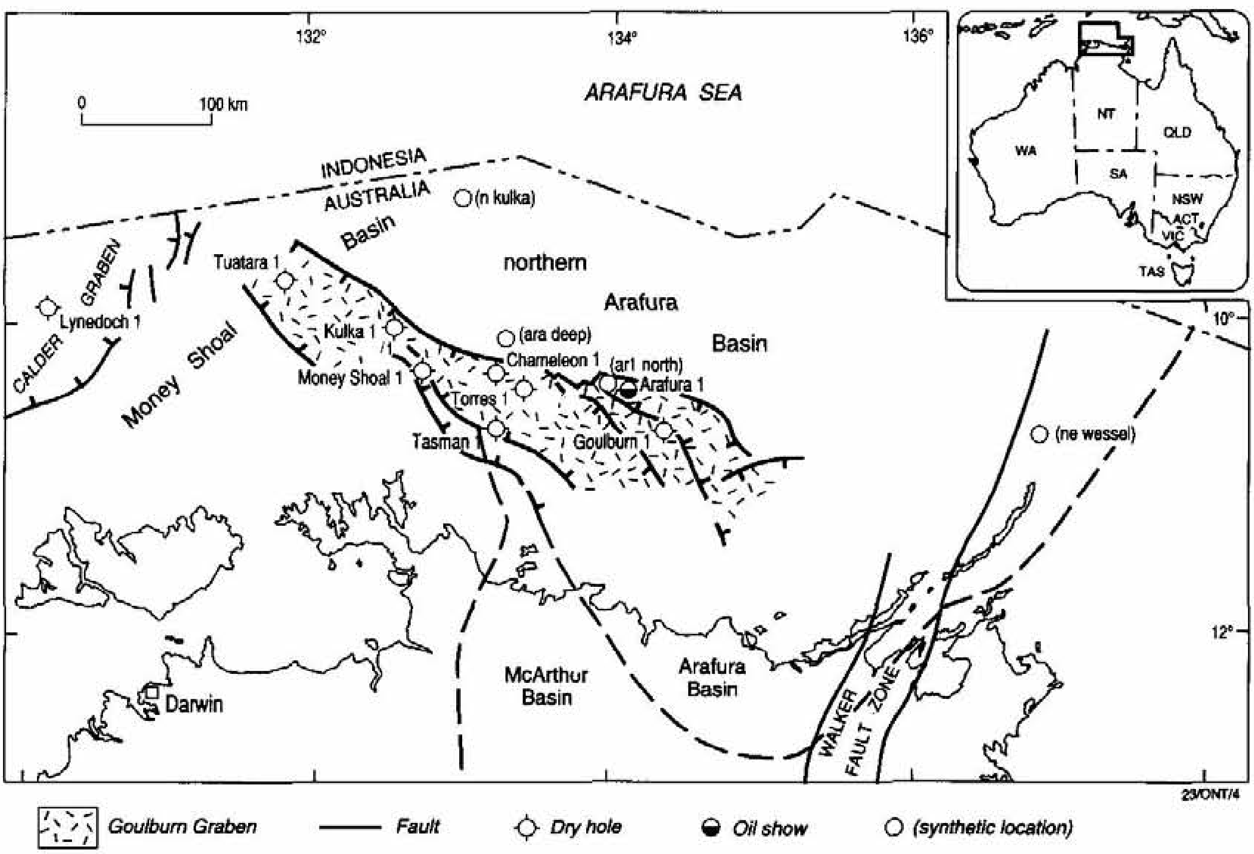

Fig. 1 - Locality map showing the Arafura Sea, with the Goulburn Graben, exploration wells and synthetic well locations in the Arafura Sea.

Introduction

The Australian portion of the Arafura Sea is a poorly known and little explored area of over 180,000 km^2 between the Timor Sea and the Gulf of Carpentaria. It lies on the northern continental margin of Australia. The area referred to in this paper extends from longitude 131° 30' East to 137° East, and from around latitude 9° South at the border of the territorial waters of Australia and Indonesia, to 12° South. Water depths range from 30 to 200 m, but are mostly less than 100 m.

The nine wells drilled in the area have all been located on structures within one tectonic feature - the Goulburn Graben - which occupies part of the Arafura Sea (Fig. 1). No wells have been drilled in Australian waters in the northern or eastern parts of the Arafura Sea outside the graben. Shallow basement with a thin cover of late Mesozoic and Tertiary sediments was widely thought to underlie this huge area. However, our interpretation of oil industry and AGSO seismic data contradicts this view.

Aeromagnetic data acquired by Shell Development in 1965 were interpreted as indicating magnetic basement at a depth of up to 10,000 m in the northern part of the Arafura Sea. Smith and Ross (1986) showed a Palaeozoic basin up to 6000 m thick north of the graben, extending as far as the Merauke Ridge. An aeromagnetic survey conducted in 1989 for BHPP in permits NT/P41 and P42 confirmed the interpretation of deep magnetic basement in the area immediately north of the graben. In addition, attempts at stratigraphic correlation have been plagued by misleading dates, both absolute and palaeontological. Absolute dates from sediments both outside the graben (on the Wessel Islands) and within it (at Arafura-1) have indicated a Proterozoic age for rocks that have subsequently yielded Middle Cambrian faunas. These circumstances were documented by Bradshaw et al. (1990), and they recommended a re-evaluation of the basins under the Arafura Sea.

In 1990 and 1991, AGSO responded by acquiring 5320 km of multichannel seismic reflection profile in the Arafura

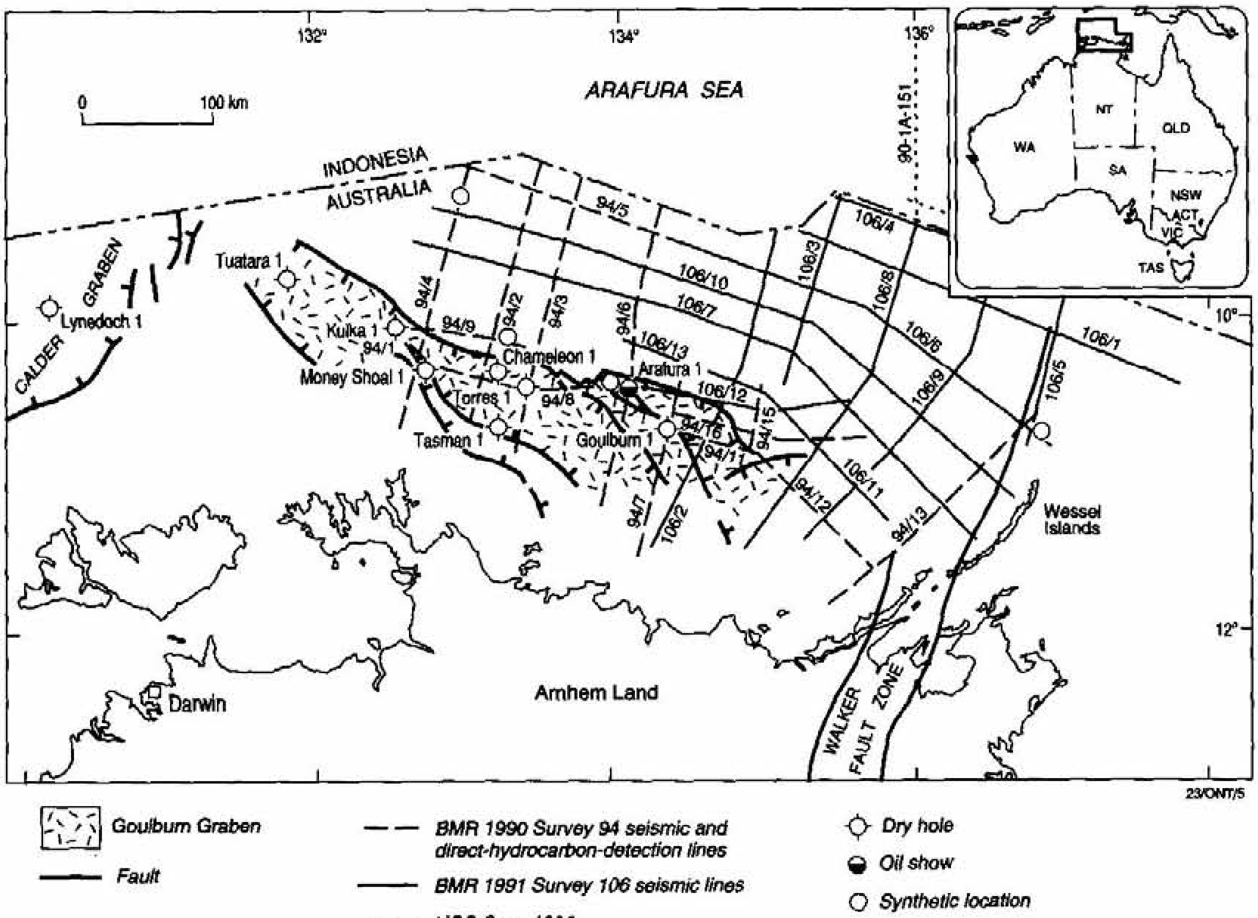

Fig. 2 - AGSO seismic surveys and well sites in the Arafura Sea.

