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Petroleum Geology of the Arafura and Money Shoal Basins

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With contributions from Jennifer M. Totterdell, Heike I.M. Struckmeyer and Karen L. Earl

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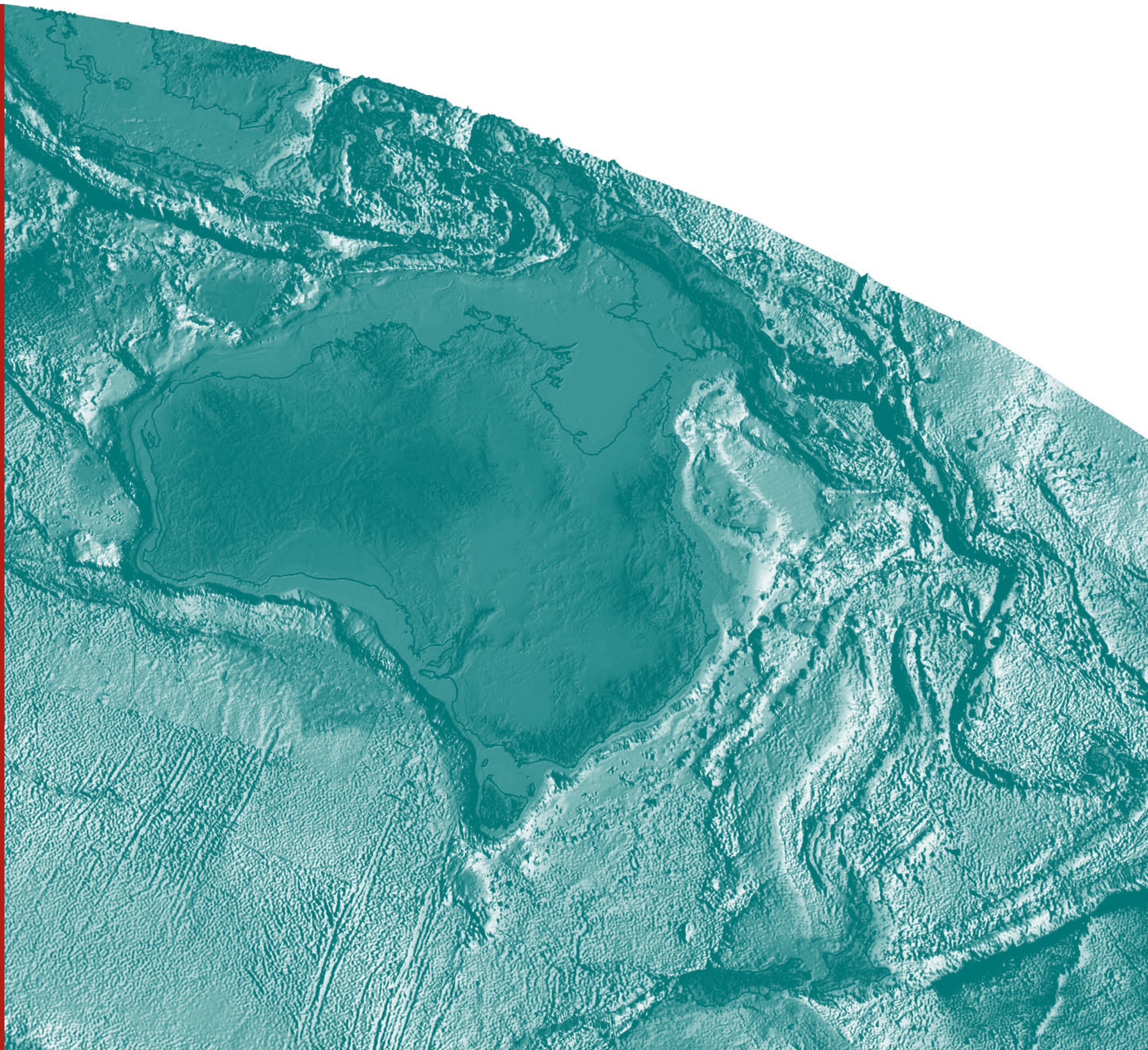

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Executive Summary

This report presents the interpretive results of a comprehensive geological framework study based on new and existing well and seismic data. The study was initiated in 2003, as part of Geoscience Australia's Big New Oil Program to address exploration risks in a shallow water frontier basin.

The Arafura Basin is a Neoproterozoic to Palaeozoic intracratonic basin that extends from onshore Northern Australia across the Arafura Sea into Indonesian waters. It is overlain by the Mesozoic to Cenozoic Money Shoal Basin. The basins are located in shallow (< 220 m deep) water and have been the target of limited petroleum exploration since the 1970s. Nine exploration wells were drilled between 1971 and 1993, with some encouraging hydrocarbon shows and indications.

The subsidence and uplift history of the Arafura Basin can be described in terms of five major basin phases – four subsidence phases, and one uplift phase. Although the depositional history of the basin covers an extremely long time span, its subsidence history has been episodic, limited to periods of basin-wide subsidence (Basin Phases 1–4) in the Neoproterozoic (Wessel Group), Middle Cambrian–Early Ordovician (Goulburn Group), Late Devonian (Arafura Group) and Late Carboniferous–Early Permian (Kulshill Group). These were separated by long, relatively tectonically quiescent periods of non-deposition and erosion. Two major episodes of upper crustal extension — NW-SE extension in the Neoproterozoic and NE–SW extension in the Late Carboniferous–Early Permian — resulted in the deposition of thick growth sections and set up the structural architecture of the basin. In comparison, other basin-wide phases of deposition in the Middle Cambrian–Early Ordovician and Late Devonian do not appear to have been controlled by upper crustal extension. Minor localised deformation in the Devonian and Carboniferous was probably due to the effect of far-field stresses associated with the Alice Springs Orogeny. During the Middle–Late Triassic, the basin, and in particular the Goulburn Graben, underwent a major phase of contractional deformation (Basin Phase 5). The impact of this event varies markedly across the basin. In the Goulburn Graben it was characterised by inversion on pre-existing faults, folding, uplift and the formation of thrust faults. The northern Arafura Basin was affected to a lesser extent, and relatively minor contractional reactivation of Neoproterozoic half graben resulted in the formation of inversion anticlines.

The overlying Money Shoal Basin is a mainly offshore, Middle Jurassic to Recent basin, up to 4.5 km thick. It is continuous with the Bonaparte Basin to the west and forms the onlap edge of the Mesozoic to Cenozoic succession which rapidly thins to the east.

Organic geochemical data indicate the presence of at least four potential source rock intervals in the Arafura and Money Shoal basins. An Early Middle Cambrian potential source rock with algal/bacterial affinities has been correlated geochemically to oil shows at Arafura 1 and Goulburn 1, and is considered to be the prime source rock in the basin. Other potential source units are present in Neoproterozoic, Devonian, Permo-Carboniferous and Middle–Late Jurassic sediments. Geohistory modelling suggests that, in the Goulburn Graben and in most of the northern Arafura Basin, expulsion of light oil and gas from a Cambrian source rock is likely to have occurred during the Palaeozoic. In the northern Arafura Basin, where the Triassic deformation was less pronounced and early formed traps probably remained intact, these hydrocarbons could be preserved. A late, Mesozoic to Cenozoic expulsion phase from the Cambrian source rock is modelled for the western part of the northern basin. Expulsion from Devonian to Jurassic potential source rocks is likely to have only occurred in the western Arafura and Money Shoal basins during the Permian to Recent.

Although limited, the available dataset strongly suggests that potential clastic reservoir rocks occur in both Palaeozoic and Mesozoic rocks, and that secondary porosity

in Palaeozoic carbonate sequences could be important for reservoir development. In the northern Arafura Basin, Palaeozoic reservoir quality could be improved because of reduced hydrothermal alteration and shallower burial. Potential seal rocks are present throughout the succession, with potential regional seals present in the Devonian and Cretaceous sections. Seismic data suggest that various potential play types are present, including large faulted anticlines and fault blocks that could provide traps at several stratigraphic levels. Inversion anticlines formed during the Triassic deformation provide large-scale potential traps. Sub-unconformity plays below the Triassic regional unconformity are present within Neoproterozoic and Palaeozoic strata. The Mesozoic Money Shoal Basin contains a variety of stratigraphic and combined structural/stratigraphic plays for hydrocarbons sourced from underlying Palaeozoic sediments and from mature Late Palaeozoic and Mesozoic source kitchens in the westernmost part of the basin

To date, no commercial discoveries have been made in the Arafura Basin, but there are numerous hydrocarbon indications in wells drilled in the Goulburn Graben, including oil shows in Arafura 1 and Goulburn 1. In the northern Arafura Basin, indirect hydrocarbon indications such as shallow gas interpreted on sub-bottom profile data and conventional seismic data, and pockmarks on the seabed coincide with a zone of degraded seismic data, which could represent hydrocarbons within the section. In the same area, SAR slicks on the sea surface align with a basin depocentre where the regional Cretaceous seal appears to be below a critical thickness. The coincidence of these indicators provides the strongest evidence yet for an active petroleum system in the northern Arafura Basin.

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INTRODUCTION

Heike I.M. Struckmeyer and Karen L. Earl

The Arafura Basin is a Neoproterozoic to Palaeozoic basin that extends from onshore northern Australia across the Arafura Sea into Indonesian waters (Fig. 1). It is located in mostly shallow water (<220 m) and has been the target of limited petroleum exploration since the 1970s. Nine exploration wells were drilled between 1971 and 1993, with some encouraging hydrocarbon shows and indications (Fig. 1). The basin is overlain by the Mesozoic to Cenozoic Money Shoal Basin.

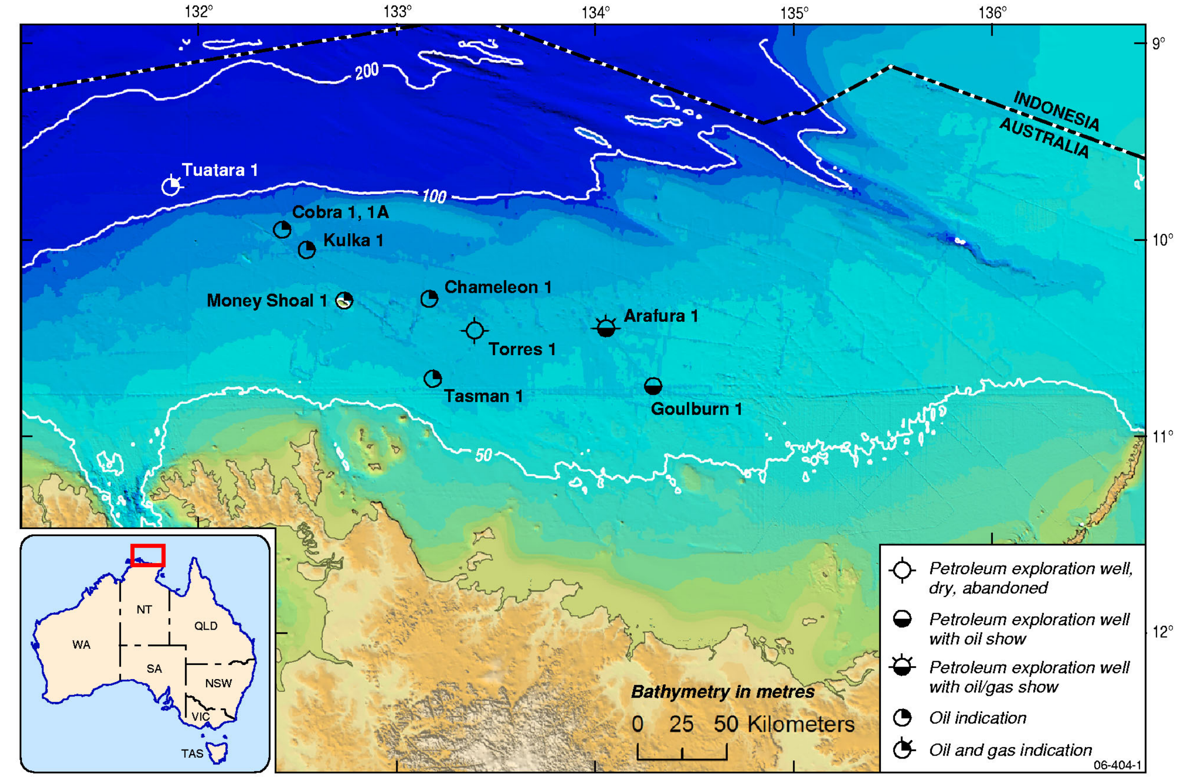

Figure 1: *Location map of the study area, showing bathymetry and petroleum exploration wells.*

In 2004–2006, Geoscience Australia conducted a study of the Arafura Basin as part of its program to investigate the petroleum potential of frontier basins. The aim of the study was to enhance the petroleum prospectivity of the Arafura Basin, particularly the northern, un-drilled part of the basin, through an improved understanding of basin geology, petroleum systems, timing of events and potential hydrocarbon seepage. This involved a comprehensive review and interpretation of existing available well and seismic data (Fig. 2). In addition, new analyses were carried out to improve biostratigraphic control, and to provide improved data on the maturity, organic geochemistry and petrology of potential source rocks (Earl, 2006; Sherwood et al., 2006; Struckmeyer, 2006). A marine survey to investigate potential hydrocarbon seepage was conducted in collaboration with the National Oceans Office in 2005 (Logan et al., 2006).

This report integrates the results of these studies with those of a seismic study carried out concurrently by providing an interpretation of the tectonostratigraphic evolution of the Arafura and eastern Money Shoal basins, the distribution of petroleum systems and the timing of critical events. One of the challenges of the seismic interpretation was that well control is restricted to the Goulburn Graben which is separated from the northern Arafura Basin by a major bounding fault system. However, there is no direct and simple correlation of the pre-Mesozoic section across the bounding fault. Correlation to the northern Arafura Basin was achieved through thorough iterative interpretation of all datasets until a consistent, sustainable correlation was attained. This was assisted by a few key seismic lines that allowed matching of the seismic character of the pre-Mesozoic stratigraphic section on both sides of the bounding fault system (Fig. 3).

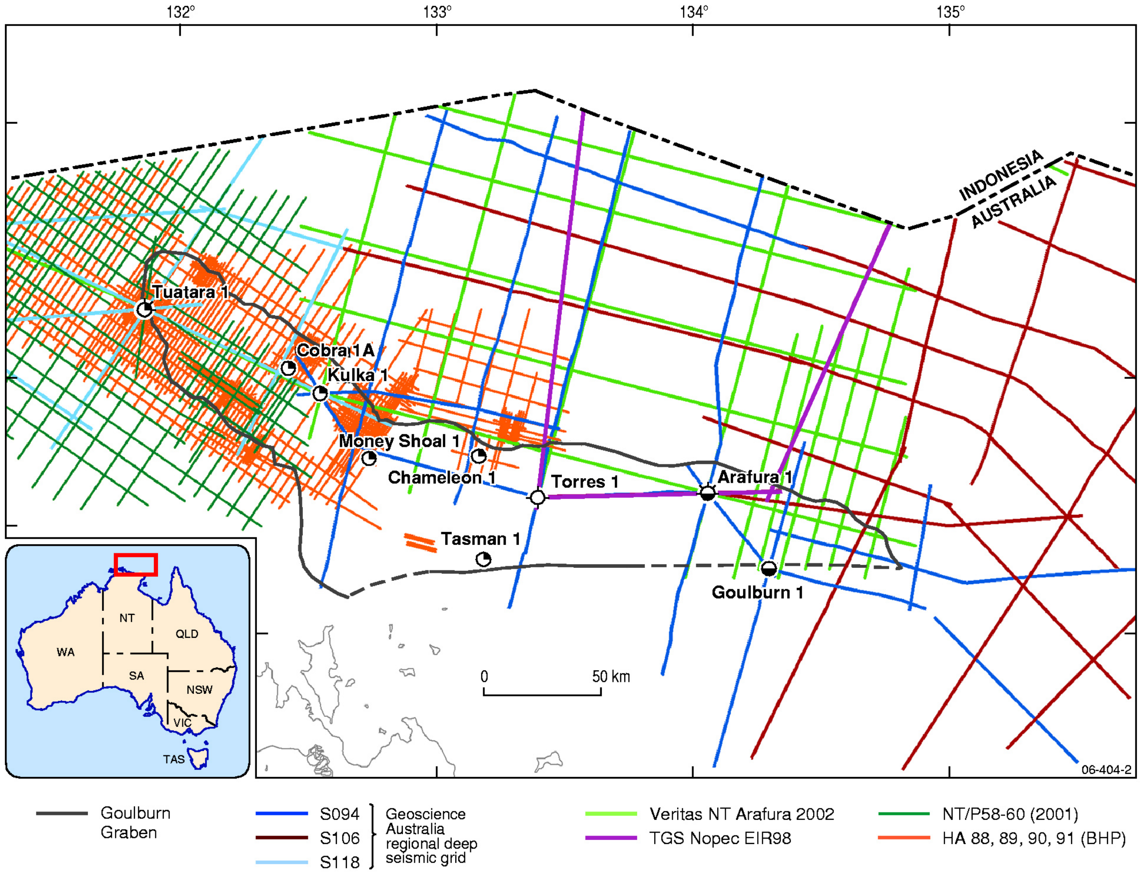

Figure 2: *Regional seismic grid used for this study.*

EXPLORATION HISTORY

Petroleum exploration in the Arafura region began in the 1920s when several boreholes were drilled on Elcho Island in response to reported bitumen strandings. In the 1960s and early 1970s, stratigraphic drilling occurred on Bathurst and Melville islands (McLennan et al, 1990). During this time Shell Development (Australia) was awarded exploration permits covering the western region of the Arafura Sea and drilled the first well in the offshore Arafura Basin, Money Shoal 1 (1971). This well was drilled primarily to test the Mesozoic Money Shoal Basin sequence. At the same time, Aquitaine was operating in the central southern region of the Arafura Sea. The two operators carried out extensive mapping based on seismic data and defined the Goulburn Graben as an important structural feature.