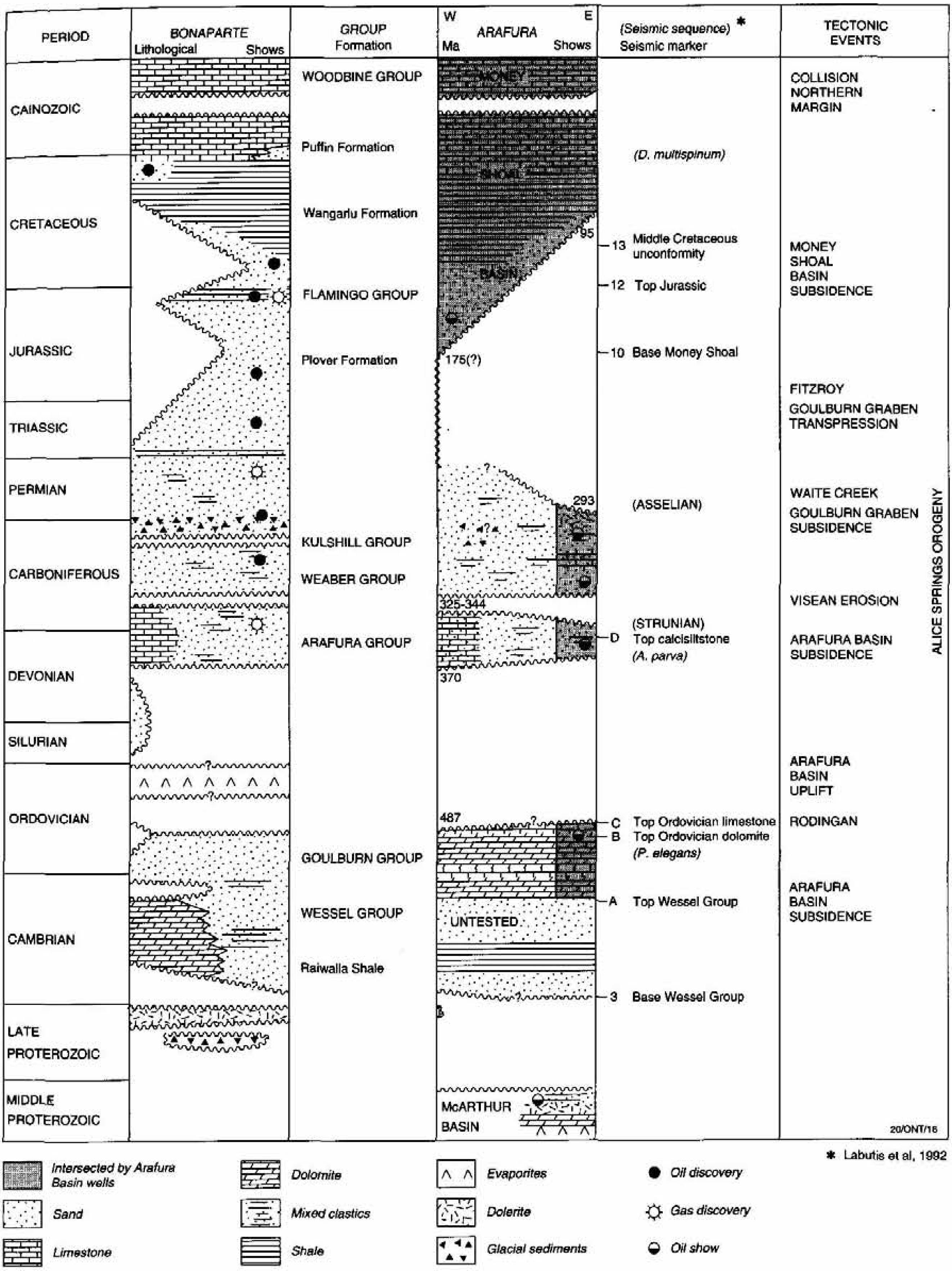

Fig. 3 - Stratigraphy and seismic horizons of the Arafura Sea basins.

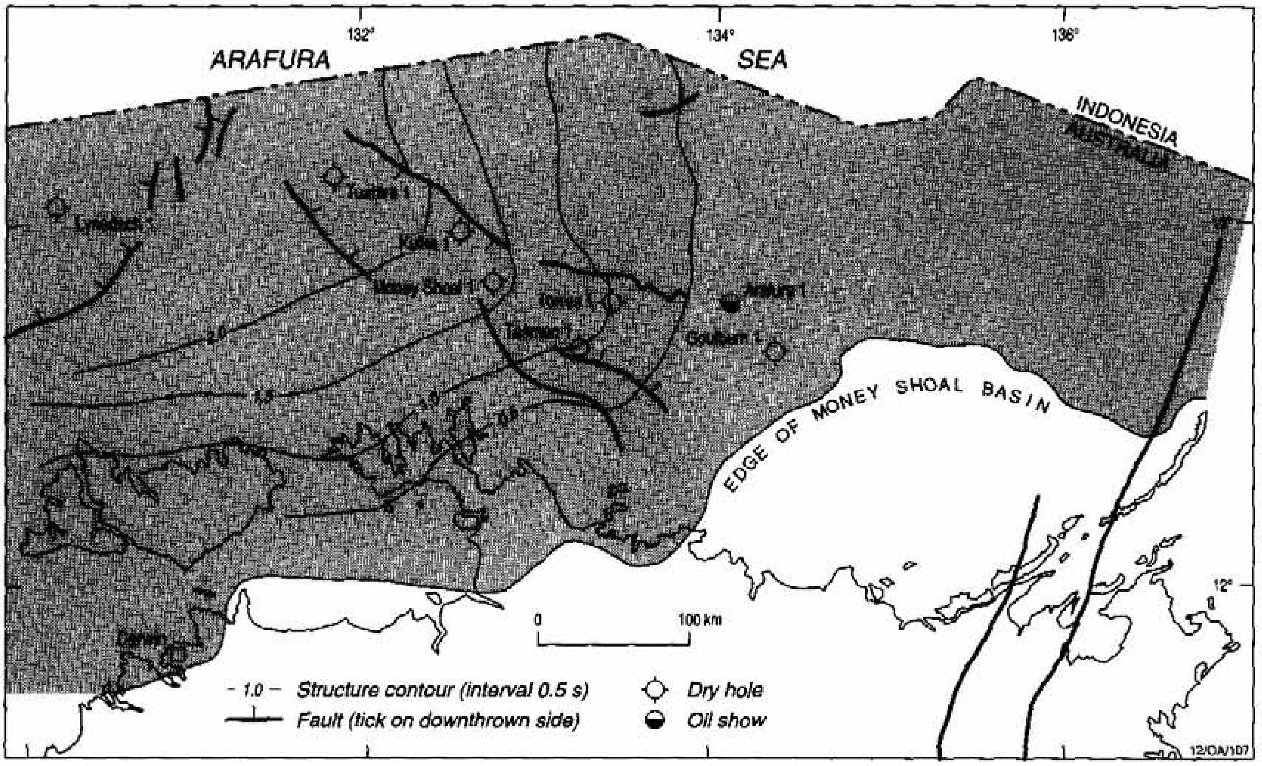

Fig. 4 - Seismic time-structure map of the base of the Money Shoal Basin. East of the Torres-1 and Tasman-1 wells, the shale-prone Cenomanian sequence at the basal uncomformity onlaps the underlying Arafura Basin succession.

Basin Reconnaissance (ABR) seismic program (Fig. 2), directed largely at the areas not explored intensively by the oil exploration industry. The data revealed a stratified succession beneath the northern Arafura Sea. It is interpreted to be of Palaeozoic to Mesoproterozoic age. The stacked and migrated reflection profiles were offered for sale to the exploration industry jointly by NOPEC and AGSO in 1992.

AGSO interpreted these seismic profiles and related reconnaissance lines acquired by the oil exploration industry. Seismic structure maps were made at some key stratigraphic levels (Labutis et al., 1992; Moore, 1995a), including the base of the Money Shoal Basin (Fig. 4), the base of the Arafura Basin (Fig. 5), and the top of the Ordovician oil reservoir in Arafura-1. Isopach or isotime interval maps between key horizons were also made.

A sequence stratigraphic correlation of the wells in the Arafura Basin, and a review of the petroleum prospectivity of the area were undertaken by Labutis et al. (1992). Moore (1995b) compiled stratigraphic and geochemical data for wells drilled prior to 1993, and used the WINBURY basin and well analysis program to study the subsidence and thermal history of the area. Hypothetical locations on seismic lines in areas of particular interest were also analysed; three outside the graben, and one near Arafura-1 (Fig. 1). Biomarker and carbon isotope analyses have focussed on organic-rich samples and oils from Arafura-1 (Hope et al., 1990). This paper integrates the conclusions drawn from the above studies.

Geological setting

The margin of Australia beneath the Arafura Sea is little known and poorly understood. It contains the Money Shoal, Arafura and McArthur Basins of mainly Mesozoic, Palaeozoic, and Proterozoic age respectively, which overlap to form a sedimentary pile more than ten kilometres thick in places. In most of the area the basinal succession has not been severely tectonised, and geothermal gradients are low. Oil exploration drilling was restricted to the Goulburn Graben, which lies on the southwestern edge of the Arafura Basin. The stratigraphy derived from the wells is described in Bradshaw et al. (1990) and in Labutis et al. (1992), and summarised on Figure 3.