The next phase of exploration occurred in the early 1980s with several companies operating in the region, including Diamond Shamrock, Esso, Petrofina and Sion Resources. A number of wells were drilled at this time, all of which tested the Palaeozoic Arafura Basin sequence. Petrofina drilled two wells, Arafura 1 (1983) and Goulburn 1 (1985). Arafura 1 recorded oil shows over a 425 m interval in the Devonian and Ordovician sections and still provides the most important Palaeozoic stratigraphic control in the basin. The company also mapped a number of large fault-related closures that remain untested (Miyazaki and McNeil, 1998). Esso drilled two wells, Tasman 1 (1983), which targeted a fault block on a domal feature originally interpreted as salt-related, and Torres 1 (1983), which targeted a prominent Palaeozoic anticline. Diamond Shamrock drilled Kulka 1 (1984), which provides important stratigraphic control for the Late Palaeozoic and Mesozoic sections.

A third phase of petroleum exploration by BHP Petroleum in the late 1980s and early 1990s targeted mostly Mesozoic plays in the Goulburn Graben. The exploration program included an extensive 17,000 km seismic survey, a regional aeromagnetic survey, and the drilling of three exploration wells, Tuatara 1 (1990), Chameleon 1 (1991) and Cobra 1A (1993). During the early 1990s Geoscience Australia (then the Bureau of Mineral Resources) acquired a total of 5342 km of regional deep seismic data across the Arafura Basin (Fig. 2).

In the past 10 years, several exploration activities have contributed to the available dataset and have high-graded the prospectivity of the region. These include, for example, non-exclusive regional 2D seismic data sets by TGS Nopec in 1998 and Veritas DGC in 2002, and Synthetic Aperture Radar acquisition and interpretation across the region by INFOTERRA Ltd in 2003.

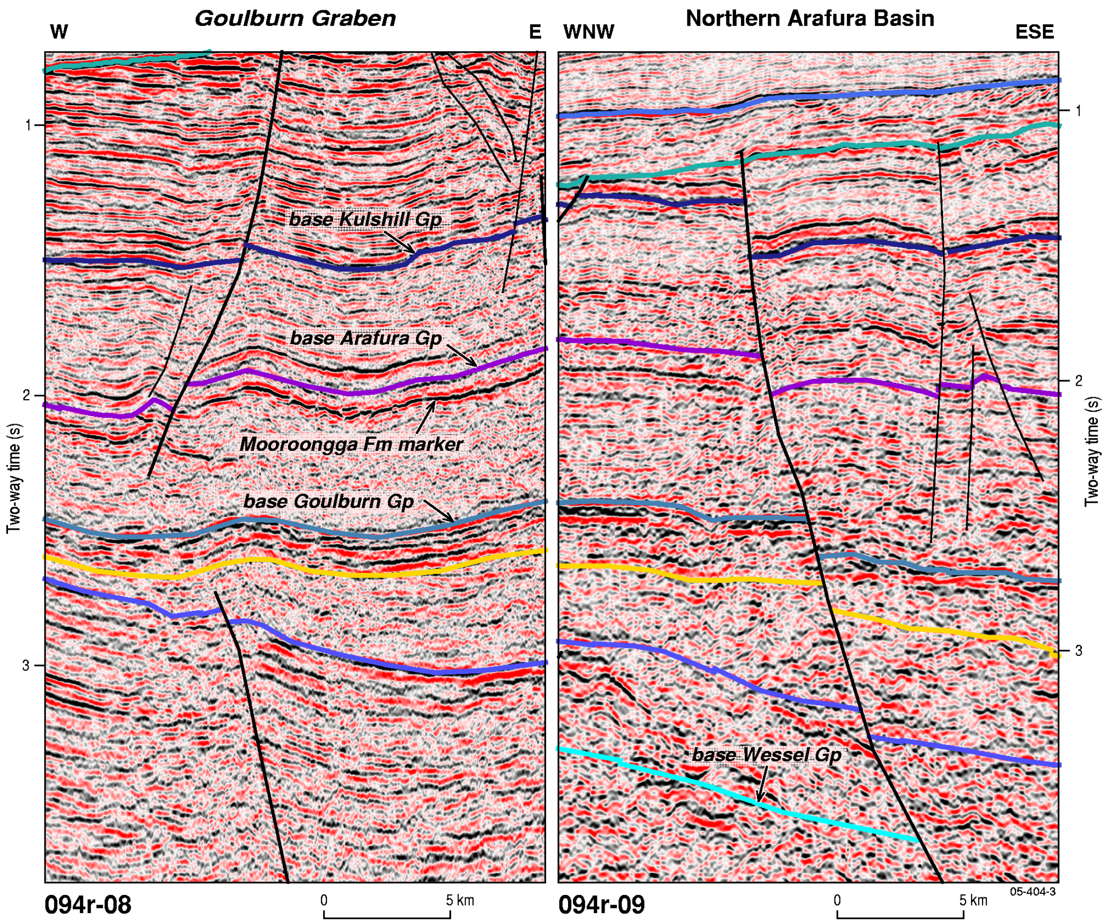

Figure 3: *Goulburn Graben – northern Arafura Basin seismic tie. Key correlation features shown are the high amplitude seismic reflection marking the base of the Early Ordovician Mooroongga Formation, and the highly reflective section at the top of the Wessel Group. The difference in seismic character of the Kulshill Group between the two seismic sections reflects the unit's rift-fill nature in the Goulburn Graben.*

BASIN EVOLUTION: ARAFURA BASIN

Jennifer M. Totterdell

REGIONAL SETTING

The Neoproterozoic to Permian Arafura Basin is located on the northern Australian continental margin (Fig. 4). Although most of the basin is situated offshore, it also extends up to 100 km onshore. The Arafura Basin unconformably overlies Archaean to Mesoproterozoic basement terranes and is overlain by the Jurassic–Recent Money Shoal Basin. The basin continues into Indonesian territory to the north.

The basin can be divided into three structural elements — the NW–SE to WNW–ESE oriented and highly deformed Goulburn Graben (Bradshaw et al., 1990), flanked to the north and east by the less deformed northern Arafura Basin (previously Northern Platform; Fig. 5), and to the south by a north-dipping but relatively undeformed ramp. The Goulburn Graben is an obliquely inverted rift that formed during a Late Carboniferous–Early Permian extensional event, and underwent contractional deformation during the Triassic. It contains up to 10 km (4500 ms TWT) of Proterozoic–Permian sedimentary section. To the north of the Goulburn Graben, the basin is up to 15 km (6500 ms TWT) thick and is characterised by Proterozoic half graben overlain by a structurally conformable Neoproterozoic–Permian section (Figs 6, 7). This part of the basin underwent relatively mild Triassic inversion.

In the Indonesian portion of the basin, a Cambrian to Permian section has been interpreted, based on well intersections offshore from West Papua (Moss, 2001). To the northwest, the poorly explored Barakan Basin exhibits gross structural and stratigraphic similarities to the Arafura Basin. Like the Arafura Basin, the flanks of the Barakan Basin were uplifted and severely eroded prior to the Jurassic (Barber et al., 2004).

BASEMENT GEOLOGY

The Arafura Basin is an intracratonic basin that formed within the Archaean–Mesoproterozoic North Australian Craton. Basement to the Arafura Basin is provided by the Pine Creek Inlier in the west and the northern McArthur Basin in the east. Both basement terranes appear to have exerted a considerable influence on the style and orientation of deformation in the basin.

Pine Creek Inlier

In the west, the Arafura Basin unconformably overlies the northernmost parts of the Pine Creek Inlier. The Pine Creek Inlier is a Palaeoproterozoic orogenic province containing a range of sedimentary, metamorphic and igneous rocks (Carson et al., 1999). The inferred depositional setting for the sedimentary rocks of the Pine Creek Inlier was an intracratonic Palaeoproterozoic basin (Carson et al., 1999). Basement to the Inlier consists of Archaean granitic and metamorphic complexes. From 1870–1850 Ma, the Inlier was affected by the Barramundi Orogeny, a regional deformation and metamorphic event. The Barramundi Orogeny was characterised by E–W compression resulting in thrust faulting, west-verging recumbent folds, NW and SW trending folds, N–NW striking faults, and the emplacement of granites (Stuart-Smith et al., 1980; Carson et al., 1999). The overall north to northwesterly trend of the offshore continuation of the Pine Creek Inlier can be seen in the satellite gravity data (Fig. 8).

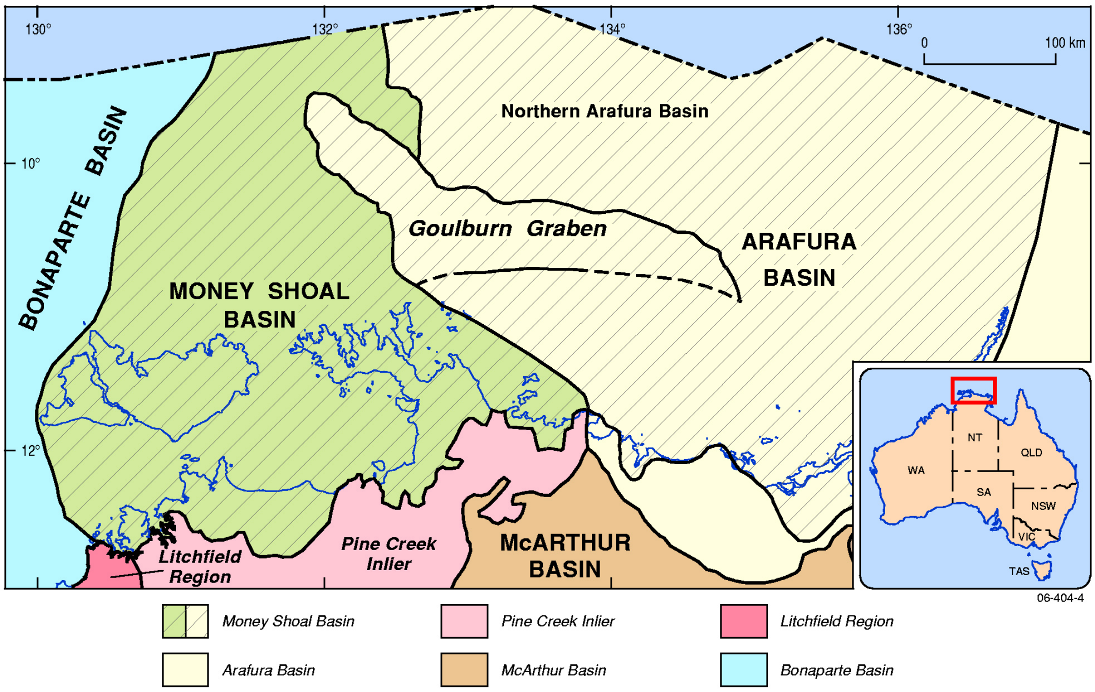

Figure 4: *Structural elements of the Arafura Basin region.*

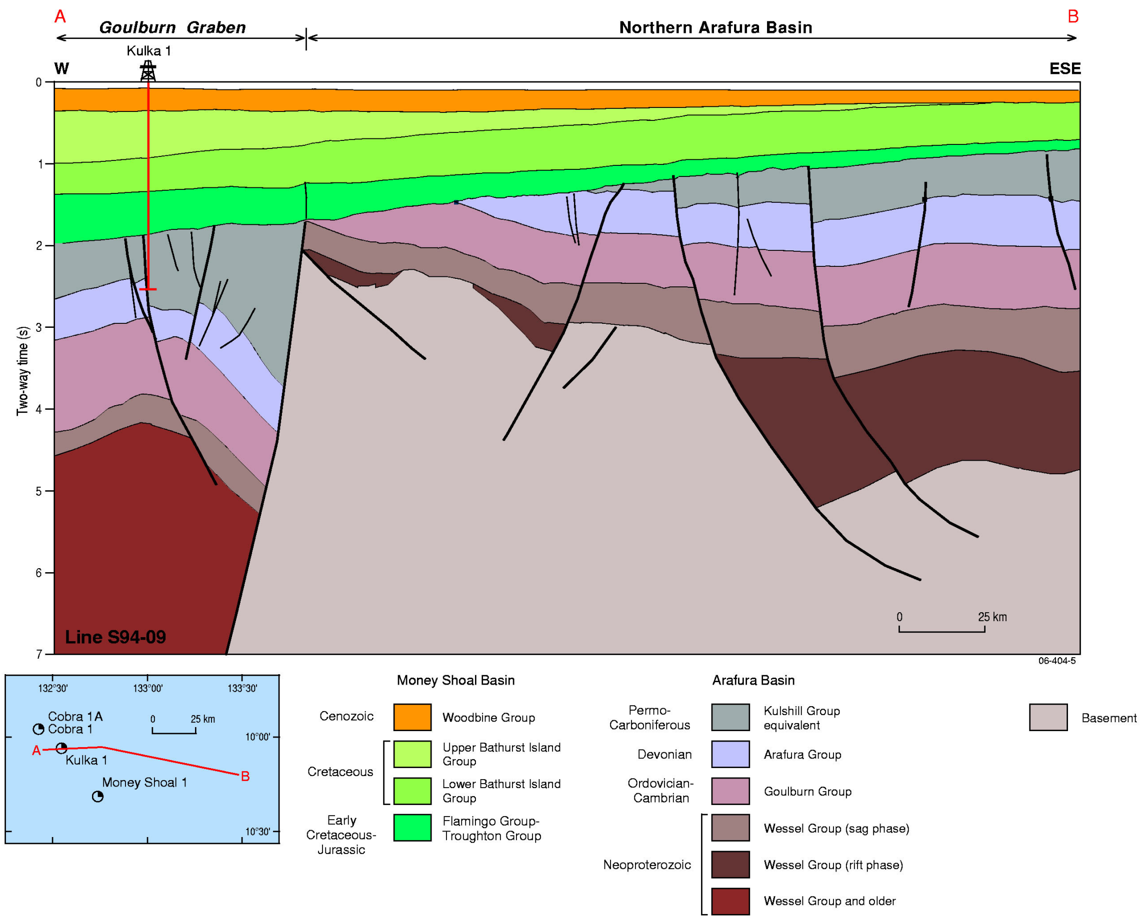

Figure 5: *Geoseismic cross-section from the Goulburn Graben to the northern Arafura Basin.*

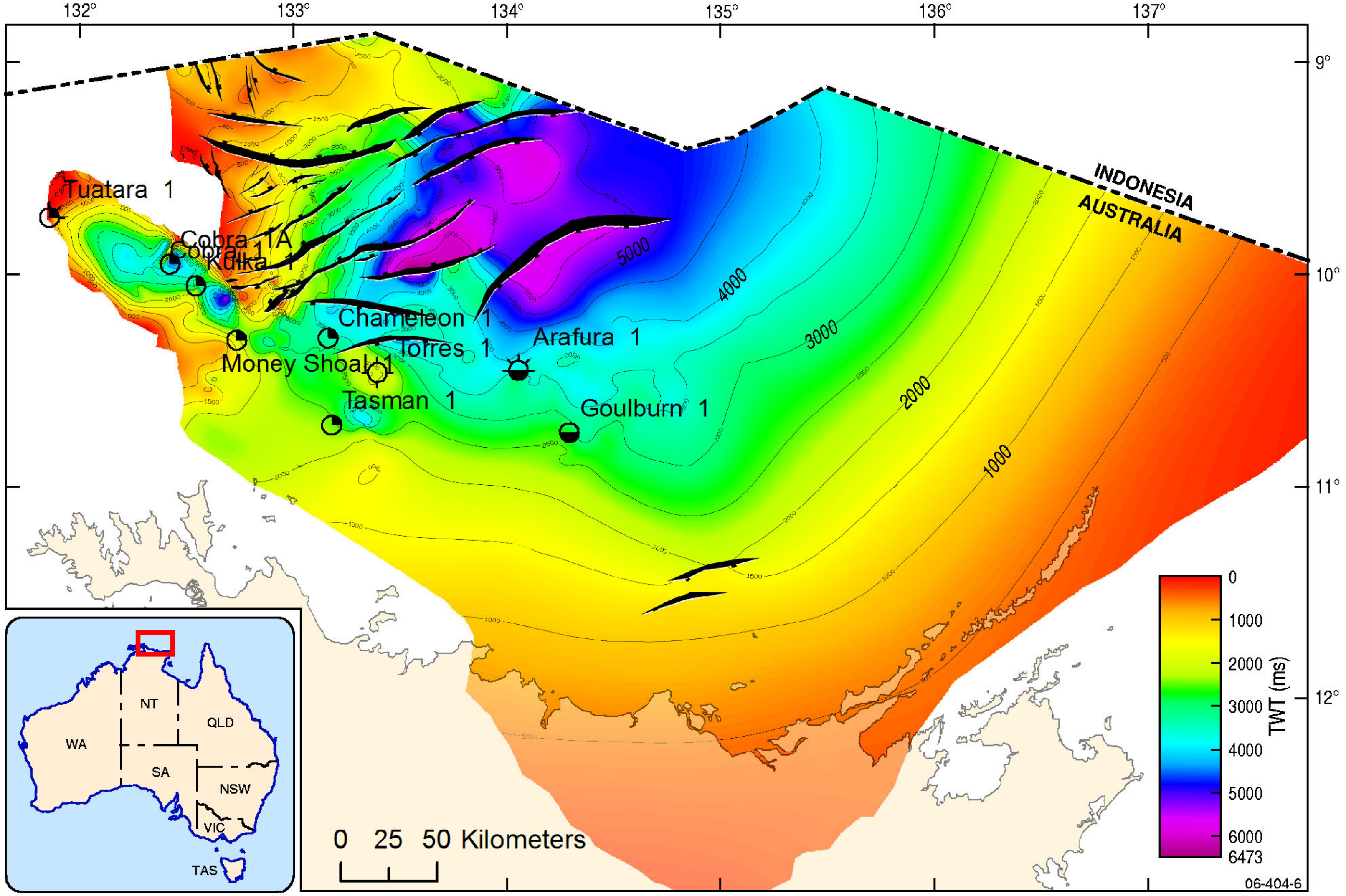

Figure 6: *Arafura Basin total sediment thickness (milliseconds two-way time).*

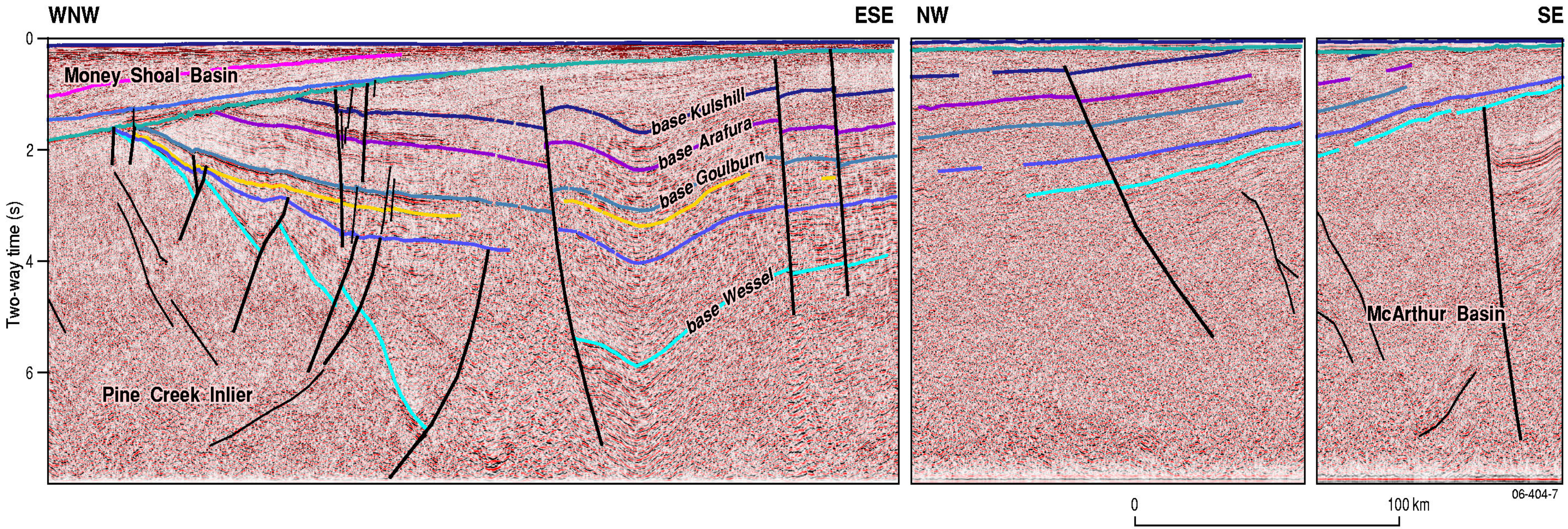

Figure 7: *Composite seismic cross-section, northern Arafura Basin. Left hand seismic image courtesy of Veritas DGC.*

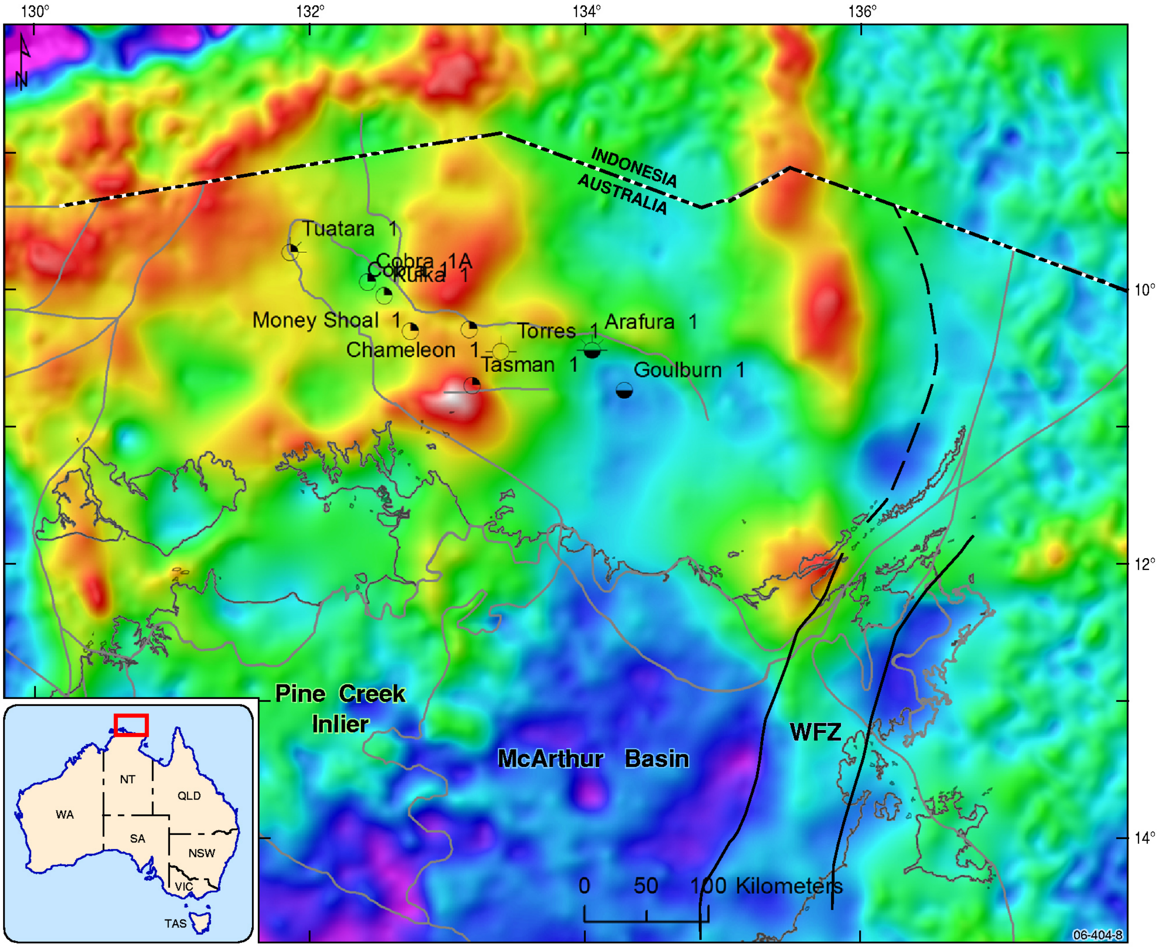

Figure 8: *Bouguer gravity anomaly image of the Arafura Basin region, showing the onshore location of basement terranes of the Pine Creek Inlier and McArthur Basin. WFZ – Walker Fault Zone of the McArthur Basin.*

McArthur Basin

The eastern Arafura Basin unconformably overlies the Palaeoproterozoic-Mesoproterozoic (approx. 1815–1400 Ma) McArthur Basin. The McArthur Basin contains a thick platform cover succession of mostly unmetamorphosed sedimentary and lesser volcanic rocks (Rawlings et al., 1997). Structurally, the northern McArthur Basin consists of the N to NE trending Walker Fault Zone (WFZ), flanked by the Arnhem Shelf in the west and the Caledon Shelf in the east (Rawlings et al., 1997). The northern McArthur Basin has been only mildly–moderately deformed, except within the WFZ. This zone has been affected by several periods of faulting and associated folding, involving multiple reactivation of older structures. The probable offshore continuation of the WFZ to the NE can be identified on seismic data near the eastern eroded edge of the Arafura Basin. The Arnhem Shelf, to the west of the WFZ, is characterised by ENE and NW striking faults and NE–SW oriented dykes (Carson et al., 1997, 1999).

The northern McArthur Basin has been extensively intruded by dolerite dykes – the ~1700 Ma Arnhem Dyke swarm and the ~1320 Ma or younger Galiwinku Dyke Swarm (Goldberg and Bagas, in press). The Galiwinku Dyke swarm appears to radiate from a point near the eastern end of the Goulburn Graben (Goldberg and Bagas, in press).

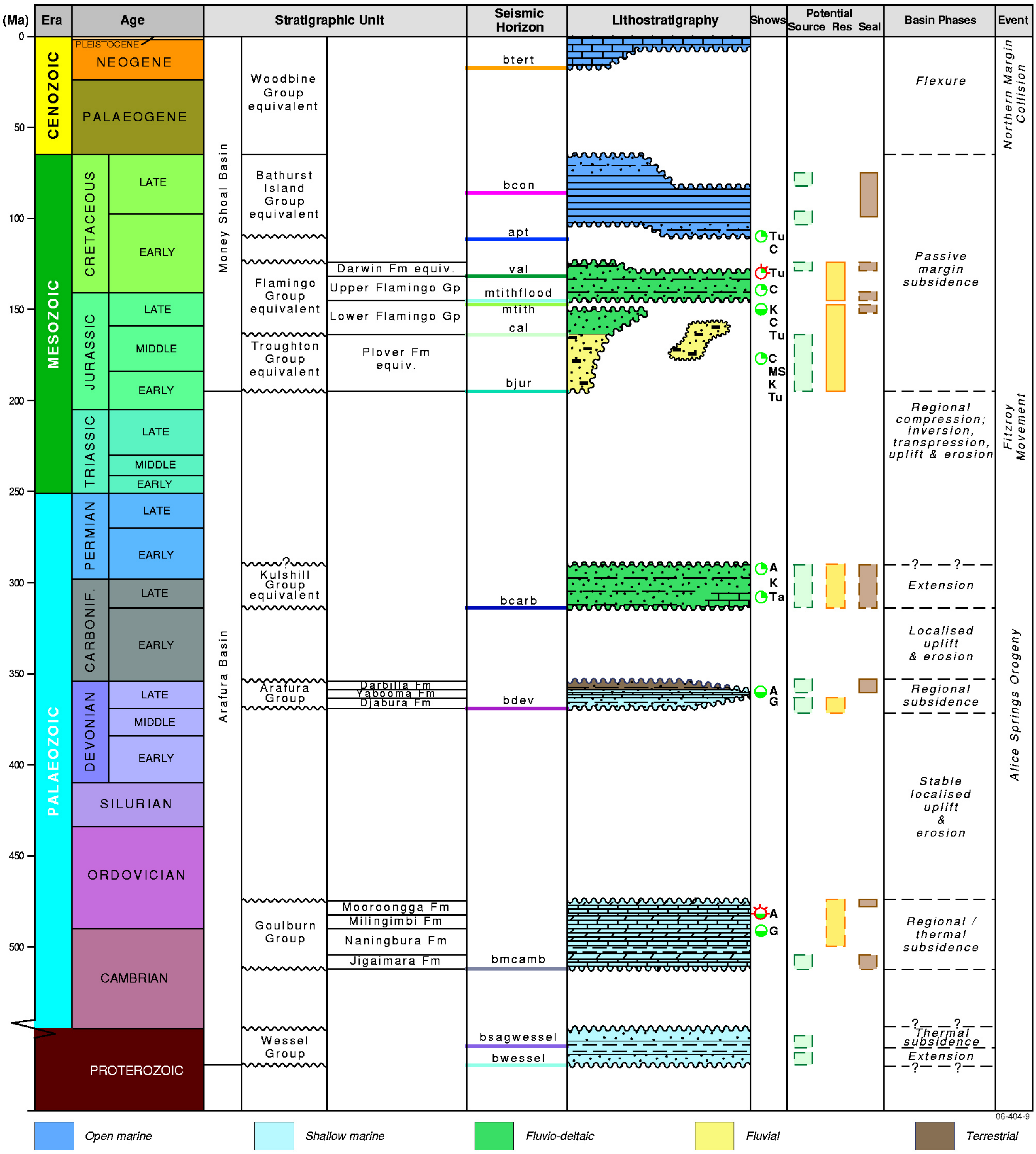

***Figure 9**: Arafura and Money Shoal basins correlation chart, showing stratigraphy, seismic horizons, petroleum systems elements, and structural setting. Due to uncertainty in the age of the Proterozoic section, absolute ages are not shown for this part of the timescale.*

SUBSIDENCE HISTORY

The subsidence and uplift history of the Arafura Basin can be described in terms of five major basin phases – four subsidence phases, and one regional uplift phase (Figs 9, 10). This section describes the stratigraphy and subsidence mechanisms of the four subsidence phases.

Although the depositional history of the basin covers an extremely long time span, its subsidence history has been episodic, limited to periods of basin-wide subsidence in the Neoproterozoic, Middle Cambrian–Early Ordovician, Late Devonian and Late Carboniferous–Early Permian (Basin Phases 1-4; Figs 9, 10). These were separated by long, relatively tectonically quiescent periods of non-deposition and erosion, with the result that the entire Neoproterozoic to Permian succession appears to be relatively structurally conformable. Prior to the Triassic, the basin underwent only minor deformation, restricted to localised uplift in the Ordovician–Devonian and Carboniferous in the southern part of the basin around Tasman 1. During the Triassic, the Goulburn Graben underwent contractional, probably transpressional, deformation, characterised by inversion on pre-existing faults, folding, uplift and the formation of thrust faults (Basin Phase 5). This event is considered to be equivalent to the Middle–Late Triassic Fitzroy Movement, which affected the Canning Basin and adjacent regions, including the Bonaparte Basin.

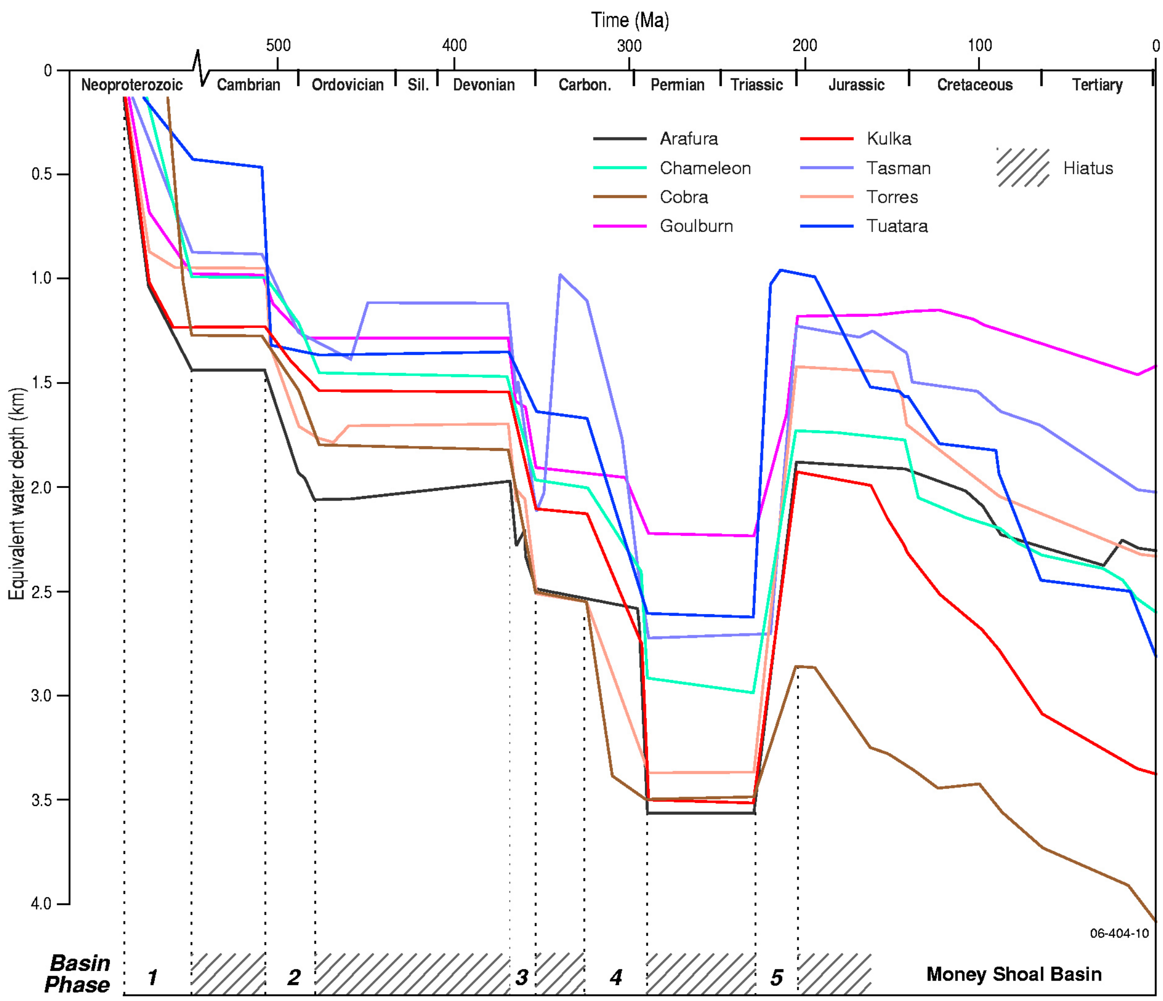

Figure 10**: Tectonic subsidence curves for the Arafura and Money Shoals basins derived for well locations in the Goulburn Graben. Basin phases for the Arafura Basin are numbered 1–5. Due to uncertainty in the age of the Proterozoic section, absolute ages are not shown for this part of the timescale..

Basin Phase 1 — Proterozoic extension and thermal subsidence (Wessel Group)

Deposition in the Arafura Basin commenced in the Neoproterozoic during a period of upper crustal extension that resulted in the formation of simple half graben across most of the basin. The fill of these half graben and the overlying sag phase sediments comprise the Wessel Group. The Wessel Group crops out onshore in an arcuate belt from the Wessel Islands westwards across Arnhem Land (Plumb & Roberts, 1992; Rawlings et al., 1997), and is present throughout the offshore extent of the basin (Figs 6, 11).