Money Shoal Basin

The Money Shoal Basin occupies the western parts of the Arafura Sea. The base is time-transgressive, and ranges in age from Late Jurassic in the west, where up to 400 m of Jurassic marine clastics occur at the base, to Late Cretaceous in the east. The Tertiary succession is thin or

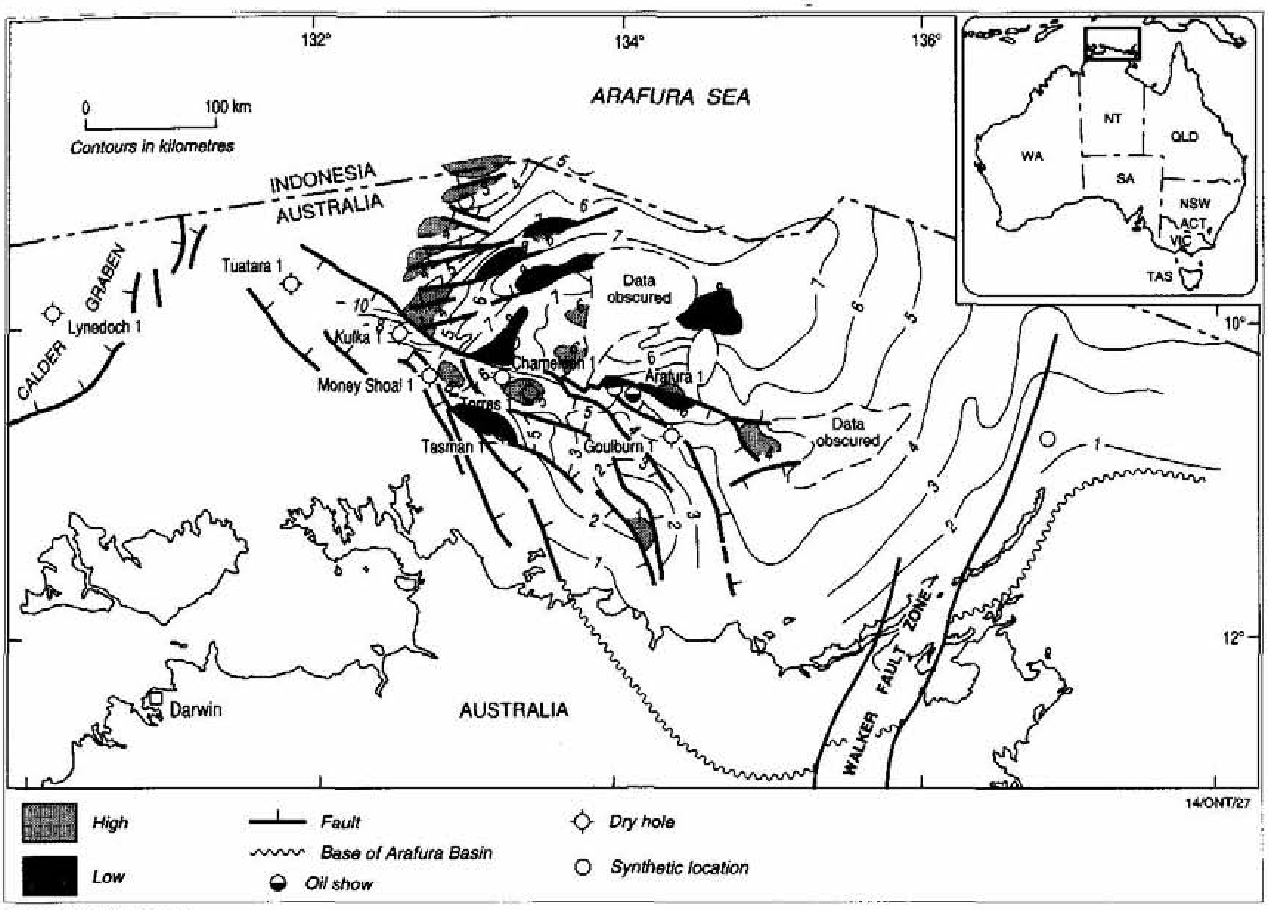

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Fig. 5 - Depth structure map of the base of the Arafura Basin, showing the fault terraces on the western flank. Contour values are in kilometres.

absent in the eastern parts of the basin, and has not been sampled in the Goulburn graben wells. The basin onlaps the angular unconformity at the top of the underlying Arafura Basin, and the shales above the 'base Cenomanian' maximum flooding surface (*D. multispinum* dinoflagellate zone, Helby and Partridge, 1982) overlie the basal unconformity in the eastern parts of the area.

Arafura Basin

The Arafura Basin extends from onshore outcrops of Cambrian rocks in Arnhem Land and the Wessel Islands (Figs 1 and 2) to the Australian-Indonesian border and beyond (Bradshaw et al., 1990), possibly as far as the mainland of Irian Jaya. In Australian waters the basin covers an area of more than 130,000 km^2. Its simple synclinal shape is interrupted by the Goulburn Graben which lies on its southern margin and trends west-northwestward. The graben fill consists of up to ten kilometres of marine and marginal marine clastics and carbonates, ranging in age from Early Cambrian to Permian. The greater part of the basin, east and north of the graben, is undrilled, and probably contains Early Palaeozoic marine clastics and carbonates (Bradshaw et al., 1990) overlying and onlapping the offshore part of the McArthur Basin.

McArthur Basin

The McArthur Basin is widely exposed onshore, and has been drilled by petroleum and minerals exploration wells and by stratigraphic and water bores, but it has not been intersected by any offshore wells. It is a thick and complex basin with ?Upper and Middle Proterozoic marine and marginal-marine sediments, and it is little deformed and unmetamorphosed, indeed, immature for hydrocarbons in areas onshore., It contains at least one major internal angular unconformity and five oil source rocks (Crick, 1992; Crick et al., 1988) and a thick dolerite sill. A `central trough' (the Walker Fault Zone) is seen in outcrop in eastern Arnhem Land and on the Wessel Islands, trending northward offshore under the eastern flank of the Arafura Basin. It contains several kilometres thickness of shallow marine sediments, mainly carbonates of the Tawallah, McArthur and Nathan Groups of Mid-Proterozoic age. The shallower Arnhem Shelf to the west contains up to three kilometres of mid-Proterozoic carbonates, basalts and quartz-rich arenites of the Katherine River Group (correlated with the McArthur Group), overlain by siliciclastic sediments of the Roper Group, which range up to five kilometres in thickness. The Arafura Basin overlies these and thickens toward the coast. In the central Arafura Sea, north of the Chameleon-1 well and the Goulburn Graben, the McArthur Basin probably lies disconformably beneath the Arafura Basin, but toward the Wessel Islands on the eastern flank, and also on the western margin of the study area, an angular unconformity separates older Proterozoic sediments (McArthur Group or Nathan Group) from the onlapping Cambrian sediments of the Arafura Basin.

Structure

The structure of the area is illustrated by the map of the base of the Wessel Group (Moore, 1995a). The horizon (seismic horizon 3 on Fig. 3) has not been intersected offshore, but the overlying succession occurs in outcrop on the Wessel Islands of northeastern Arnhem Land (Plumb et al. 1976), and on the mainland. Offshore, Arafura-1 intersected Middle Cambrian carbonates above 3596 m KB (horizon F of Petroconsultants Ltd, 1989); the underlying succession was originally estimated to be of Proterozoic age, but is now identified (Bradshaw et al. 1990) as the Wessel Group of Middle Cambrian age.

The depth structure map of the base of the Wessel Group is shown in Figure 5. Highs are shown in light shading, lows in a darker shade. The depth of the horizon varies from more than ten kilometres at the western end of the Goulburn Graben, to zero (the edge of the Arafura Basin) in the east. The age of the horizon is thought to be Middle Cambrian, and it is slightly time transgressive on the eastern and western margins of the basin. Within the graben the horizon is highly structured, with large anticlines and numerous fault terraces.

The Goulburn Graben was formed during the period now represented by the unconformity between the Permian and the middle Jurassic successions (Fig. 3). The major movements forming the features present today are thought to have occurred during the later Triassic. The Goulburn Graben is not a normal extensional feature, a `keystone

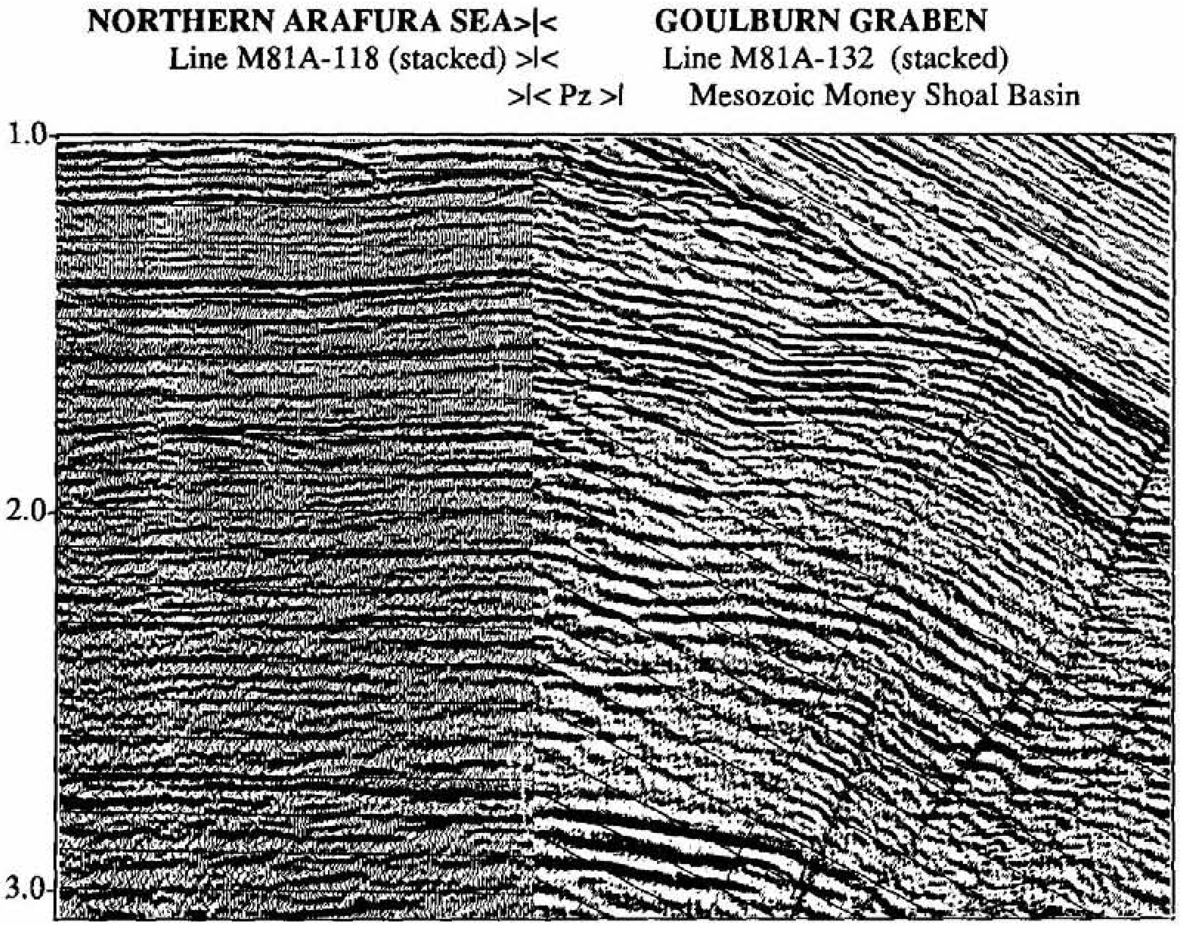

Fig. 6 - Correlation of seismic in Goulburn Graben and northern Arafura Sea.