Onshore, the group reaches an inferred maximum thickness of about 2300 m (Rawlings et al., 1997). It has been subdivided into four component formations — the Buckingham Bay Sandstone, Raiwalla Shale, Marchinbar Sandstone, and Elcho Island Formation — which consist of mainly shallow marine sandstone and mudstone, with lesser conglomerate and carbonate rocks (Plumb & Roberts, 1992; Rawlings et al., 1997).

Offshore, the Wessel Group is interpreted on seismic data to form the fill of a series of large half graben that underlie much of the northern Arafura Basin, as well as the overlying post-rift succession, which onlaps basement rocks on the eastern, southern and western margins of the basin. The Wessel Group half graben form a northeasterly trending depocentre that continues into Indonesian territory (Fig. 11). Figure 12 shows the typical structural architecture of the Wessel Group, with half graben overlain by a sag section that thickens slightly into the centre of the basin. The group reaches a maximum thickness of about 10 km (4.3 s TWT) in the central part of the basin (Fig. 11a). Probable Wessel Group rocks consisting of highly indurated interbedded siltstone and mudstone were intersected at the base of Arafura 1 (Van Roye, 1983). This interpretation is consistent with the correlation of base Wessel Group and base Goulburn Group seismic horizons towards the onshore outcrops of these rocks on Howard and Elcho islands and the Wessel Islands. This seismic mapping suggests that the lower, rift-fill section of the offshore Wessel Group is not represented in the onshore outcrops.

The age of the Wessel Group is poorly constrained, however several lines of evidence suggest it is Neoproterozoic. Radiometric ages of 790 and 770 Ma (McDougall et al., 1965) on glauconite from the Elcho Island Formation are Neoproterozoic, however these dates could represent a diagenetic age. The carbonaceous fossil *Chuaria*, which is considered to be Neoproterozoic, has been reported from the Raiwalla Shale (Haines, 1998). Rocks from Elcho Island containing a Middle Cambrian fauna, which were believed to be part of the Wessel Group (Plumb et al., 1976), are now assigned to the Jigaimara Formation, the basal unit of the overlying Goulburn Group (Rawlings et al., 1997; Laurie, 2006a, b, c). Stratigraphic constraints on the age of the Wessel Group are provided by these overlying Middle Cambrian rocks, and a possible Mesoproterozoic age for deformation of the underlying McArthur Basin succession, the youngest unit of which is also inferred to be Mesoproterozoic (Rawlings et al., 1997).

The mid- to late Neoproterozoic in Australia was characterised by an extended period of basin development, related to rifting along the eastern margin of the continent (Betts et al., 2002). Numerous authors (e.g. Lindsay and Korsch, 1991; FrOG Tech, 2005) have postulated that this rifting event marked the break-up of a Proterozoic super-continent (Rodinia). The Neoproterozoic basins of the interior of the Australian continent, including the Amadeus, Georgina, Officer, and Ngalia basins, are believed to represent the remnants of a larger depositional entity — the Centralian Superbasin (Walter et al., 1995). FrOG Tech (2005) documented the development of the superbasin, arguing that the main phases of basin subsidence were driven by NE–SW oriented extension. This is consistent with the orientation of mafic dyke swarms in the Musgrave Block and Gawler Craton (Betts et al., 2002). Lindsay and Korsch (1991), however, postulated that the extension direction in the Amadeus Basin at this time was approximately E–W.

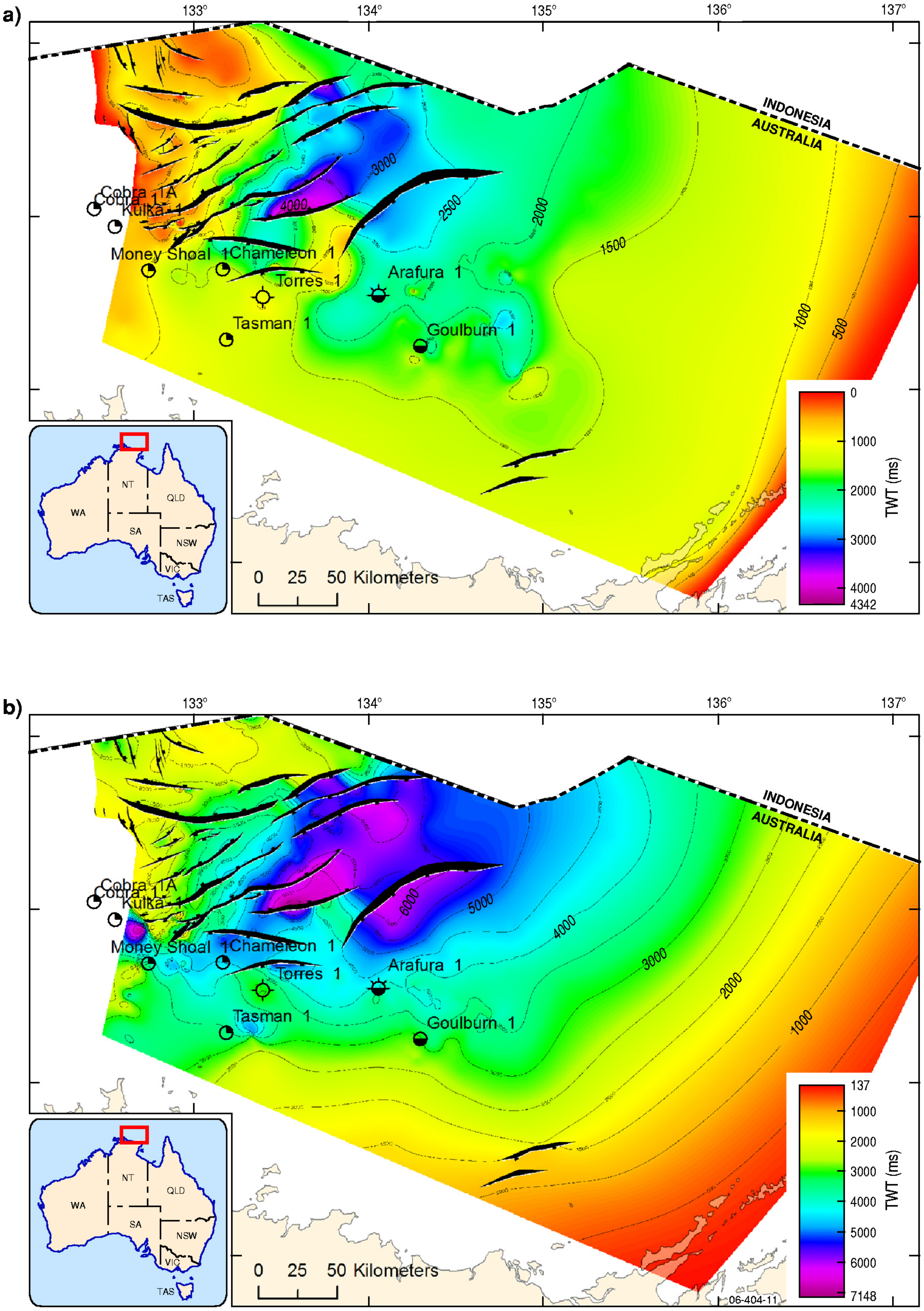

Figure 11: *Maps showing a) thickness of Wessel Group and b) depth to base Wessel Group (in milliseconds two-way time).*

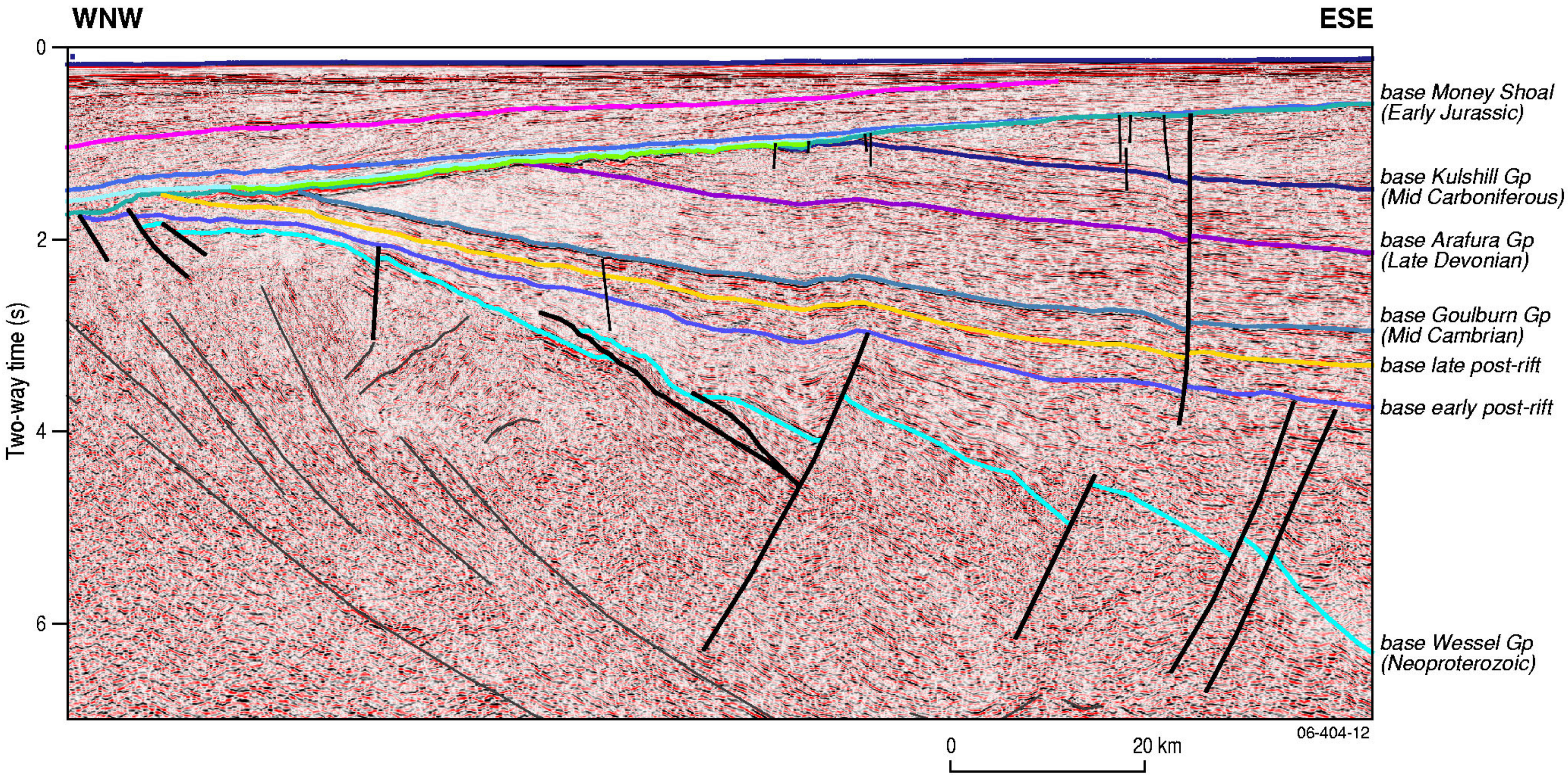

Figure 12: *Seismic image from the northern Arafura Basin showing Neoproterozoic half graben and the overlying structurally conformable Neoproterozoic–Permian section. Seismic line courtesy of Veritas DGC.*

Given the absence of a definitive age for the Arafura Basin Neoproterozoic succession, its relationship to the Centralian Superbasin is difficult to assess. However, the NW-SE extension direction determined from mapping of the Wessel Group faults in the Arafura Basin (see below) is not consistent with either the NE–SW or E–W oriented stress fields generally proposed for the Centralian Superbasin. This may indicate that the initiation of the Arafura Basin was not related to development of the Centralian Superbasin, and may have been driven by plate margin processes to the north or northwest of the continent, rather than the east. A plate tectonic reconstruction for ~700 Ma presented by Li (1998) places the Arafura Basin in an intra-plate setting, close to the northern margin of the Proterozoic supercontinent Rodinia. The reconstruction shows a convergent plate boundary between northern Rodinia and the Tarim Block, to the northwest of the Arafura Basin. This configuration would place the extensional deformation in the Arafura Basin in a back-arc tectonic setting.

Basin Phase 2 — Cambrian–Ordovician subsidence (Goulburn Group)

The Wessel Group is overlain disconformably by the early Middle Cambrian–Early Ordovician Goulburn Group (Bradshaw et al., 1990; Nicoll et al., 1996, Nicoll, 2006a; Figs 9, 12, 13). Given the uncertainty in the age of the Wessel Group, the hiatus between the Wessel and Goulburn groups could represent as little as 40 m.y., or as much as 400 m.y. The Goulburn Group has a sag to sheet-like geometry and is structurally conformable with the upper, post-rift portion of the Wessel Group. The group reaches a maximum thickness of about 2000 m (950 ms TWT) in the central part of the northern Arafura Basin. The Goulburn Group time-thickness map shows the relatively uniform thickness of the group across the basin (Fig. 13a).

The Goulburn Group represents prolonged deposition on a shallow marine shelf. Palaeogeographic reconstructions indicate that the region lay in mid–low latitudes at this time (Scotese, 2006). The basal unit is the early Middle Cambrian Jigaimara Formation (Nicoll et al., 1996; Laurie, 2006a, b, c), which consists of marine shelf limestone, shale and dolomite. It is overlain by the largely dolomitic Naningbura Formation. The upper part of this unit has a Late Cambrian–earliest Ordovician age (Nicoll, 2006a), but the base of the unit may be as old as Middle Cambrian. The Early Ordovician mixed carbonate and clastic rocks of the Milingimbi and Mooroongga formations form the uppermost units of the Goulburn Group. The shaly sediments of the Mooroongga Formation, which have a distinctive high amplitude seismic character (Figs 3, 14), were eroded in places prior to deposition of the overlying Devonian succession (e.g. around the Torres 1 well).

During the Cambrian–Early Ordovician, the Arafura Basin was in a stable intra-plate setting, inboard of the northern margin of Gondwana (Metcalfe, 1996; Scotese, 2006). Within the basin, there is no seismic evidence for any structural control on subsidence during deposition of the Goulburn Group. It is proposed that accommodation was driven by regional thermal subsidence following the flood basalt magmatism represented by the Antrim Plateau Volcanics, as has been postulated for the Cambrian–?Silurian section in the Bonaparte Basin (Colwell & Kennard, 1996). This flood basalt province, which covered broad areas of northern Australia to the SW of the Arafura Basin, is believed to be Early Cambrian in age, based on stratigraphic relationships and limited radiometric dating (Hanley & Wingate, 2000).

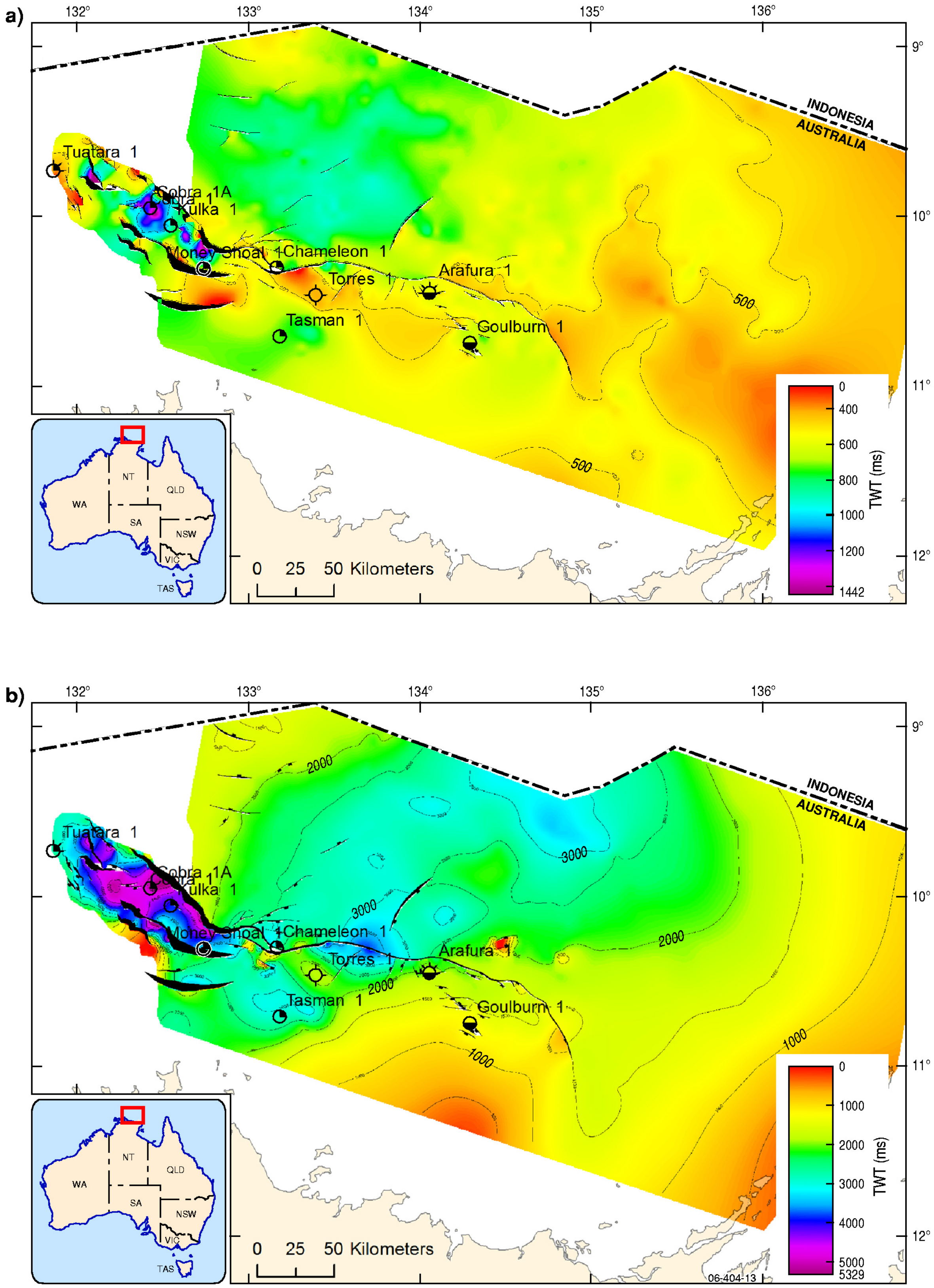

Figure 13: *Maps showing a) thickness of Goulburn Group and b) depth to base Goulburn Group (in milliseconds two-way time).*

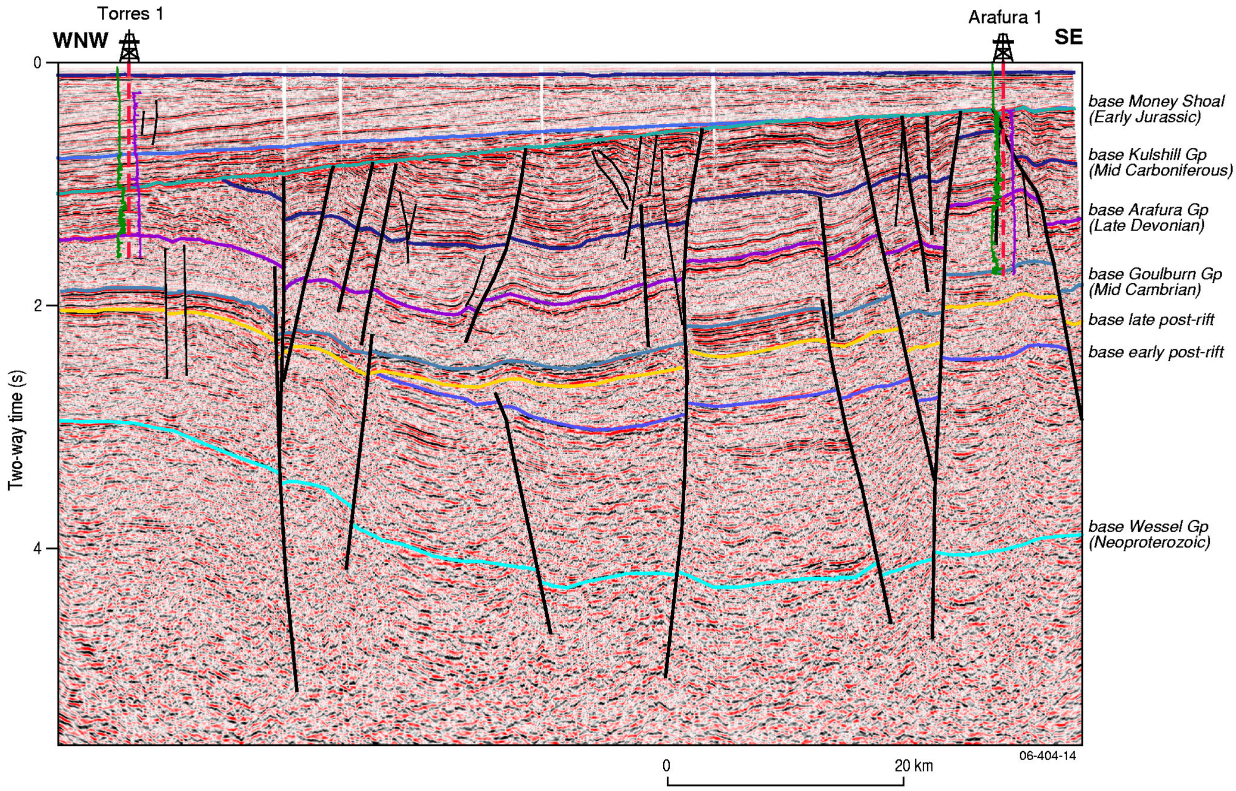

Figure 14: *Seismic line from the Goulburn Graben showing the correlation between Torres 1 and Arafura 1 exploration wells.*

Basin Phase 3 — Devonian subsidence (Arafura Group)

The Late Devonian Arafura Group (Petroconsultants, 1989; Bradshaw et al., 1990; McLennan et al., 1990) overlies the Goulburn Group (Figs 9, 14, 15). A hiatus of about 100 m.y. separates the two groups, which are generally structurally conformable. The Arafura Group has a sag to sheet-like geometry in the Northern Arafura Basin, and reaches a maximum thickness of approximately 1500 m (750 ms TWT; Fig.15a). The geometry of the group is more difficult to determine within the Goulburn Graben, but no convincing evidence of structural growth into the bounding faults of the graben has been identified.

Where intersected in wells, the Arafura Group consists of shallow marine to non-marine interbedded mudstone, siltstone, sandstone and minor carbonates. The oldest unit is the Djabura Formation, which consists of interbedded clastics and minor limestone deposited in a dominantly shallow marine environment. Conodont biostratigraphy indicates an Early Fammenian age for the Djabura Formation (Nicoll, 2006b), but palynological dating suggests it is older (Frasnian; Purcell, 2006). It is overlain unconformably by interbedded clastics and carbonates of the ?Frasnian–Famennian Yabooma Formation (Bradshaw et al., 1990), which is also interpreted to represent dominantly shallow marine deposition. The overlying Famennian (Strunian) Darbilla Formation is a mudstone and siltstone dominated succession interpreted to have been deposited in a largely non-marine environment (Petroconsultants, 1989; Bradshaw et al., 1990).

The time thickness map for the Arafura Group shows its relatively uniform thickness across the basin (Fig. 15a). Although deposition does not appear to have been fault-controlled, there is some well evidence of minor structuring prior to and during deposition of the Arafura Group (see *Structural Events* below).

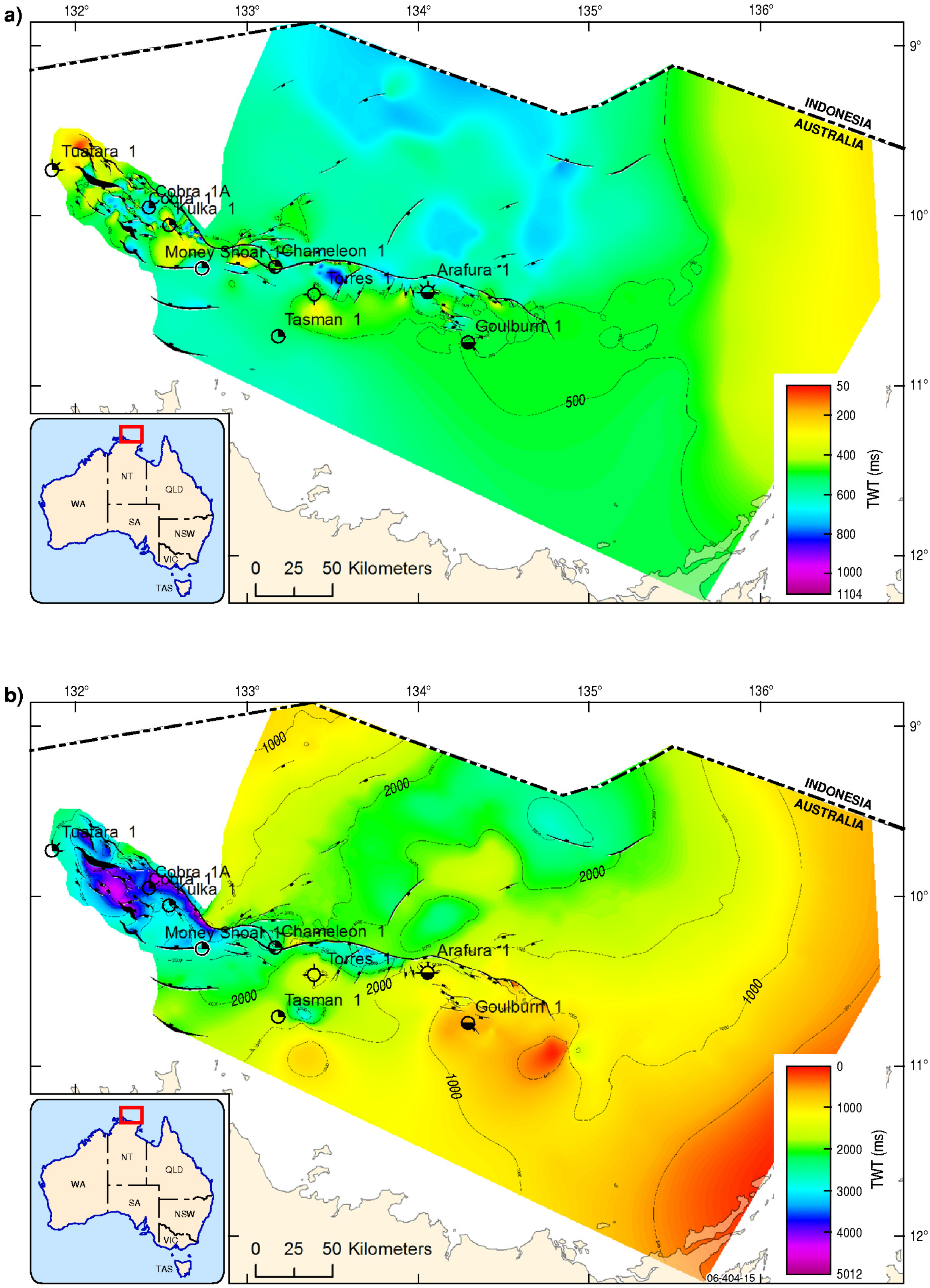

***Figure 15:** Maps showing a) thickness of Arafura Group and b) depth to base Arafura Group (in milliseconds two-way time).*

During the Devonian, the Arafura Basin was in an intra-plate tectonic setting, close to the northern margin of Gondwana. By the Late Devonian a divergent margin had developed on the northern Gondwanan margin (to the west of the Arafura Basin), and seafloor spreading there resulted in the rifting off of numerous continental fragments and the initiation of Palaeo-Tethys (Metcalfe, 1996). The tectonic driver for subsidence during the Late Devonian was therefore either regional extension prior to formation of Palaeo-Tethys, or regional subsidence following formation of Palaeo-Tethys. Given the lack of seismic evidence for extensional faulting affecting the Devonian section, the latter scenario is preferred. In this case, the Late Devonian section in the Arafura Basin may have accumulated as a result of regional thermal subsidence following a rifting event focused in the Petrel Sub-basin to the west (Colwell & Kennard, 1996).

Basin Phase 4 — Carboniferous–Permian extension (Kulshill Group)

The Arafura Group is overlain unconformably by a Late Carboniferous–Early Permian succession that is approximately equivalent in age to the Kulshill Group of the Bonaparte Basin (Figs 9, 14). Recent palynological studies (Helby, 2006) have indicated that most of this succession is Early Permian in age (*G. confluens* to *C. alutas* [Lower Stage 2 equivalent] spore-pollen zones), and that only the basal ~100 m intersected in Tasman 1 corresponds to the Late Carboniferous *D. birkheadensis–S. ybertii* zones. A schematic diagram showing the distribution of biostratigraphic control for the Late Carboniferous–Early Permian section is shown in Figure 16.

Well intersections of the Kulshill Group consist of non-marine to marginal marine interbedded sandstone, siltstone and claystone, with minor coal, and dolomitic rocks. North of the Goulburn Graben, the Kulshill Group has a sag to sheet-like geometry, is structurally conformable with the underlying rocks, and reaches a maximum preserved thickness of about 3000 m (1700 ms TWT) (Fig. 17). Apparent thickening of the Kulshill Group near the Indonesian border is poorly constrained by widely spaced and poor quality seismic data. However, if real, it may indicate the presence of another rift depocentre in the Indonesian portion of the basin. The group is thicker in the Goulburn Graben, reaching a maximum thickness of around 5000 m (2200 ms TWT). This is not the original maximum thickness, as up to 3 kilometres is interpreted to have been lost following the Triassic uplift (Struckmeyer et al., 2006). In the Goulburn Graben, the lower part of the Kulshill Group thickens into the bounding planar normal faults. The upper part

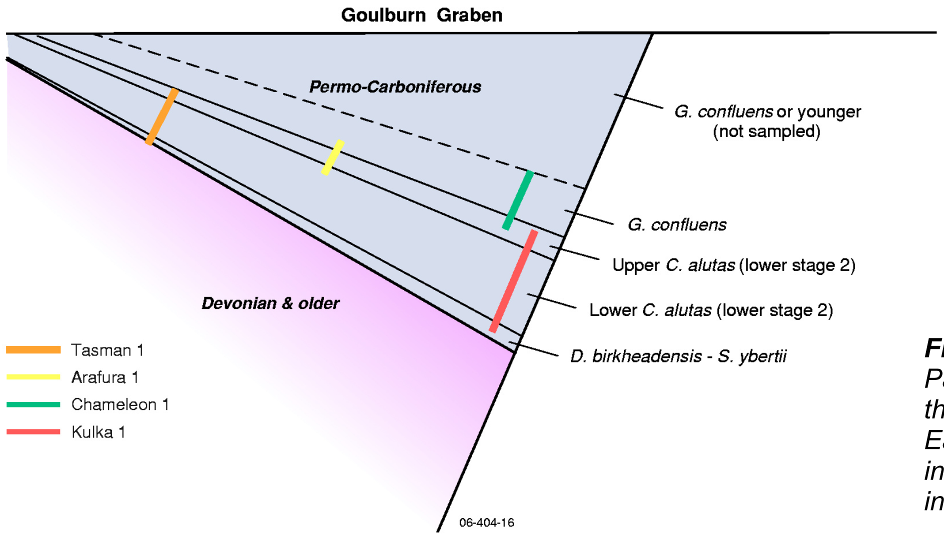

Figure 16: *Palynostratigraphy of the Late Carboniferous-Early Permian rift-fill intersected in four wells in the Goulburn Graben.*

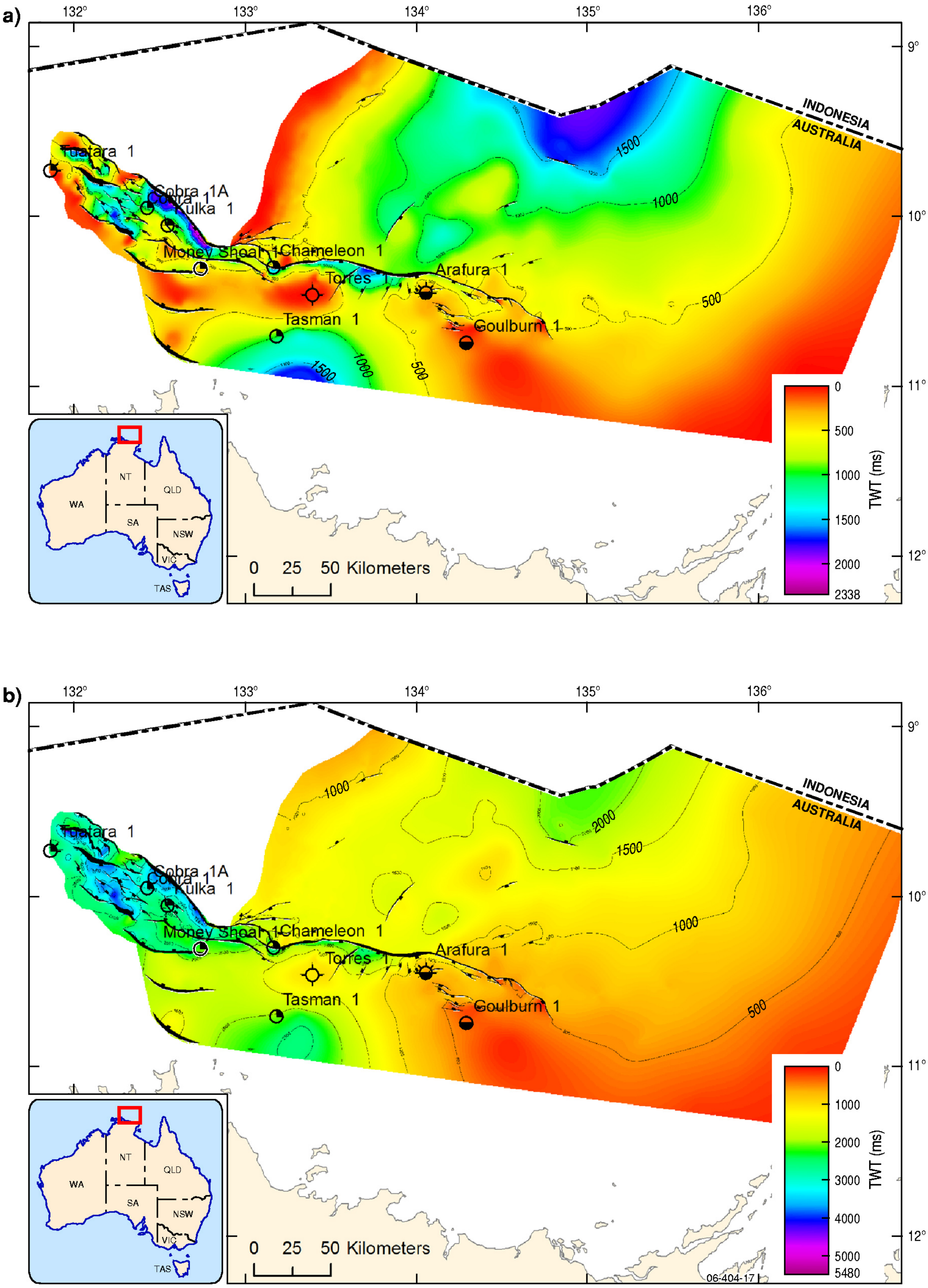

Figure 17: *Maps showing a) thickness of Kulshill Group and b) depth to base Kulshill Group (in milliseconds two-way time). Note: apparent thickening of Kulshill Group to the south of Tasman 1 is a gridding artefact.*

of the succession does not exhibit any noticeable divergence into the faults and is therefore considered to represent post-rift deposition. The Kulshill Group rocks north of the Goulburn Graben have a relatively uniform thickness, except where eroded around the margins of the basin (Fig. 17a), and are also interpreted to be part of the post-rift succession.