graben'; the effects of strong transpressional forces are evidenced by the large-scale erosion found everywhere within it, even on the deeper flanks adjacent to the bounding faults. There is no `growth section' contemporaneous with these faults showing their development. There is evidence of repeated tectonic movements in the absence within the graben area of most of the Ordovician, the whole of the Silurian and the Early and Middle Devonian, as well as most of the Carboniferous, the middle and Late Permian, and the Triassic and Early Jurassic. The full amount of erosion associated with the Goulburn Graben diastrophism is unknown, but where it can be partly measured on seismic it exceeds two kilometres. Erosion may range up to more than four kilometres at the crests of anticlines, and up to two on the flanks. Seismic mapping of Early Palaeozoic units (Moore, 1995a) shows thinning from the northern bounds of the graben toward the south. The graben axis may have been an early and persistent hingeline, on the margins of the Arafura and McArthur Basins, responding more readily than the rest of the basin to later tectonic forces. The southern bounding faults appear to be normal, probably listric, down-to-the-basin faults, except that the succession showing contemporaneous growth is missing, presumably eroded during the uplift that followed the faulting. The major faults bounding the graben on the northern side are steeply dipping, and show sinistral strike-slip movement with a significant compressional component (Bradshaw et al., 1990; Etheridge & O'Brien, 1994), resulting from the last big diastrophic event, which was in the ?Late Triassic. They do not show the growth associated with normal antithetic faults. They may have been normal basinward-throwing faults in the Early Palaeozoic. In today's configuration, the bounding faults and the fold axes, e.g. the Torres Anticline, are compatible with a sinistral relative movement azimuth of 70°-250° (following Harding, 1974; Park, 1988), but the orientation of elements in the graben does not fit a simple tectonic model, indicating a change in the direction of tectonic stress over time, as well as a change from extension during the Early Permian to strike-slip and, finally, transpression during the ?Late Triassic.

The undrilled northern province of the Arafura Basin is a simple syncline, apart from the western rim, where it infills a series of tilted fault blocks which trend northeast. It extends from the northern bounding faults of the Goulburn Graben to the limit of Australian territorial waters, and beyond into Indonesian waters and the Merauke Basin south of the Aru Islands and Pulau Dolak in Irian Jaya. Although there are areas of poor seismic signature, especially adjacent to major faults, the AGSO seismic in the northern province shows a thick stratified succession in areas of good data. Although the northern succession has high seismic stacking velocities, its seismic signature is unlike that of the indurated sediments on the southern margin of the basin near Money Shoal-1. These latter sediments also appear on aeromagnetic maps as shallow basement, whereas the magnetic basement in the northern Arafura Basin is as deep as ten kilometres.

The northern succession is difficult to tie on seismic southward across the bounding faults of the graben to the wells, but it is considered to be of Palaeozoic age, ranging from Cambrian to possibly as young as Permian. This opinion is based on interpretation of aeromagnetic data, on correlation with outcrop using regional dip, on seismic character correlation, and on structural configuration. The AGSO reconnaissance seismic lines extended as far as feasible toward the outcrop of the Cambrian on the Wessel Islands, leaving a small coastal gap of between one and three kilometres (Fig. 2). The base of Wessel Group horizon was extrapolated across the gap from outcrop to the AGSO reflection profiles using regional dip, in the presumed absence of intervening steep dips or faults.

A seismic character correlation between portions of industry reflection profiles on opposite sides of the bounding faults of the graben was described by Bradshaw (1989). Shotpoint 2800 on line M81A-132, inside the graben, 21 km south-southeast of Torres-1, is character-correlated with shotpoint 4600 on line M81A-118, outside the graben in the northern province. The latter point is near shotpoint 2400 on AGSO line 94/02, and 11 km northwest of the Ara deep synthetic location. The correlation is shown on Figure 6, with the respective shotpoints juxtaposed.

Torres-1 lies on line 132 some distance to the right of the diagram, across intervening faults. It intersected Devono-Carboniferous clastics and Cambro-Ordovician dolomites, with the top of Devonian lying at about 2.0 seconds on the figure. The highly reflective sequence on line 132 above this level was not intersected by the well, but it resembles the lowermost Permian intersected by Tasman-1. The succession on line 118 appears to be similar. Correlation of this kind cannot be done with a high level of confidence - caution is warranted - but it does suggest the possibility of a Palaeozoic basin north of the graben.

The minimum thickness of the northern Arafura Basin succession is between one and two kilometres in the west, where it is truncated at the top by an angular unconformity at the base of the Money Shoal Basin, and underlain by a series of fault blocks of unknown age. The faults trend northeast, and the infilling sediments are thought to be of Cambrian age. This configuration of tilted fault blocks with onlapping sediments matches the structural configuration of

Proterozoic and Palaeozoic sequences in the onshore McArthur and Arafura Basins. The western rim may be a southerly continuation of the Aru Rise.

The basin thickens to greater than seven kilometres in the central area, north of the Goulburn Graben and Chameleon-1. Beneath it, the Proterozoic McArthur Basin thickens rapidly from the west to form a succession several kilometres thick under the northern Arafura Basin and disconformable with it. In this area, the McArthur Basin is likely to contain one or more of the oil source rocks found onshore (Crick, 1992; Crick et al., 1988).

The eastern rim adjacent to the Wessel Islands is uplifted and bevelled off by erosion at the seabed, without much sign of internal thinning. The basal Cambrian succession is partially exposed on the islands. The thickness of the Wessel Group there, added to the intersection of its top near TD in Arafura-1, was used to help identify the base of the offshore Arafura Basin succession on seismic sections. North of the Wessel Islands, a north-south trending rift (the Walker Trough) is visible underneath the peneplaned base of the Cambrian.

The northern basinal area shows very little evidence of tectonic deformation, whereas the Goulburn Graben is heavily folded and faulted. The graben was the focus of later tectonic movements in the Arafura Sea, while the northern Basin acted as a rigid plate. This contrast has important implications for the petroleum prospectivity of the Arafura Sea.

Well history analysis

The BURY software

BURY is a commercial software program developed for the modelling and analysis of burial and thermal histories of well sequence and basin development in petroleum exploration (Paltech, 1993). A discussion of the theoretical foundations and features of BURY and comparisons with other similar packages such as MATOIL and BASINMOD can be found in Radlinski (1991), although the software has evolved greatly since then. The WINDOWS version (WINBURY 1.4c) was used in this study.

The input data

The most important wells for defining the history of the Arafura Basin are Arafura-1, Chameleon-1, Tasman-1 and Torres-1. Arafura-1 has the most complete Lower Palaeozoic succession, as well as a large present-day temperature database from the many log runs. Tasman-1 and Chameleon-1 together have the most complete Upper Palaeozoic and Mesozoic successions, while Torres-1 shows the most uplift and the most highly developed unconformities. The most important wells for understanding petroleum generation in the basin are Torres-1, Arafura-1 and Goulburn-1. A suite of well history diagrams for all the wells, and explanations of the subsidence and thermal history models and their consequences, may be found in Moore (1995b).

Data input to the WINBURY software were taken from Labutis et al. (1992) and from well completion reports (WCRs). Observed downhole temperatures were plotted using the Horner method to yield a corrected formation bottom hole temperature (BHT), or an already corrected BHT was taken from the WCR. Where a reliable BHT was not available for a well, e.g. at Kulka-1 and Goulburn-1, an assumed initial value was calculated from a supposed geothermal gradient of about 30°C/km.

The equivalence of Money Shoal Basin and Arafura Basin lithostratigraphic units to named formations of the same age in the Bonaparte Basin is not assured. Hence, formal stratigraphic names were used sparingly. Stratigraphic units have been referred to by their biostratigraphic affiliations rather than by formation names, e.g. *D. multispinum* seismic sequence, (which includes the *D. multispinum* biostratigraphic zone at its base but has a broader time span), rather than Wangarlu Formation. These named seismic and well sequences are shown in square brackets in Figure 3.

Heatflow modelling

Heatflow modelling was a major part of the basin history analysis. Published maps of heatflow in northern Australia, even of recent vintage, are based on Cull and Conley (1983). They show the present-day value in the Arafura Sea as greater than 2 heatflow units (HFU), that is, above 84 mW/m^2. Their map of data sources does not show any in the offshore Arafura Sea, and indeed their paper predates nearly all of the drilling in this poorly known area. Money Shoal-1 was the only well then in the basin, and it has an atypically high heatflow, being drilled in a shallow basement area near the northern edge of the Darwin Platform and possibly outside the Arafura and McArthur Basins (Moore, 1995a, b). Measured temperature data at Arafura-1, Goulburn-1 and Tuatara-1, indicate a much lower value of 1 HFU or less within the basins, especially in the east.

The average geothermal gradient 'g' at a location was calculated from the recorded BHT, the seabed temperature, and the depth of the well. The sea bed temperature of 18°C

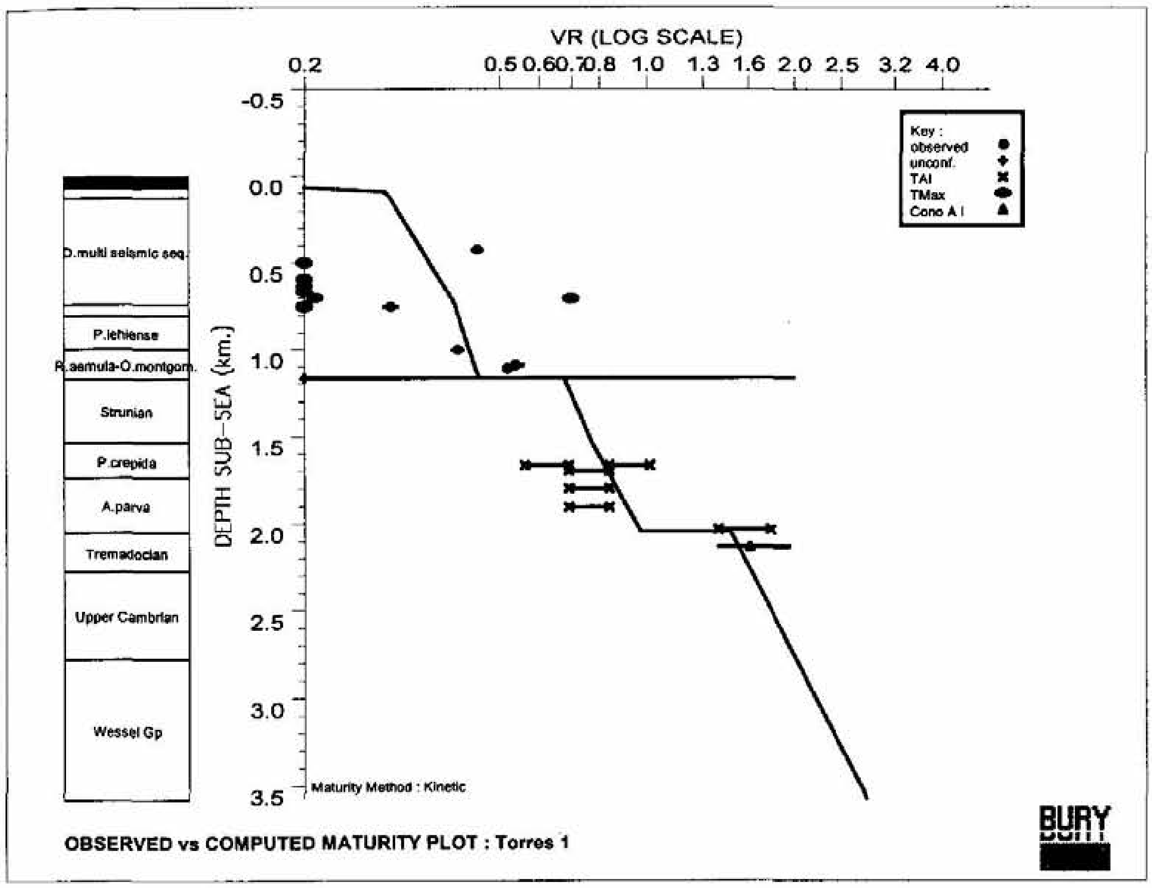

Fig. 7 - Measured thermal maturity in Torres-1 well, and the modelled maturity profile (plotted line). Horizontal steps indicating sudden increases in maturity are seen at the two main uncomformities.

used in some reports is wrong. The water temperature at 10m depth was measured by AGSO's vessel Rig Seismic at 31°C. At Arafura-1, the sea bed temperature at 64 m depth was measured as 26°C. The underestimation of sea bed temperature is one of the factors leading to an overestimation of the gradient (g) and the heatflow (HF). Modelling of past values began, initially with a constant HF based on the present-day value. This resulted in plots of expected thermal maturity. These expected values were then compared with the measured values of maturity, and other indications of past thermal regimes measured at various depths and by various methods in the wells. It was found that a constant heatflow based on the present-day value was much too low when compared with the measured maturity parameters. The palaeo heatflow was modelled iteratively until it matched the observed values of vitrinite reflectance and other maturity indices as closely as possible.

Maturity profiles and unconformities

The Torres-1 well, drilled on the crest of the largest anticline in the Goulburn Graben, best shows the effects of the tectonic events that influenced the development of the graben. There is a good record of thermal maturity measurements in this well (Fig. 7), including vitrinite reflectance (VR), thermal alteration index (TAI) Tmax from Rock-Eval pyrolysis and conodont alteration index (CAI). The resulting thermal maturity profile (the plotted line) constrained the thermal history and subsidence/erosion models in this and other wells.

A major erosional episode is revealed by a rightward step in the plot at 2068 m KB. There is a large increase in the measured maturity, evidence of deep burial and elevated heatflow followed by erosion. This coincides with a 100 million year (Ma) gap in the stratigraphic succession, embracing the time period from the Early Ordovician (470 Ma) to the Middle Devonian (370 Ma). To explain the maturity increase, a small (15 mW/m^2) heatflow anomaly has been postulated, together with a large amount (4000 m) of burial, uplift and erosion (Fig. 8). This event, though recorded at many wells in the Arafura Basin, is not clearly evident on seismic sections (Petroconsultants, 1989) and, although the stratigraphic gap is widespread in northern Australia, it is not well understood. The event is thought to be related to the Rodingan Movement in the Amadeus Basin, or even to the rifting of one of the China terranes from Gondwana at 420 Ma (Metcalfe, 1994).

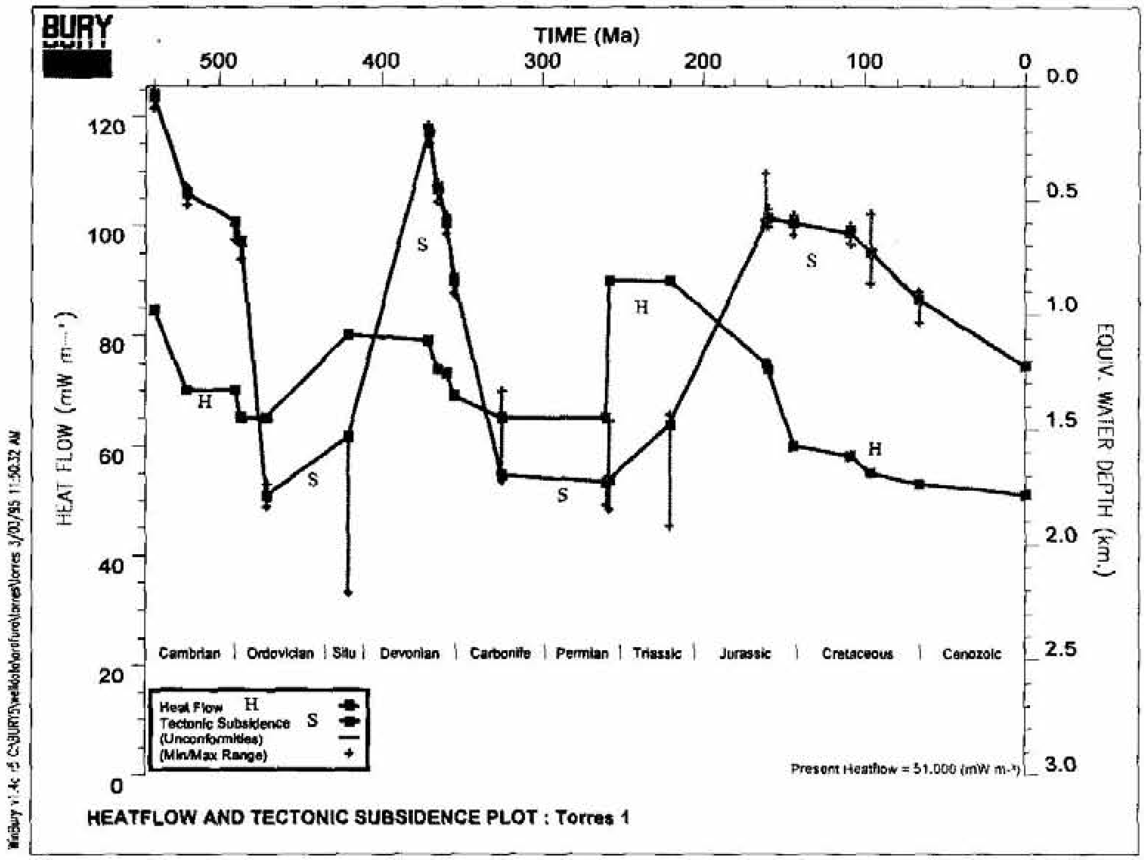

Fig. 8 - Model of subsidence (S) and heatflow (H) at Torres-1 well.

The base Callovian/latest Devonian (Famennian) unconformity at 1188 m KB in Torres-1 spans 193 million years from 354 to 161 Ma. Using evidence from other wells, e.g. Tasman-1 and Chameleon-1, the minimum disturbance compatible with the observations has been modelled, namely a modest heatflow elevation of 25 mW/m^2 (from 65 to 90) and erosion of 2500 m. The seismic evidence of uplift and erosion at the site agrees with this model.

The main heatflow anomaly has an abrupt onset, taking only 3 million years, from 260 to 257 Ma, to reach maximum, but the higher heatflow persists to 220 Ma. This is in agreement with the stratigraphic and thermal evidence from the other wells, and reconstructions of the history of the northern Australian margin incorporating a Permian heating event, and a Late Triassic tectonic episode which initiated the final stage in the creation of the Goulburn Graben (Petroconsultants, 1989; Bradshaw et al., 1990). In this model the heatflow does not return to base level until 143 Ma.