There is some evidence of magmatic activity in the basin during this extensional phase. Sills and dykes can be seen on seismic (Fig. 18), and one, a dolerite of Carboniferous–Permian age (Diamond Shamrock, 1985), was intersected in Kulka 1. In addition, a large magmatic body within the graben in the vicinity of the Kulka and Money Shoal wells, is interpreted on the basis of seismic and magnetic data.

Extensional deformation in the Arafura Basin during the Late Carboniferous–Early Permian took place within the regional context of rifting along the northern margin of eastern Gondwana (e.g. Metcalfe, 1996; Stampfli & Borel, 2002). Rifting on the Australian western margin led to the initiation of the Westralian Superbasin (Yeates et al., 1987; Etheridge and O'Brien, 1994), and culminated in the separation of numerous continental fragments from the northern margin of Gondwana (Metcalfe, 1996).

Plate reconstructions for the Carboniferous–Permian (e.g. Metcalfe, 1996) generally show that the Arafura Basin was located well to the east of the western divergent margin. Reconstructions by Stampfli and Borel (2002) further show that the basin lay inboard of a north-facing section of the continental margin rift. The tectonic history of this section of the margin is poorly constrained, however it is possible that the regional stress directions here were very different to those affecting the western margin, and that the extension direction evident in the Arafura Basin may reflect divergent plate boundary processes on this more E–W oriented section of the Australian continental margin.

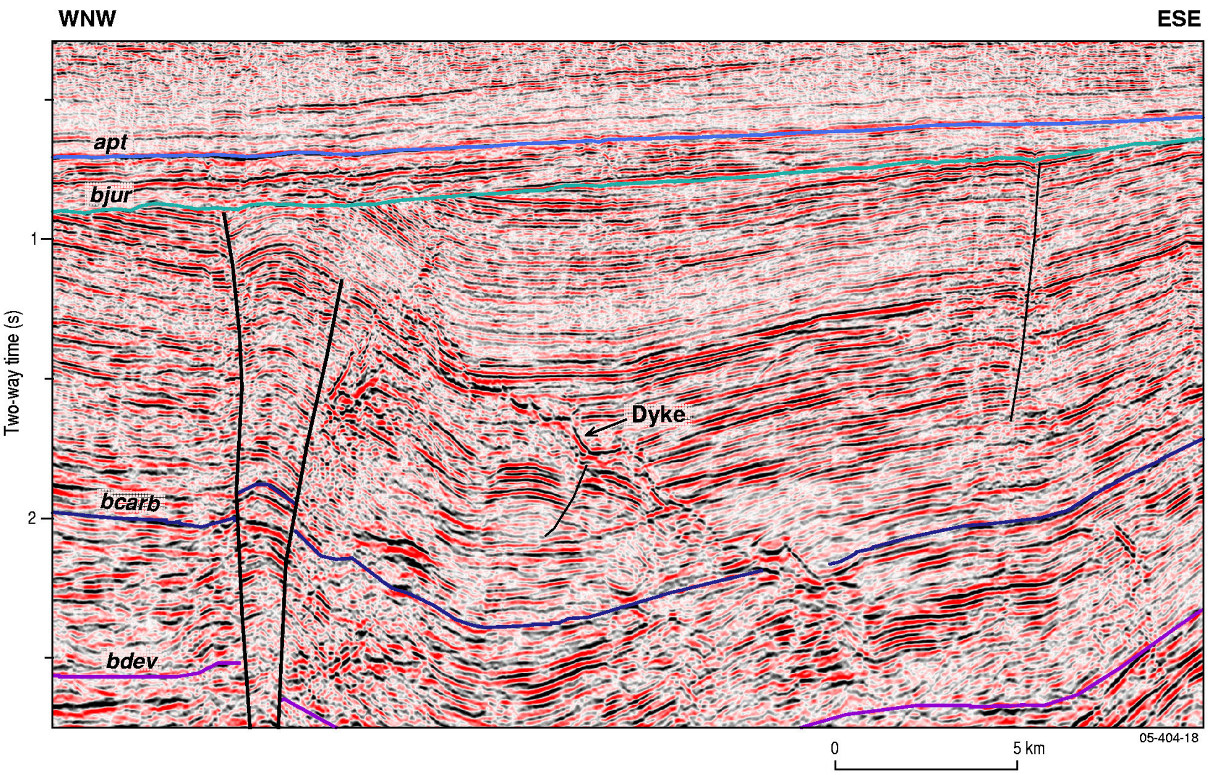

Figure 18: *Seismic line from the Goulburn Graben showing a cross-cutting igneous dyke. Seismic line courtesy of Veritas DGC.*

STRUCTURAL EVENTS

Neoproterozoic extensional faulting

The Neoproterozoic Wessel Group half graben are bounded by simple planar normal faults that have a generally NE–SW strike, and dip to either the northwest or southeast (Fig. 19). Towards the centre of the basin, the displacement on these faults is up to 3 seconds (TWT). Assuming high seismic velocities in these old and indurated rocks, this is equivalent to around 7000 m. Accommodation zones in the western part of the northern Arafura Basin, across which the polarity of rifting switches, have a roughly WNW–ESE orientation (Figs 19, 20). In general, the orientation of the faults and the simple fault style suggest that the extension direction was relatively orthogonal to the strike of the faults i.e. approximately NW–SE. A series of small extensional faults on the western margin of the basin have a NNW–SSE orientation, sub-parallel to the interpreted extension direction. Seismic data show that the basement underlying these small half graben is highly structured. Given the N to NW structural trend of the onshore Pine Creek Inlier, it is possible that the orientation of the cross faults may have been influenced by the pre-existing structural fabric of the underlying basement. In general, the NE strike of Neoproterozoic faults in the Arafura Basin is similar to the dominant fault pattern seen in the onshore Arnhem Shelf.

In the eastern part of the basin, poor seismic imaging hinders interpretation, but there does appear to be a change in architecture in this region to large displacement, widely-spaced faults (Fig. 7). This change in structural style could well reflect the variations in underlying basement fabric from west to east, from the complex deformation and strong structural fabric of the Pine Creek Inlier, to the mildly deformed and eastwards thickening Arnhem Shelf of the McArthur Basin.

Minor Palaeozoic deformation

From a regional perspective, the key structural event during the mid–Late Palaeozoic was the Alice Springs Orogeny, which affected large areas of central and northern Australia resulting in significant contractional deformation in the Arunta Block, Amadeus Basin and adjacent areas (e.g. Wells et al., 1970; Forman & Shaw, 1973; Bradshaw & Evans, 1988; Shaw, 1991; Roberts and Houseman, 2001). There is no seismic evidence of deformation within the Arafura Basin corresponding to the Alice Springs Orogeny, however well evidence of minor structuring suggests that it may have had some minor influence on the basin.

Despite the lengthy hiatuses present between the Wessel, Goulburn and Arafura groups (Fig. 9), the Cambrian to Late Carboniferous basin succession is remarkably structurally conformable (Figs 7, 12, 14). The only indication of structural movement is the absence of parts of the Goulburn and Arafura groups in some of the wells drilled in the Goulburn Graben. Up to 400 m of Late Cambrian–Early Ordovician Goulburn Group section is missing at Tasman 1, suggesting that there was some localised uplift and erosion prior to deposition of the Arafura Group. This timing coincides with the major phase of the Alice Springs Orogeny, the Middle Devonian Pertnjara Movement (Wells et al., 1970). A more widespread unconformity is present within the Arafura Group, between the Djabura and Yabooma formations. This hiatus, which may represent up to 5 my, has been identified biostratigraphically in Arafura 1, Torres 1 and Goulburn 1 (Petroconsultants, 1989; Bradshaw et al, 1990; Nicoll, 2006b). It is not clear if the unconformity is tectonic in origin. The hiatus of approximately 45 million years between the Arafura Group and the overlying Kulshill Group correlates with the final, Early Carboniferous phase of the Alice Springs Orogeny. Although there is no seismic evidence of any widespread contractional deformation of the Arafura Basin at that time, there is evidence of significant localised uplift and erosion, with at least 1000 m of Arafura Group missing at Tasman 1.

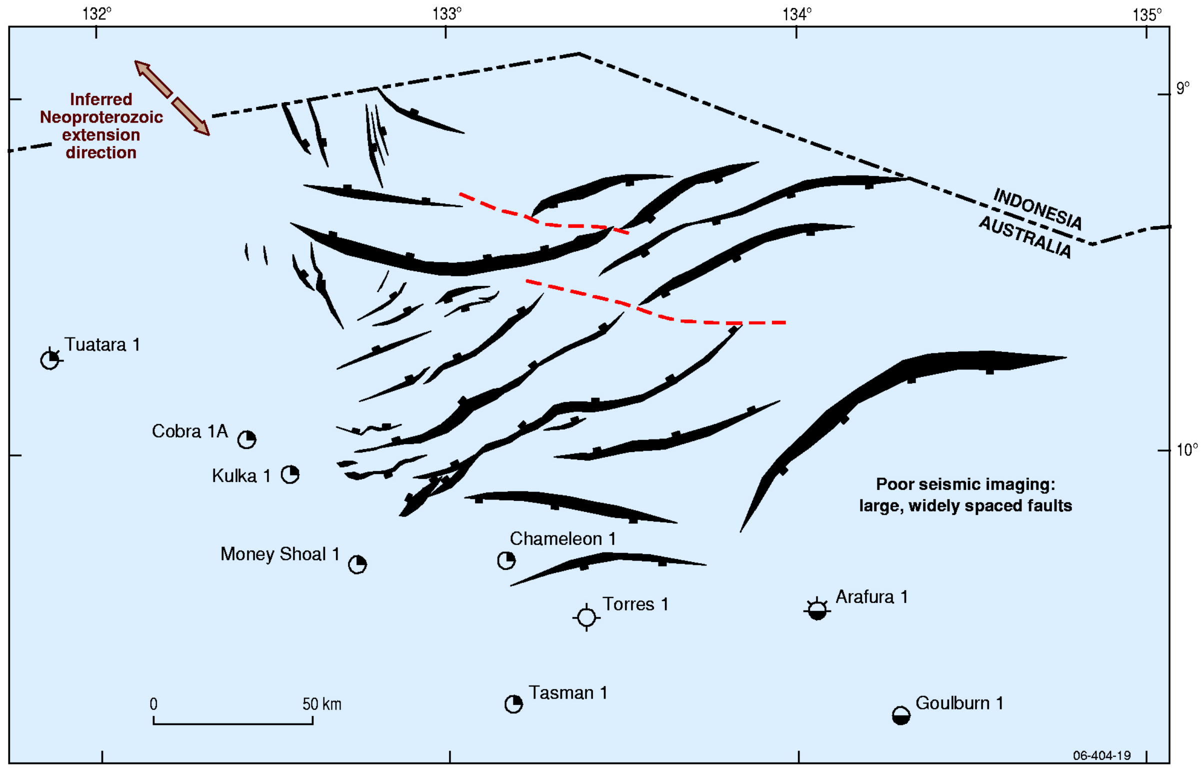

Figure 19: *Neoproterozoic fault map, showing faults mapped at the base of the Wessel Group. Accommodation zones shown by dashed red line*

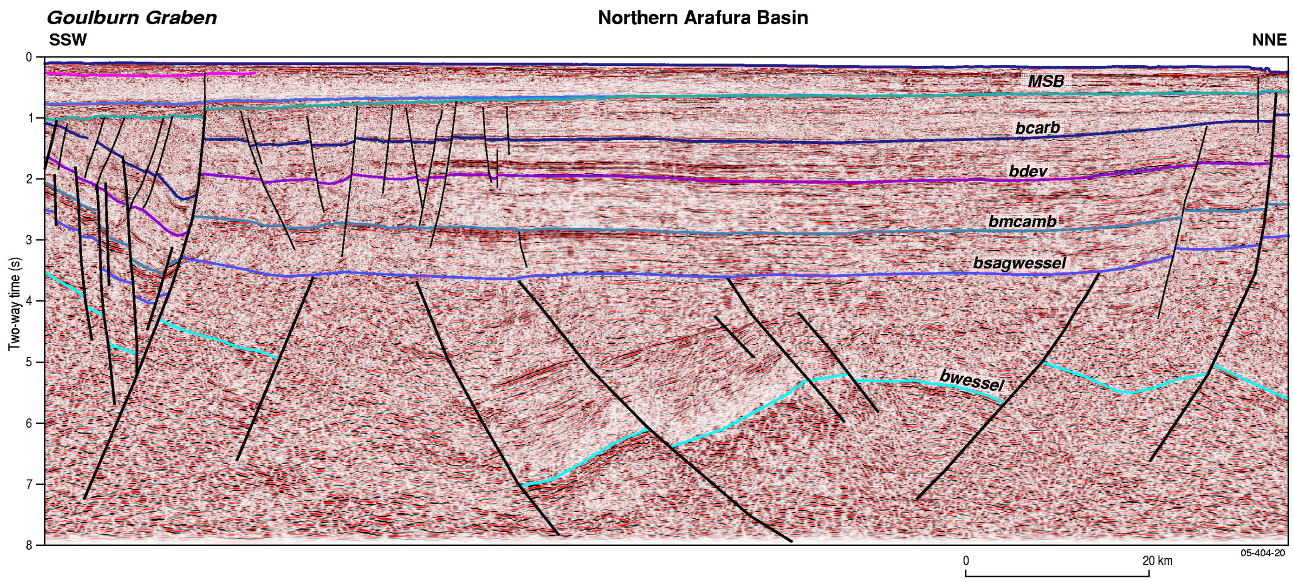

Figure 20: *Seismic line showing a change in polarity of Neoproterozoic faults across an accommodation zone. Seismic line courtesy of Veritas DGC.*

Late Carboniferous–Early Permian extensional faulting

The Goulburn Graben formed during a phase of Late Carboniferous–Early Permian extension. The Goulburn Graben is a narrow, highly structured zone that has a WNW–ESE trend in the east and a NW–SE trend in the west (Fig. 21). The change in orientation of this extensional feature is possibly a reflection of underlying basement fabric. Despite its name, the Goulburn Graben does not necessarily have a classical graben morphology. Along much of its length it can best be described as a highly faulted half graben system, with southern bounding faults only intermittently developed.

The northern bounding fault system consists of WNW and NW striking fault segments that are slightly offset in an *en echelon* fashion (Fig. 21). These segments are linked by approximately E–W oriented fault segments. It is presumed that these faults formed as a result of breaching of relay structures as extension progressed, but unfortunately, the amount of section lost during Triassic inversion precludes displacement analysis of the fault system. The bounding fault system dips to the SSW to SW, and a dip angle of around 50º has been measured from seismic sections in the western part of the graben. A complex fault linkage system is present near the centre of the graben, where the direction of the bounding faults changes from dominantly WNW to NW striking (Fig. 21). This fault linkage system involves localised reactivation of favourably oriented Neoproterozoic faults. Carboniferous–Permian extensional faulting appears to have been confined to the Goulburn Graben as there is no seismic evidence of extensional faulting of this age north of the Goulburn Graben bounding fault system, or on the southern basin ramp.

The style and orientation of faulting in the Goulburn Graben and the general lack of reactivation of the Neoproterozoic faults in the northern Arafura Basin suggests that the extension direction for this event was approximately NE–SW, i.e. parallel to the Neoproterozoic fault trend (Fig. 21). In the eastern part of the graben, small NE–SW oriented cross-faults may be the result of reactivation of Wessel Group faults due to strain partitioning in this more oblique part of the rift. The dip of the bounding faults and presence of simple extensional growth wedges, particularly in the NW trending section of the fault system, argue against deformation being driven by the NW–SE (Etheridge and O'Brien, 1994; FrOG Tech, 2005) or NNW–SSE (AGSO North West Shelf Study Group, 1994) extension directions commonly postulated for the development of Carboniferous–Permian basins on the North West Shelf.

Although the underlying Neoproterozoic faults were not generally an influence on Carboniferous–Permian faulting, the orientation and location of faulting does appear to have been influenced by basement structures. The fact that the deformation was so focused and localised during this time suggests reactivation of a major structure. Goldberg and Bagas (in press) proposed that the orientation of the Goulburn Graben coincided with the postulated orientation of dykes of the Galiwinku Dyke swarm. These dykes form a radial pattern across northern Arnhem Land, and their distribution suggests an origin close to the eastern end of the Goulburn Graben. Dykes propagating westwards from this centre would be parallel with the bounding fault system of the Goulburn Graben. Goldberg and Bagas (in press) have suggested therefore, that the major structure (or structures) reactivated during Carboniferous–Permian NE–SW extension was a Proterozoic dyke(s). Further basement influence can be seen in the change in orientation of the western half of the graben. Highly deformed rocks of the Pine Creek Inlier can be seen on seismic data to the north of this part of the rift (Fig. 12). It is proposed that the change in orientation marks the western edge of the Arnhem Shelf, and a transition to the north to northwesterly structural fabric of the Pine Creek Inlier.

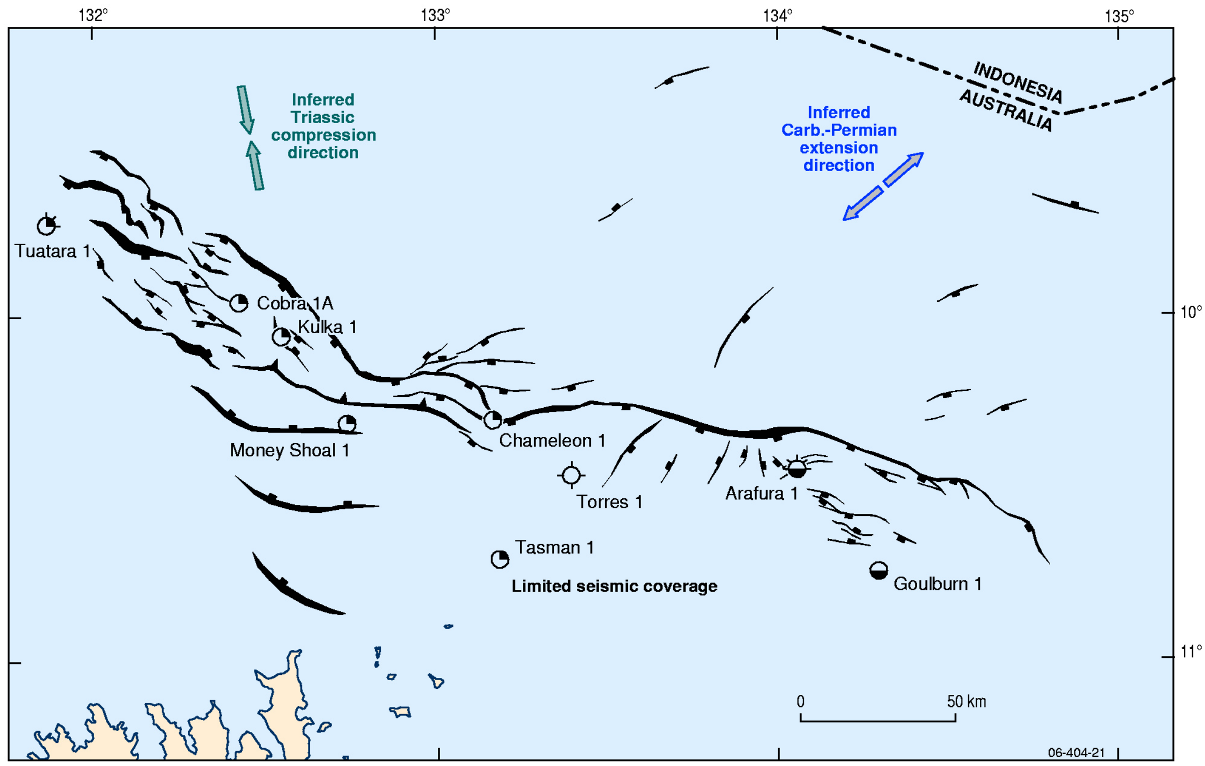

Figure 21: *Base Kulshill Group fault map. Faults shown are mostly Late Carboniferous extensional faults, many of which underwent reverse reactivation in the mid-Late Triassic. Thrust fault shown south of Kulka 1 formed during Triassic deformation.*

Mid–Late Triassic contraction (Basin Phase 5)

During the Middle–Late Triassic, the Arafura Basin, in particular the Goulburn Graben, underwent a major phase of contractional deformation. This was a key event from a petroleum systems perspective as it has both positive and negative implications for the creation of traps, and preservation of accumulations.

As noted by Etheridge and O'Brien (1994), the Mid–Late Triassic was a time of widespread contractional deformation in Australia. The retroarc foreland basins in eastern Australia, in particular, underwent considerable deformation at this time, with thrust faulting and inversion of Early Permian rifts (Korsch et al., 1998). In western Australia, this event has been named the Fitzroy Movement (Forman and Wales, 1981). It affected the Canning Basin and adjacent onshore regions, including the Bonaparte Basin (Colwell et al, 1996). On the western margin, basins such as the Browse also underwent a period of inversion at this time (Struckmeyer et al., 1998). The continent-wide nature of the deformation suggests that the driving factor was plate tectonic in scale, and indeed, the Mid–Late Triassic was a time of active global tectonism. This included the accretion and collision of terranes in Asia and the closing of Palaeo-Tethys (Korsch and Totterdell, 1995; Metcalfe, 1996; Borel & Stampfli, 2002). A sharp bend in the North American Apparent Polar Wander Path and a less well constrained one in the Australian path also indicate a major change in global plate relationships at this time (Korsch and Totterdell, 1995; Klootwijk, 1996).

Contractional deformation in the Arafura Basin was largely focused on the Goulburn Graben, but the rest of the basin was affected to a lesser extent. Deformation in the Goulburn Graben is characterised by folding, inversion on pre-existing faults, the formation of new thrust faults, uplift and erosion (Figs 22, 23). During this phase of deformation, the northern bounding fault system of the Goulburn Graben acted as a buttress, and there is little or no contractional deformation in the footwall of the fault system. This suggests that the stress direction was highly oblique to the bounding faults (Fig. 21), a proposition supported by seismic evidence of strike-slip or transpressional movement on parts of the fault system (Fig. 23b).

The effects of the deformation vary along the Goulburn Graben and across the basin in general. In the Goulburn Graben, the style of deformation was largely determined by the pre-existing fault pattern. In the westernmost part, where the rift geometry was that of a half graben, the deformation style is one of synclinal folding. Bedding-parallel thrust faults developed in the Ordovician shaly section to accommodate shortening, and there was a high degree of inversion on the bounding fault system (Fig. 22a). Further to the southeast, near Kulka-1, the original rift geometry was more graben-like with bounding faults on either side of the structure. Shortening was accommodated by intra-graben anticlinal folding, and inversion on the original extensional faults (Fig. 22b). The two examples shown in Figure 22 represent deformational end-members.

In the complex fault linkage area in the central part of the graben, the bounding faults appear to have been more orthogonal to the compression direction. As a result, as well as folding and inversion, new thin-skinned back-thrusts developed within the deformed hanging wall (Fig. 23a). In the easternmost part of the fault system, east of Arafura-1, there was no pre-existing extensional fault system. It is only in this part of the Goulburn Graben that true strike-slip faults developed; Figure 23b shows a very simple pop-up structure developed on a restraining bend in the fault.

Whereas the spectacular deformation was focused on the Goulburn Graben, structuring in the rest of the basin was more subtle. In the northern Arafura Basin, limited inversion took place on some Neoproterozoic extensional faults; in the eastern part of the basin, this resulted in the formation of large inversion anticlines (Fig. 7). The margins of the basin were uplifted, resulting in a basinward tilt. Subsequent erosion resulted in the formation of a peneplain across the basin and adjacent basement areas (Fig. 7).

In the western part of the northern Arafura Basin, the deformation took the form of minor inversion on the Wessel faults, which were optimally oriented (NE–SW) for reactivation. In some cases, significant reverse reactivation appears to have been prevented, perhaps due to the dip of the fault. In the example shown in Figure 12, the footwall acted as buttress, and some component of shortening was accommodated by back-thrusting. Higher in the section, the deformation takes the form of simple low amplitude folds. In the eastern part of the northern Arafura, the style of deformation is slightly different, perhaps reflecting the different structural architecture of the underlying Neoproterozoic extension. In this region, the Triassic folds are larger and more widely spaced, and in places, the fault reactivation appears to propagate higher into the section (Fig. 7).

The style of contractional deformation seen in the Arafura Basin, with inversion along the graben, the formation of new thrust faults, and mild reactivation of the NE–SW striking Neoproterozoic faults, is consistent with the NNW–SSE regional compression direction proposed for this event in the Petrel Sub-basin of the Bonaparte Basin (O'Brien & Higgins, 1996; Fig. 21). This stress direction was highly oblique to the dominant fault trends of the Goulburn Graben and resulted in an element of dextral strike-slip. The resultant feature could be best described as an obliquely inverted rift.

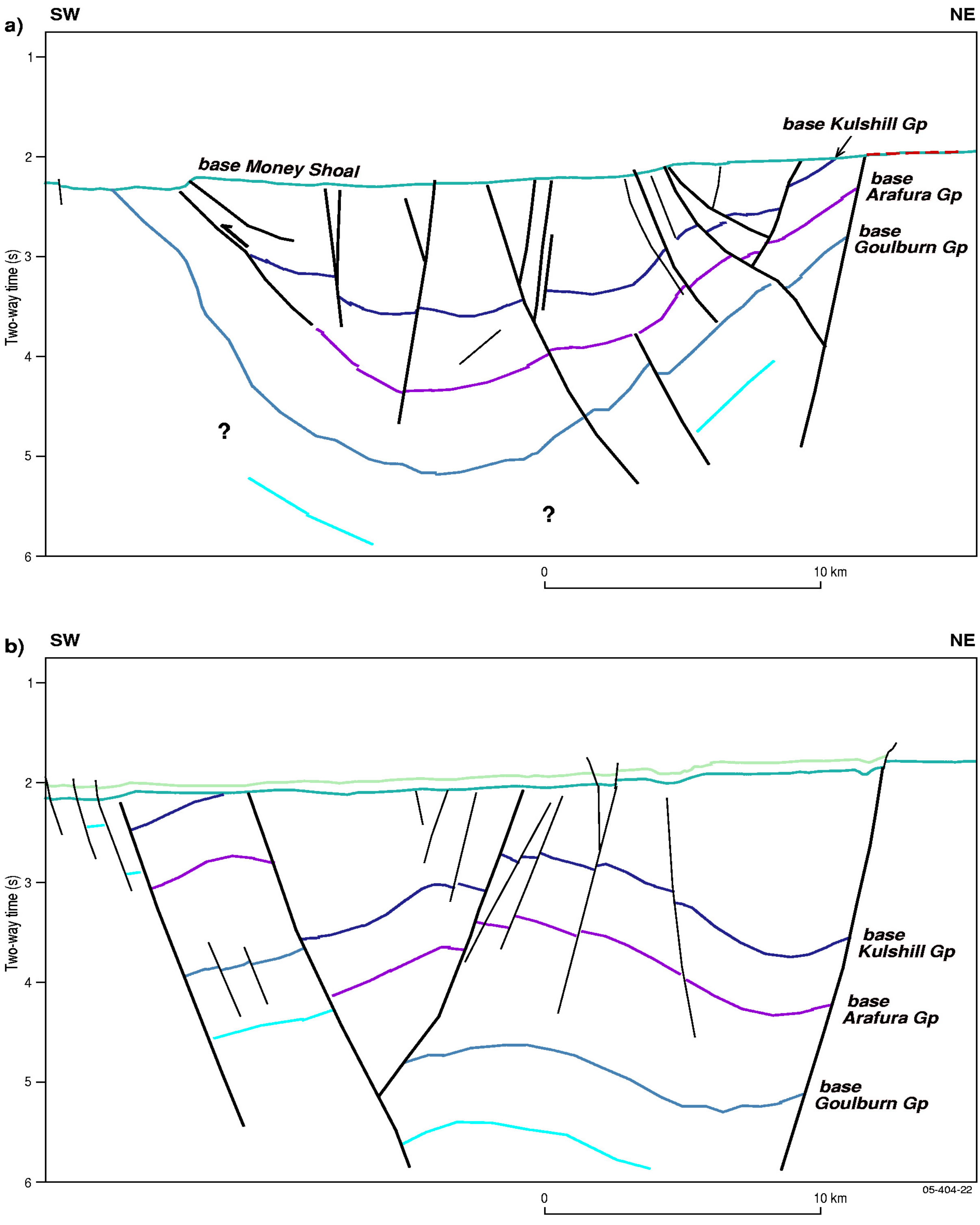

Figure 22: *Examples of the different styles of Triassic deformation in the western Goulburn Graben ranging from a) synclinal deformation of original half-graben morphology, to b) anticlinal deformation of original graben morphology.*

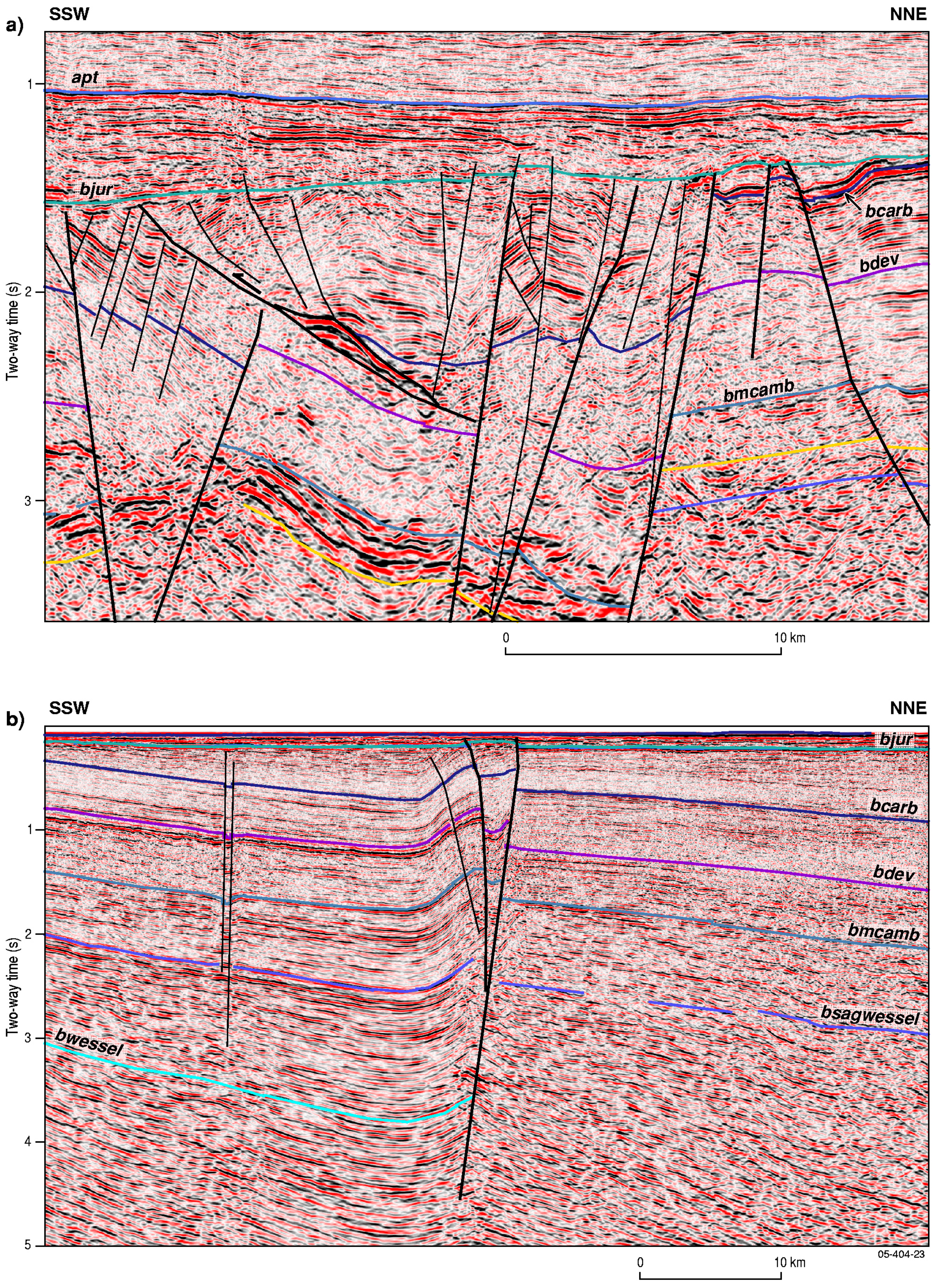

Figure 23: *Examples of the different styles of Triassic deformation in the central and eastern Goulburn Graben: a) inversion and thin-skinned thrusting west of Chameleon 1; b) pop-up structure caused by strike-slip movement in the easternmost "Goulburn Graben". Seismic lines courtesy of Veritas DGC.*

Minor Latest Triassic/Early Jurassic extensional faulting

Erosion following the Triassic deformation eventually resulted in the development of a peneplain across the basin. During this period of erosion, the basin appears to have been affected by a minor extensional episode. Relatively small displacement planar normal faults affect the upper part of the section (Fig. 12). On the western margin of the basin, some of the older faults were reactivated and the Triassic inversion anticlines were offset (Fig. 24). The faulting does not appear to offset the base Money Shoal unconformity and therefore probably predates the later Jurassic extensional episodes that partly controlled deposition of the Money Shoal succession (Struckmeyer, this volume).

The tectonic driver for this phase of faulting and fault reactivation is unclear. It may have been caused by far-field stresses related to rifting episodes along the northwestern continental margin, in particular the rifting away of either the Lhasa or West Burma blocks in the Norian or Hettangian respectively (Metcalfe, 1996; Longley et al., 2002). Alternatively, these faults could have been caused by extensional stresses at the crests of the Triassic anticlines during the uplift and erosion that followed the main phase of contractional deformation.