Hydrocarbon occurrences and their sources

Oil shows and bitumen were observed in fractures and vuggy porosity throughout the Late Devonian (lower Fammenian) and Early Ordovician successions at Arafura-1, with low amounts of bitumen also being present in early Middle Cambrian carbonates (Petrofina, 1983). Two zones of live oil were reservoired beneath claystone seals; the uppermost oil was present in Late Devonian (*A. parva* zone) dolomitic siltstones over the depth interval 1408-1464 m, and the lower oil occurred towards the top of an Early Ordovician (Tremadoc *P. elegans* zone) dolomite between 1835 and 1898 m. A drill stem test (DST 1) within the latter depth range recovered only water. Significant gas shows were encountered in Late Devonian dolomitic siltstones below 1409 m and in Cambrian carbonates at 3494 m.

Rock-Eval pyrolysis shows that potential oil-prone source rocks containing Type II/III kerogen are present within the Late Devonian (lower Fammenian) and Middle Cambrian successions at Arafura-1 (Table 1). The Late Devonian claystones and siltstones have low thermal maturity (mean Tmax = 435°C: CAI = 1: Bob Nicoll, AGSO, pers. comm.), whereas the Middle Cambrian calcareous claystones are within the conventional peak oil generation window and hence, they have most probably generated the oil found in Arafura-1. Palynological and geochemical studies have not identified *Gloeocapsomorpha prisca*-rich Ordovician source rocks, comparable to those of the Amadeus and

AGSO No.	Sample Type	Depth m	Age	TOC %	Tmax °C	S1 kg hc/tonne	S2 kg hc/tonne	S3 kg hc/tonne	S1/S1+S2	HI mg hc/gTOC
*	Core 1	1424.37	Late Devonian	3.86	429	1.26	11.42	0.43	0.10	296
*	Core 1	1425.35	Late Devonian	0.75	438	0.17	1.91	0.20	0.08	255
*	Core 1	1425.95	Late Devonian	1.26	437	0.40	1.96	0.39	0.17	156
*	Core 2	1435.16	Late Devonian	1.01	437	0.24	2.14	0.04	0.10	212
5097	Cuttings	3294-3296	early Middle Cambrian	0.58	450	0.25	0.88	nd	0.22	152
*	Cuttings	3295.50	early Middle Cambrian	1.26	435	0.60	1.93	0.88	0.24	153
5098	Cuttings	3488-3492	early Middle Cambrian	3.64	451	1.59	7.43	nd	0.18	204
*	Cuttings	3492.60	early Middle Cambrian	8.65	446	2.76	10.69	0.89	0.21	124
5099	Cuttings	3494-3496	early Middle Cambrian	3.78	450	2.11	7.37	nd	0.22	195
5100	Cuttings	3574-3576	Early-Middle Cambrian	1.05	457	0.48	1.29	nd	0.27	123

* Data from WCR (Petrofina, 1983).

Table 1. TOC and Rock-Eval pyrolysis data for Arafura-1 source rocks.

Canning Basins, in this or any of the other wells within the Goulburn Graben.

Geochemical and carbon isotopic data were obtained for the Late Devonian reservoired Arafura-1 oil (sample 5092) and for two Cambrian source rock extracts (samples 5099 and 5100). The oil is a biodegraded aromatic-naphthenic crude oil (Petrofina, 1983). The saturates chromatogram of the oil exhibits a large unresolved complex mixture (Fig. 9) and most of the *n*-alkanes have been removed by bacterial alteration in the reservoir. However, the level of biodegradation is only moderate (level 3; Peters and Moldowan, 1993) and appears not to have affected the terpane and sterane biomarkers. The saturates chromatograms of the Cambrian extracts, which show some variability due to local facies differences, are reminiscent of Neoproterozoic, Cambrian and Ordovician oils and source rocks of the Amadeus Basin (Summons and Powell, 1990). For example, the unimodal n-alkane profiles are dominated by the low molecular weight homologues (range = C_{12}-C_{34}; maximum at C_{15}) with no odd or even carbon number preference, and there is an abundance of monomethyl alkanes.

The similarity between the biomarker assemblages and isotopic signatures of the Arafura-1 oil and the Middle Cambrian organic-rich rocks implies that these marine calcareous claystones are the source of the oil. The biomarker compounds indicate an input of marine algal and bacterial remains to the source beds. Tricyclic terpanes dominate the biomarker assemblages and although the origin of these compounds is unknown, they are commonly found in mature marine source rocks and their derived oils. The C_{27}-C_{29} sterane distributions of the oil and the source rocks show a slight preference of the C_{29} homologue which is consistent with their Early Palaeozoic age (Grantham and Wakefield, 1988) and derivation from green algal

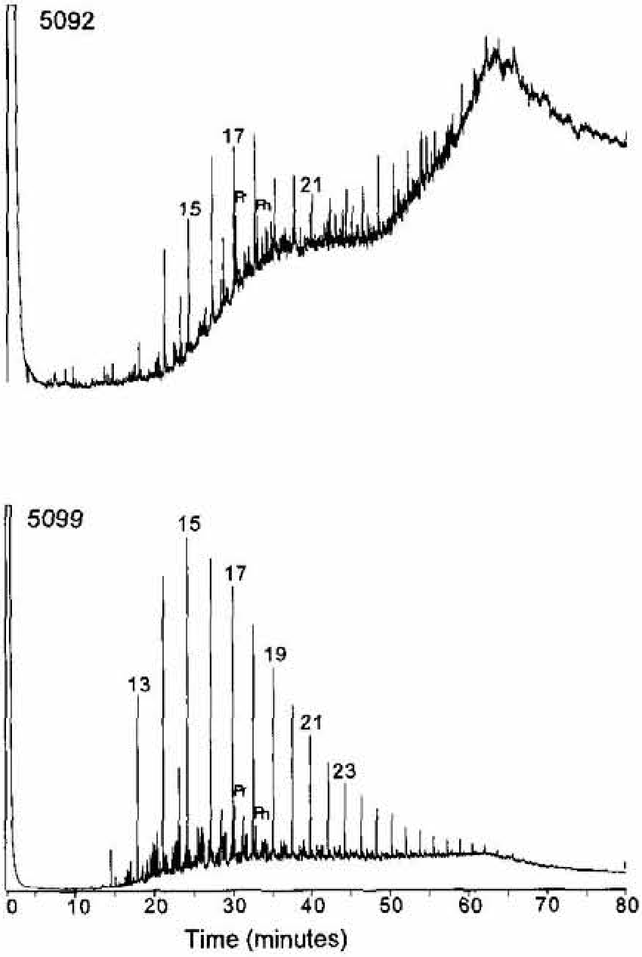

Fig. 9 - Gas chromatograms of saturated hydrocarbons of a Late Devonian reservoired oil (5092) and a representative extract of Middle Cambrian claystone (5099) from Arafura-1. Numbered peaks refer to carbon number of n-alkanes; Pr denotes pristane and Ph phytane.

AGSO No.	Sample Type	Depth m	Saturates %	Saturates $\delta^{13}C$	Aromatics %	Aromatics $\delta^{13}C$	Polars %
5092	Oil stain Core 2	1433.60	34.5	-31.98	25.5	-31.52	40.00
5099	Source rock Cuttings	3494-3496	49.9	-32.75	19.4	-31.64	30.6
5100	Source rock Cuttings	3574-3576	58.2	-31.56	16.0	-30.59	25.8

Table 2. Compositional and carbon isotopic data ($\delta^{13}C$ PDB) for oil and source rocks, Arafura-1.

precursors. In the oil, rearranged steranes and hopanes are present in lesser abundance than their non-rearranged homologues which is compatible with hydrocarbons generated from a calcareous claystone. The presence of 28,30-dinorhopane indicates that the organic matter was deposited under anoxic conditions.

The carbon isotopic signature of the oil and the Cambrian claystones is light (Table 2) and is typical of Early Palaeozoic oils (Stahl, 1977). Comparison of the carbon isotopic signature of the Arafura-1 oil with Early Palaeozoic (Ordovician, Devonian and Carboniferous) oils in the neighbouring Petrel Sub-basin and Canning Basin shows that the Arafura-1 oil has a greater affinity with the Cambrian rock extracts and Ordovician oils than to either Devonian or Neoproterozoic-sourced oils (Fig. 10).

In view of the similarity between the biomarker and isotopic signatures of the Arafura-1 oil and the Middle Cambrian organic-rich rocks it is concluded that these marine calcareous claystones are the source of the oil.

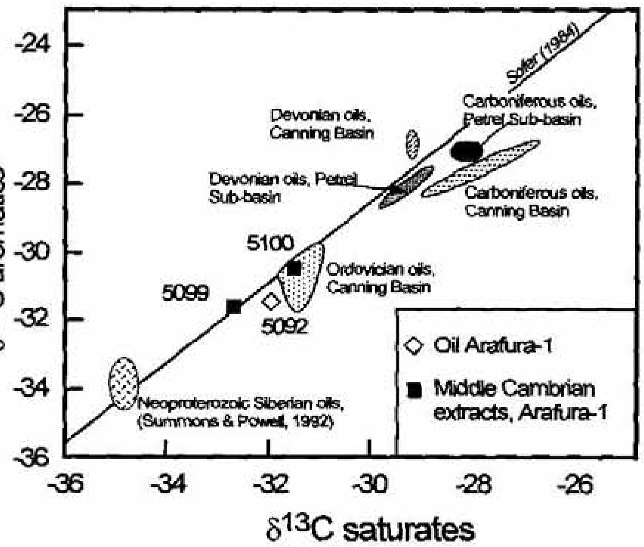

Fig. 10 - Carbon isotopic compositions (relative to PDB) of C12+ saturated and aromatic hydrocarbons for oil (sample 5092) and Cambrian source rocks (5099 and 5100), Arafura-1: comparison with Neoproterozoic and Early Palaeozoic oils.

Timing of hydrocarbon generation, migration and entrapment

Goulburn Graben

Figure 11 shows the temperature history of the succession at Arafura-1. The succession is not now at its maximum temperature - that occurred during the Early Permian. It can be seen that the Devonian and the Early Ordovician levels at which the oil shows were found have not been exposed to temperatures greater than about 80°C. They are not now in the oil generation window at the site, and the likelihood that they achieved sufficient maturity to begin expulsion of hydrocarbons during their period of maximum temperature is problematical. The oil in the well, therefore, probably migrated there either laterally from a mature sequence of the same age downdip, or vertically, from the Cambrian or Proterozoic succession. Generation from the Middle Cambrian Wessel Group occurred between the Carboniferous and the Triassic periods, from 350 to 200 million years ago.

A synthetic wellsite downdip from Arafura-1 and just inside the Goulburn Graben was analysed. This site, Ar1 north on Figure 1, is the deepest location near the well, being near the northern bounding fault. It is 10 km from Arafura-1, and contains an extra 1500 m of Late Carboniferous and Early Permian sediments. Present-day heatflow was calculated using the same thermal gradient as in Arafura-1. The analysis (Moore, 1995b) showed that oil generation and expulsion from the Lower Devonian *A. parva* zone could have commenced in a small volume of mature source rock in the Early Permian, but stopped during the Late Triassic. The immediately underlying Early Ordovician *P. elegans* zone yielded a similar conclusion, being mature deep in the graben only.

In contrast, the Middle Cambrian succession reached full maturity around the Arafura-1 site, and is the most likely source of the shows in the well.

The seismic cross-sections demonstrate that the magnitudes of subsidence, faulting and uplift were greater further to the

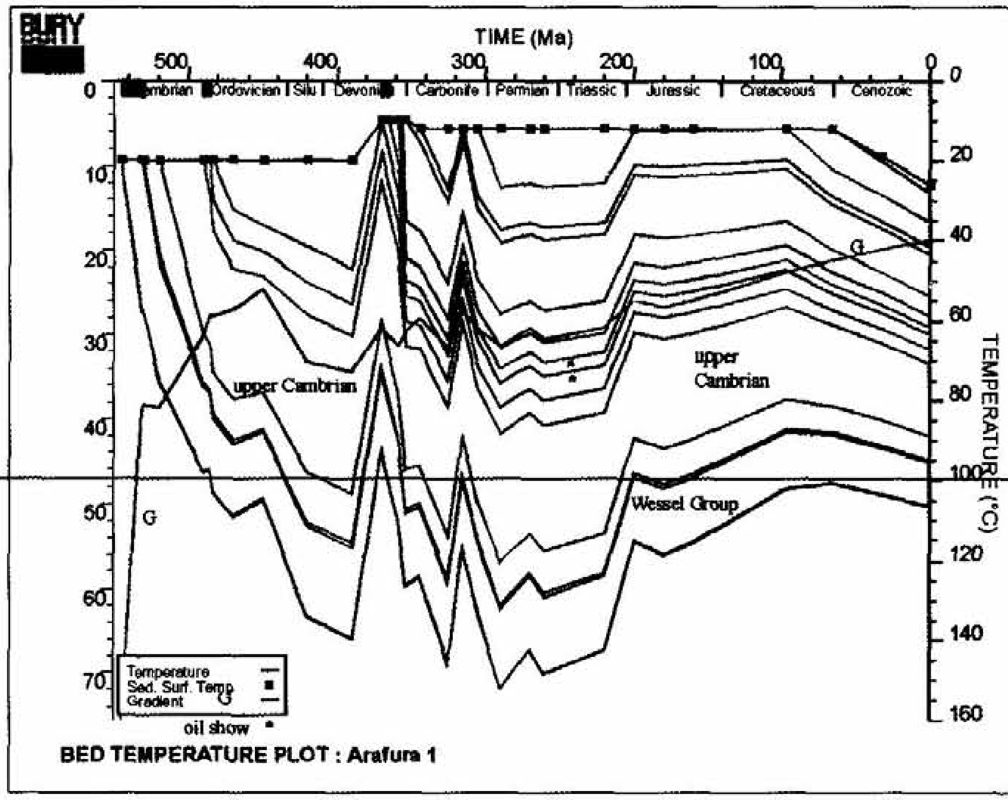

Fig. 11 - Bed temperature history of Arafura-1. Intervals that had oil shows in the well are shown with an asterisk.

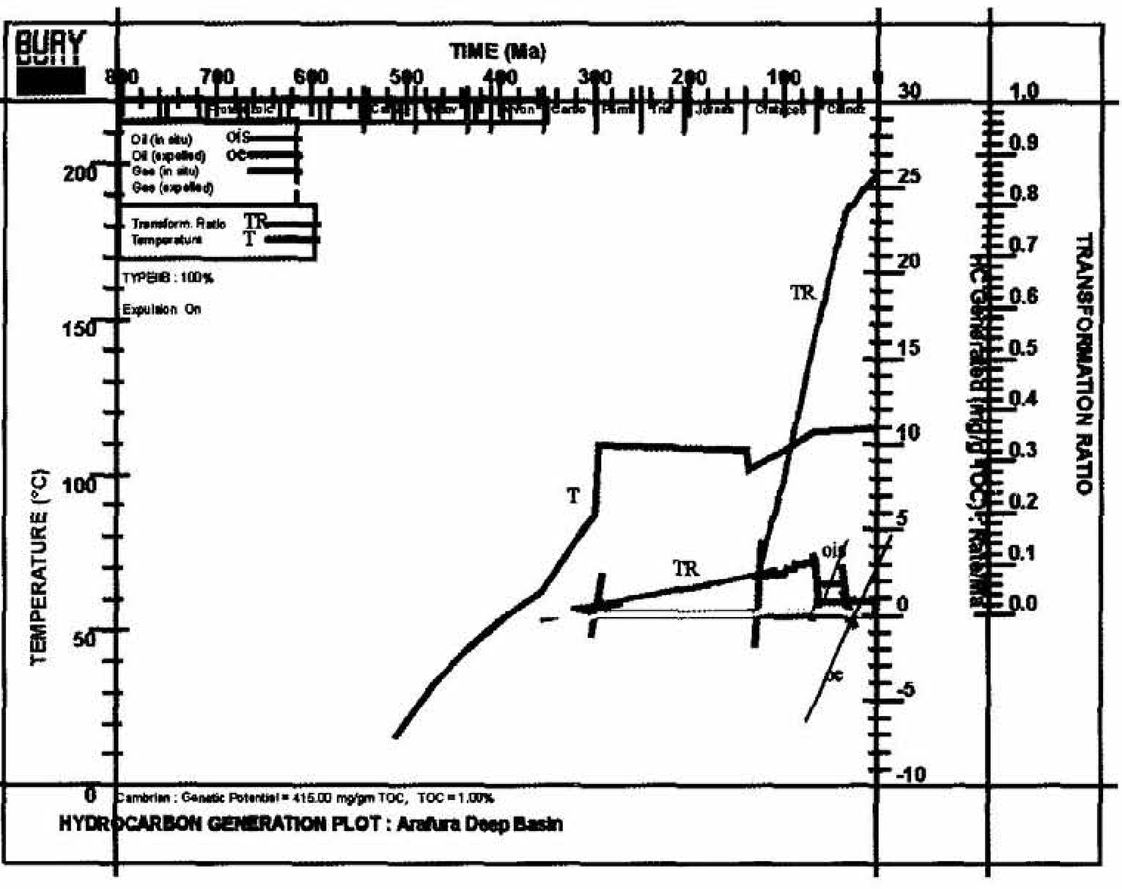

Fig. 12 - The timing of hydrocarbon generation at the depocentre of the northern Arafura Basin.

west. The geohistory analyses of Torres-1 and other wells reinforce this conclusion and make it clear that the Cambrian to Devonian rocks were buried to maturity and then uplifted prior to the formation of the Goulburn Graben during the Triassic. During this deep burial any potential hydrocarbons were generated and expelled. The final destination of those hydrocarbons is unknown, because little information about the configuration of the basin in this early stage of its development has survived.

Cooling during the Silurian uplift terminated the generation of hydrocarbons in the area now occupied by the Goulburn Graben. The Cambro-Ordovician sediments were buried again, though not as deeply, during the Permo-Triassic, so that generation did not resume, and has not done so since, in the area of the graben. A very small volume of the Lower Devonian succession that yielded shows at Arafura-1 was also buried and heated to maturity during this later tectonic episode. Large-scale uplift of the Torres Anticline and other areas followed, during formation of the Goulburn Graben. Existing traps were disrupted by the transformation of structure that occurred in the Triassic. Tectonic movements were not as great in the east, so early formed traps there might have survived the Triassic diastrophism, or, alternatively, source rocks might not have been as deeply buried during graben formation. The very small closure, formerly containing oil, in the vicinity of Arafura-1 (Moore, 1995a), suggests that hydrocarbons may survive better in a gentler tectonic environment.

Northern Arafura Basin

The northern basin has had a much quieter tectonic history than the Goulburn Graben. Early-formed traps there may have survived, or source rocks might not have become generative until more recent times. The synthetic site Arafura Deep Basin (ara deep on Fig. 1) is located in the deepest part of the northern basin, outside the graben and north of Chameleon-1. Most of this northern province does not show signs of deformation, and unconformities are not visible on seismic cross-sections, except at the base of the Money Shoal Basin succession. The extent of epeirogenic movement and consequent erosion is unknown, but it is assumed to be small here in the basin centre, and greater on the flanks.

The pre-Mesozoic succession is assumed to be Permian to Cambrian in age, with the Proterozoic McArthur Basin underneath. Figure 12 shows the evolution of Type II kerogen in the Cambrian succession, according to the geohistory model. The transformation of kerogen into hydrocarbons (expressed as a percentage on trace TR) began in the Carboniferous, and proceeded slowly until the Early Cretaceous, when generation became significant. There was no oil migration during this time. The accumulation of Money Shoal Basin sediments during the Cretaceous triggered full generation within the source (ois), followed by oil expulsion (oe) and migration, which began during the Cenozoic. By this time, traps existed at many locations, including the upthrown rim of the graben, and a regional seal was deposited widely during the Late Cretaceous. This area, therefore, is far more attractive for hydrocarbon exploration than the Goulburn Graben, since the timing of oil generation and trap formation is correctly aligned, and source rocks may be currently generating hydrocarbons. The risk is that large epeirogenic movements, subsidence and erosion, triggered earlier oil migration before trap formation, and then uplifted the area sufficiently, so that the Money Shoal Basin overburden did not return it to generative temperatures. In the basin centre, that is less likely; it is more likely on the flanks.

Eastern and western flanks

Structural highs are shown on the northwestern flank (Fig. 5), where the Arafura Basin infills older fault blocks (Labutis et al., 1992). The fault blocks probably comprise Mesoproterozoic sediments of the McArthur Basin, but the onlapping 'rift-fill' is thought to be of Cambrian age. Hydrocarbons from the Middle Cambrian source that generated the Arafura-1 oil could have been trapped and preserved there.

The synthetic site North Kulka (n kulka on Fig. 1) was modelled in this area, using depths based on the interpretation of an AGSO seismic profile. One kilometre of uplift and erosion deep within the Arafura Basin succession has been incorporated in the model, and the Ordovician and Silurian successions are missing. Figure 13 shows that hydrocarbon generation from Type II kerogen in the basal Cambrian/top Roper Group has only recently begun, driven by the accumulation of Money Shoal Basin sediments. The Mesoproterozoic Velkerri Formation source rock (Crick et al., 1988; Crick, 1992) could be within the 'oil window' and generating. If more uplift and erosion had occurred, say one kilometre more at the top of the Devonian, then the generative interval (the oil window) should now be at a shallower level in the Cambrian succession, having recently resumed generation after a pause since the Devonian. In that case, there is a risk to reservoir quality except where pre-existing hydrocarbon accumulations might have preserved it.

On the eastern flank a synthetic site (ne wessel) located north of the Wessel Islands was analysed. Here the base of the Cambrian/top of Roper Group is immature for

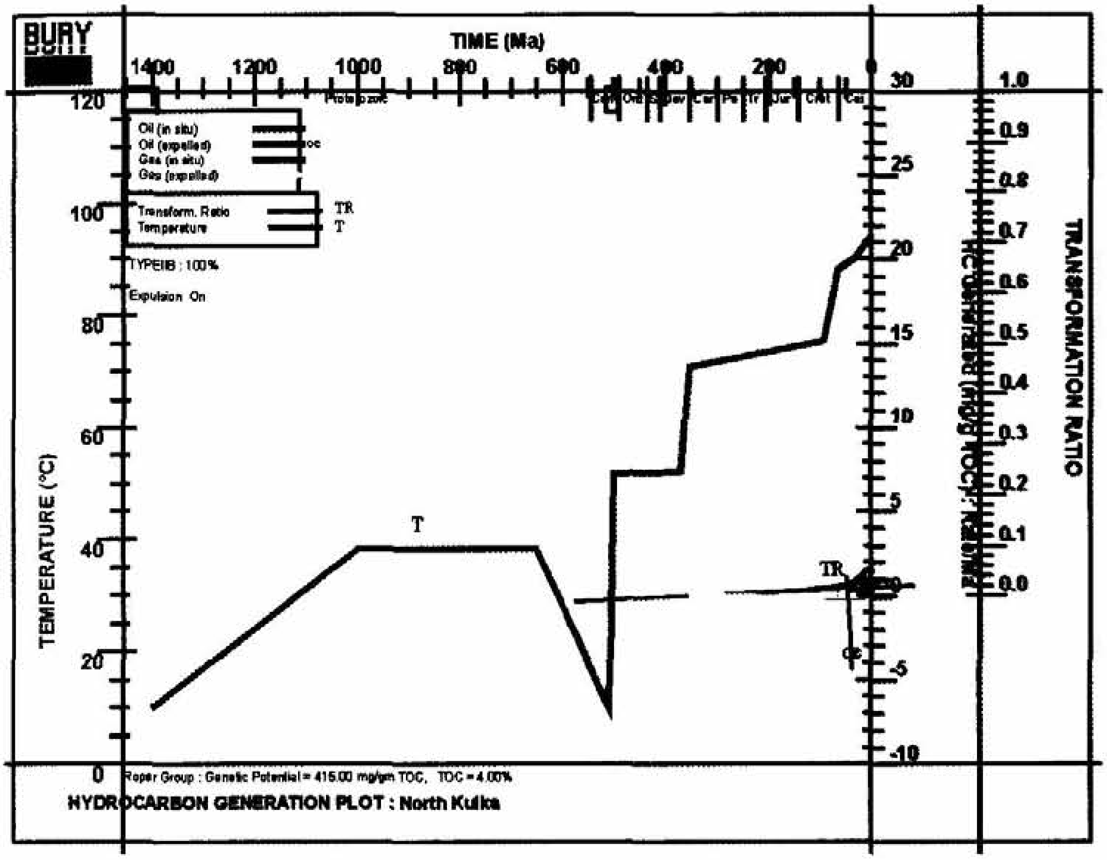

Fig. 13 - At the North Kulka site on the northwestern rim of the Arafura Basin, hydrocarbon generation has only recently begun at the level of the basal Cambrian, top of Roper Group. Maturity is higher than this, and possibly near peak oil generation, at the level of the Velkerri Formation oil source rock (Crick et al., 1988) within the Group. In this model, 1000 m of sediments younger than the Roper Group have been eroded from the basal Cambrian uncomformity.

hydrocarbon generation (Moore, 1995b). The Proterozoic sequence beneath the base of the Cambrian shows clear signs of uplift and peneplanation. The source rocks, e.g. the Barney Creek Formation, expelled their hydrocarbons at an early (ie Precambrian) date. Very early structuring would be required to preserve hydrocarbons in this area. There is some evidence of old structuring in the Walker Fault Zone, of which signs are visible nearby on seismic profiles.

Conclusions

The eastern Arafura Sea contains a suite of overlapping sedimentary basins extending northward from Arnhem Land to the limits of Australian territorial waters and on into eastern Indonesia. Only one part of this complex, the Goulburn Graben, has been explored by drilling.

North of the graben, the mainly Mesozoic Money Shoal Basin partially overlies a thick sedimentary basin, possibly an intracratonic sag resembling the Williston or the Amadeus/ Georgina Basins. The unexplored basin dates from the Mesoproterozoic, and persisted on the northeastern rim of Gondwana through the Palaeozoic. Signs of deformation, uplift and erosion are absent in the centre, but obvious on the flanks, on one of which (the southwestern) the Goulburn Graben is located.

The Goulburn Graben is far from being a normal extensional feature, a 'keystone graben'. It is the site of an Early Palaeozoic hingeline that was subjected, first to transtension in the Early Permian, and then to left lateral wrenching and transpression, probably during the Triassic.

The depocentre of the Palaeozoic Arafura Basin lies north of the graben. The Mesoproterozoic McArthur Basin, which outcrops onshore and contains proven oil source rocks, probably continues under this depocentre. If large scale uplift and erosion has not occurred there, then large volumes of these two basins north of the graben are now at a temperature at which oil generation and migration can occur.

The oil seen in Arafura-1 in the calcareous Devonian (*A. parva* zone) and in the Lower Ordovician dolomite (*P. elegans* zone) originated in a marine Cambrian source rock.

The oil has been in its present site since about the Late Permian period. It survived the Triassic diastrophism, possibly because the movement was gentler in the east than further west, and because the time of trap formation preceded that of oil migration.

Within the future site of the Goulburn Graben, the most prospective successions, the Cambrian and Lower Ordovician (Tremadocian), achieved maturity for hydrocarbons at an early epoch. This maturity was the result of both burial and elevated heatflow, and occurred as early as the Silurian in places. Likewise, the Devonian and the Permo-Carboniferous successions reached maturity for oil during the subsidence that accompanied the initiation of the graben during the Permian, and before the transpression that caused the uplift of the Torres Anticline during the Late Triassic. Most structural traps within the graben are products of the latter process, and thus post-date the main episodes of hydrocarbon generation.

The tectonism, exposure and erosion that followed the early burial of Palaeozoic source rocks allowed remigration or escape of the hydrocarbons that were generated. The extensive uplift that ensued brought formerly very deeply buried reservoirs within range of the drill. These reservoirs have been degraded by the consequences of deep burial, such as compaction, and pressure solution of quartz.

The Mesozoic-Tertiary succession that followed the last phase of tectonism in the Triassic is almost everywhere immature for hydrocarbons.

Hydrocarbon exploration strategy should look for early-formed traps that might have intercepted any hydrocarbons migrating during the Palaeozoic. The most likely location for such traps is outside the Goulburn Graben to the north, where structuring appears to be older. Within the graben, the Cambro-Ordovician and the Devonian-Ordovician time-thickness (isotime) maps (Moore, 1995a) show features east of Money Shoal and southwest of Arafura-1 that suggest early structuring there, but the deep burial that accompanied the formation of the graben may have degraded the reservoirs.

If the Early Palaeozoic succession was not subjected to deep burial outside the graben, it should have remained immature in places until more recent burial by the Money Shoal Basin succession. If, as appears likely, the areas north of the graben were not subjected to the same intensity of subsidence, tectonism and uplift, then the reservoirs may not be as greatly damaged by diagenesis as those in the graben have proven to be. There is an analogy here with the Canning Basin, where reservoirs commonly are poor in the Fitzroy Graben, but often very good on the flanking terrace or platform areas.

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