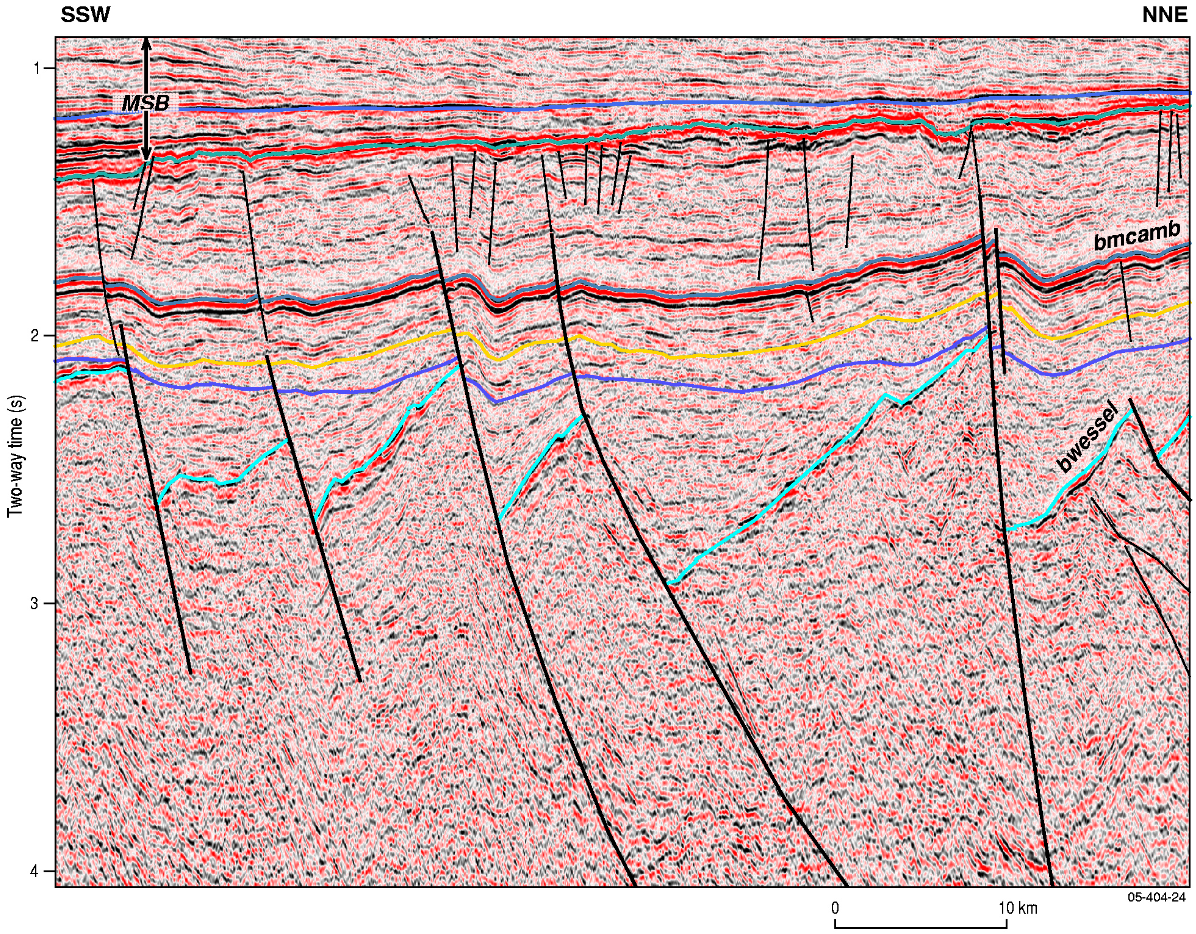

Figure 24: *Seismic line from the western margin of the northern Arafura Basin showing small Triassic inversion anticlines affected by minor late Triassic or Early Jurassic extensional faulting. The faults reflect 3 phases of deformation — extension in the Neoproterozoic, compression in the Triassic and extension in the Late Triassic– Early Jurassic. MSB = Money Shoal Basin.*

BASIN EVOLUTION: MONEY SHOAL BASIN

Heike I.M. Struckmeyer

The Money Shoal Basin (Fig. 4) is a mainly offshore, Middle Jurassic to Recent basin, up to 4.5 km thick. It covers an area of about 230,000 km^2 and lies in water depths of up to 230 m. In the west, the basin is bounded by the Lynedoch Fault System, which separates the Money Shoal Basin from the Calder and Malita graben of the Bonaparte Basin. In the east, a Mesozoic hinge separates the Money Shoal Basin from the Carpentaria Basin. The southern basin boundary is defined by the depositional edge of Mesozoic to Recent sediments. The northern part of the basin extends beyond the Australian-Indonesian boundary. The basin thins rapidly eastwards to less than 500 ms two-way time (< 600 m) of ?Late Cretaceous and Late Cenozoic sediments (Fig. 25).

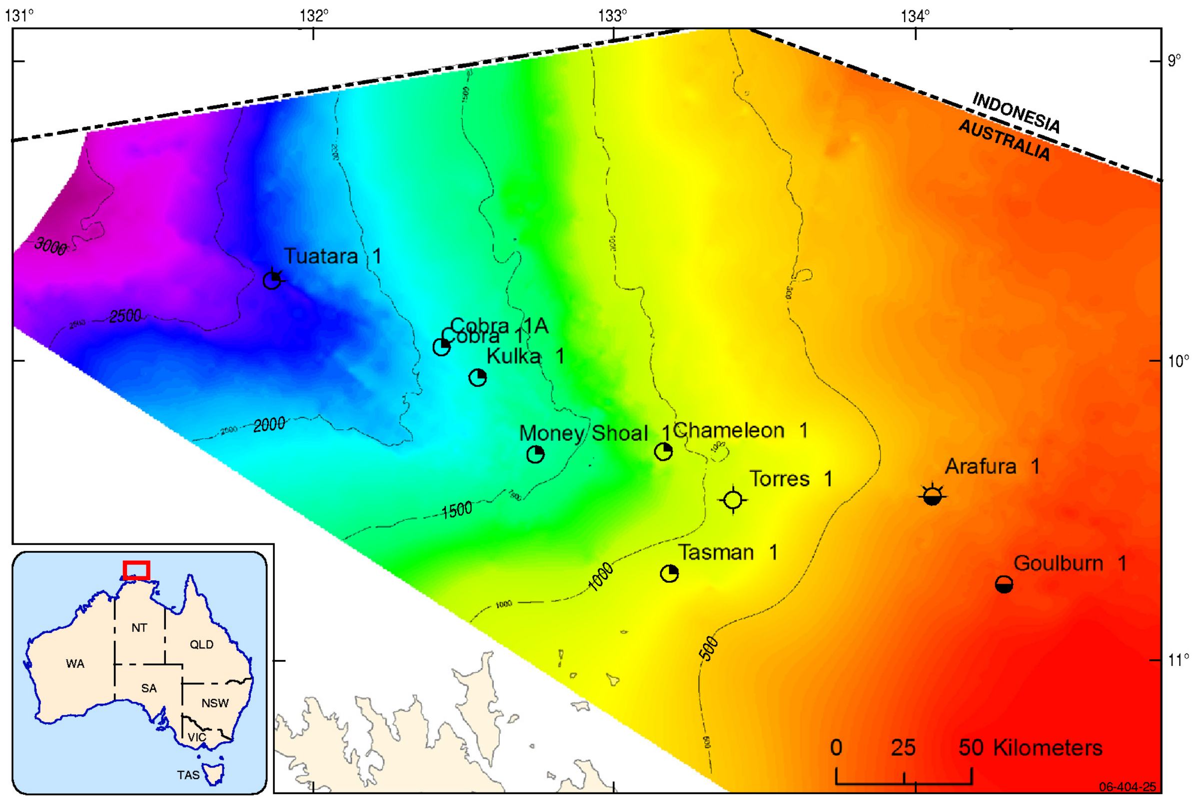

Figure 25: *Thickness (milliseconds two-way time) of the Money Shoal Basin in the study area.*

In terms of post-Triassic stratigraphy (Fig. 26), the Money Shoal Basin contains a sedimentary succession equivalent to that of the Bonaparte Basin to the west (e.g. Mory, 1988, 1991; McLennan et al., 1990; Miyazaki & McNeil, 1998). However, the Money Shoal succession is thinner and less complete than that of the Bonaparte Basin because it consists of the proximal onlap edge of the Mesozoic to Cenozoic succession. Stratigraphic units identified in the study area have been named largely following Mory's (1988, 1991) definitions. The basal sediments range in age from Early Jurassic in the western part of the basin to Late Cretaceous in the east, and unconformably overlie the Arafura Basin and basement rocks of the Pine Creek Inlier and McArthur Basin.

Sediments of the Money Shoal Basin onlap the regional angular unconformity of probable Triassic age. Although the Triassic uplift and erosion event resulted in the formation of a peneplain across the region, it is likely that some topography remained facilitating initial deposition of the Troughton Group equivalent. The Arafura region probably provided the source of sediments deposited in the proto-Malita and Calder graben and in the Barakan Basin during the Late Triassic to Early Jurassic (Barber et al, 2004).

In the Bonaparte Basin, the Late Jurassic was characterised by Oxfordian to Tithonian rifting events that led to the formation of the Malita Graben, Calder Graben and Vulcan Sub-basin (eg Patillo & Nicholls, 1990; Longley et al., 2002). In the study area, this is reflected in relatively small-scale normal faulting along the boundaries of the Goulburn Graben, particularly along the southern boundary (Fig. 27). These faults are likely to be reactivated Late Carboniferous faults, which controlled sedimentation during the Late Jurassic to Early Cretaceous. The Jurassic faults underwent further, compressional reactivation in the Neogene resulting in both small and large scale anticlinal features (Fig. 27). Figure 28 shows the distribution and thickness (in milliseconds two-way time) of the Jurassic to Early Cretaceous succession and illustrates that the depocentres align along the western Goulburn Graben and continue northwest towards the Calder Graben.

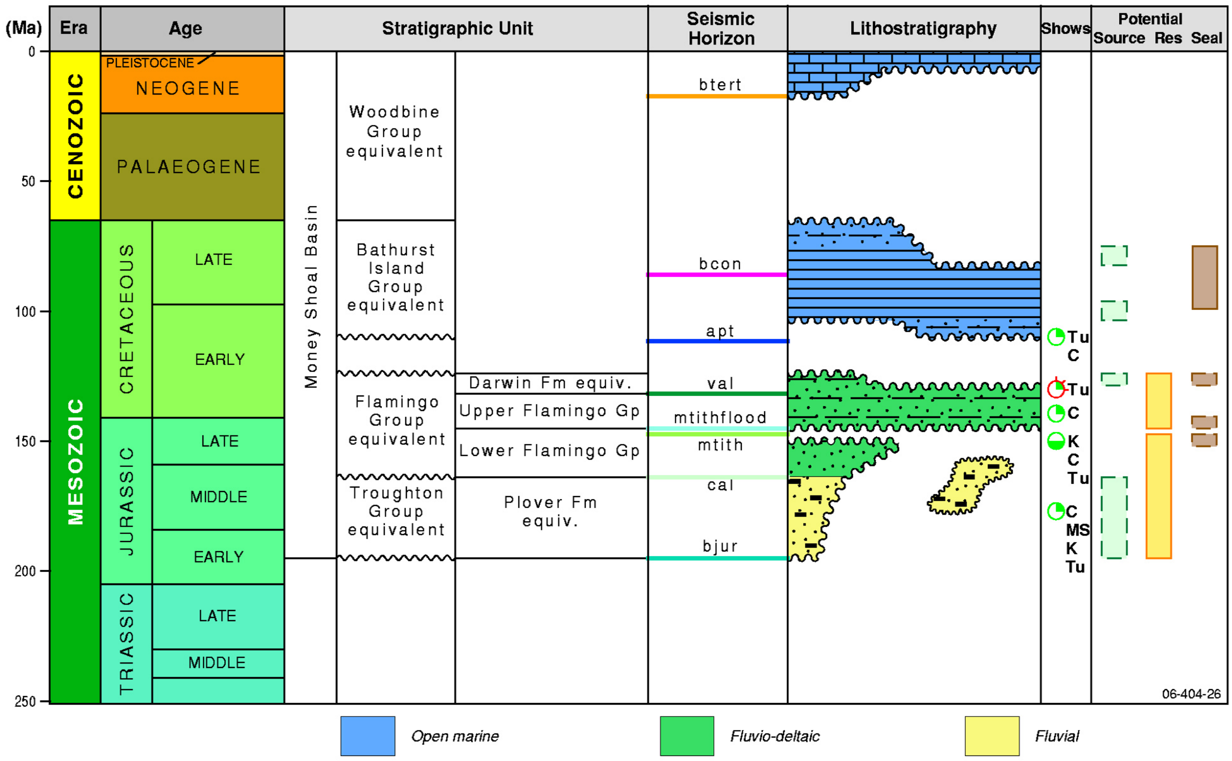

Figure 26: *Money Shoal Basin correlation chart, showing stratigraphy, seismic horizons and petroleum systems elements.*

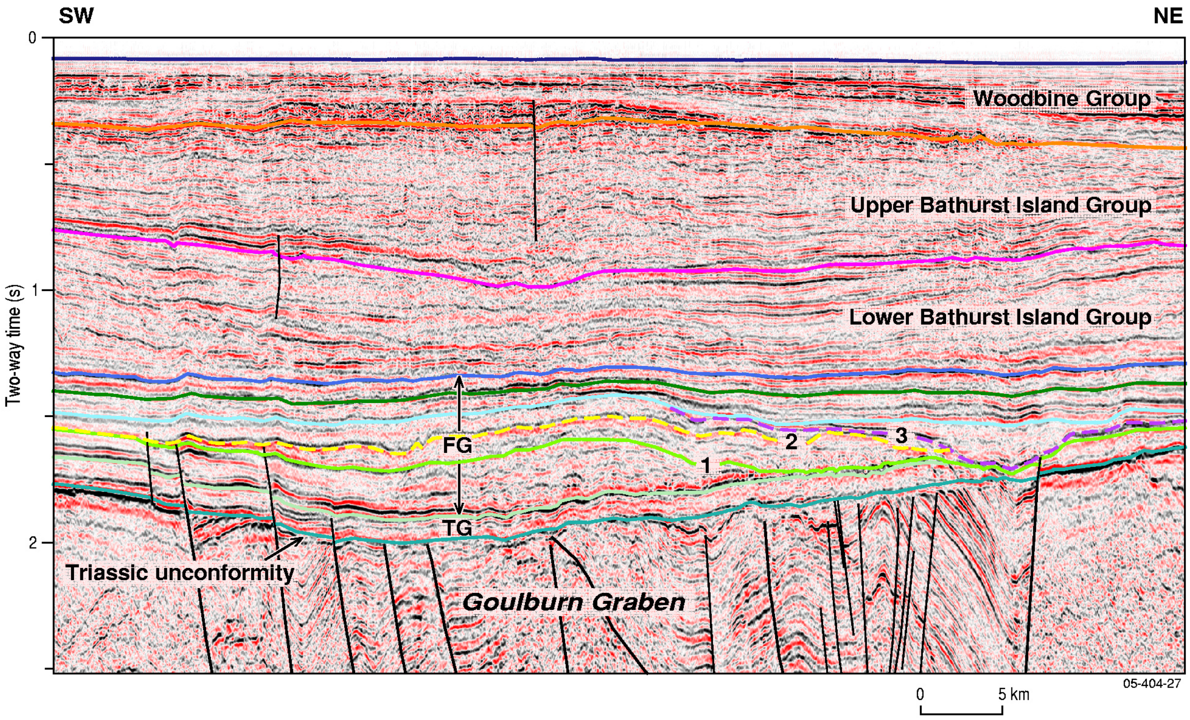

Figure 27: *Seismic example (courtesy Australian Seismic Brokers) illustrating the stratigraphy of the Money Shoal Basin. TG = Troughton Group equivalent, FG = Flamingo Group equivalent; 1, 2 and 3 indicate unconformities within the Flamingo Group equivalent.*

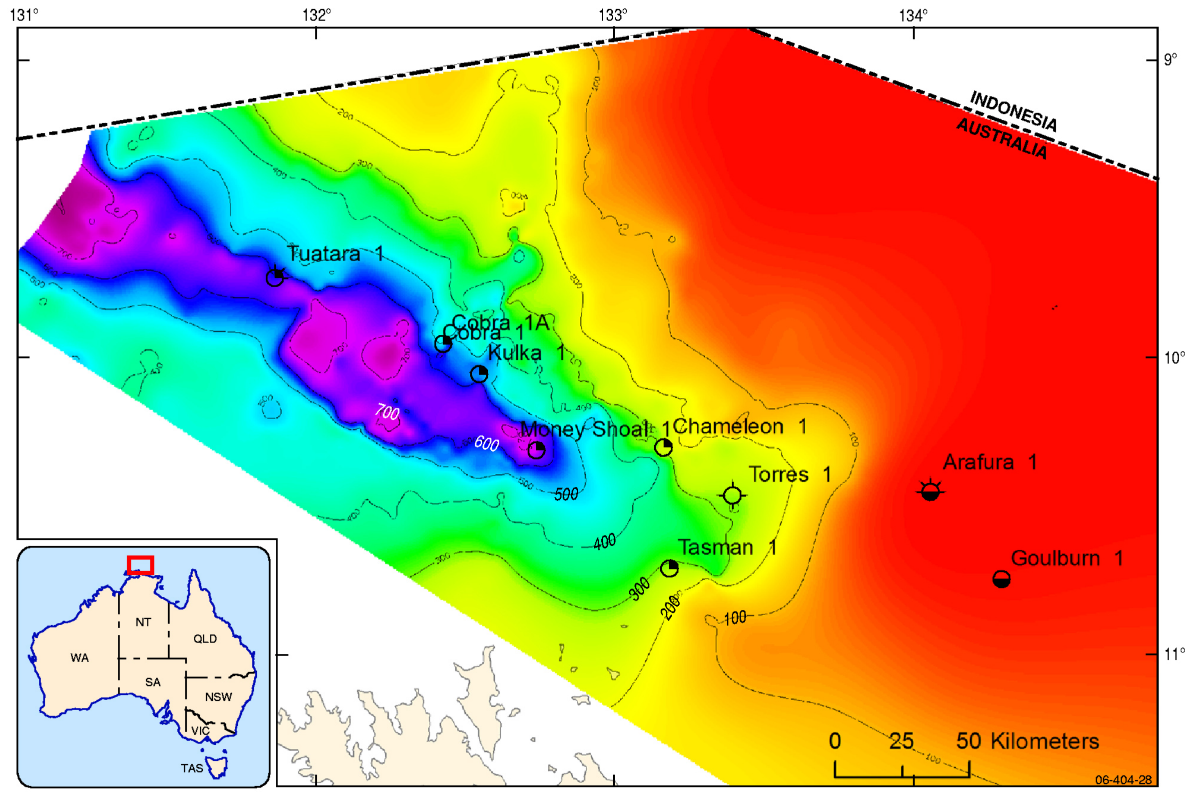

Figure 28: *Thickness (milliseconds two-way time) of Jurassic to Early Cretaceous sediments (Troughton and Flamingo groups) in the Money Shoal Basin.*

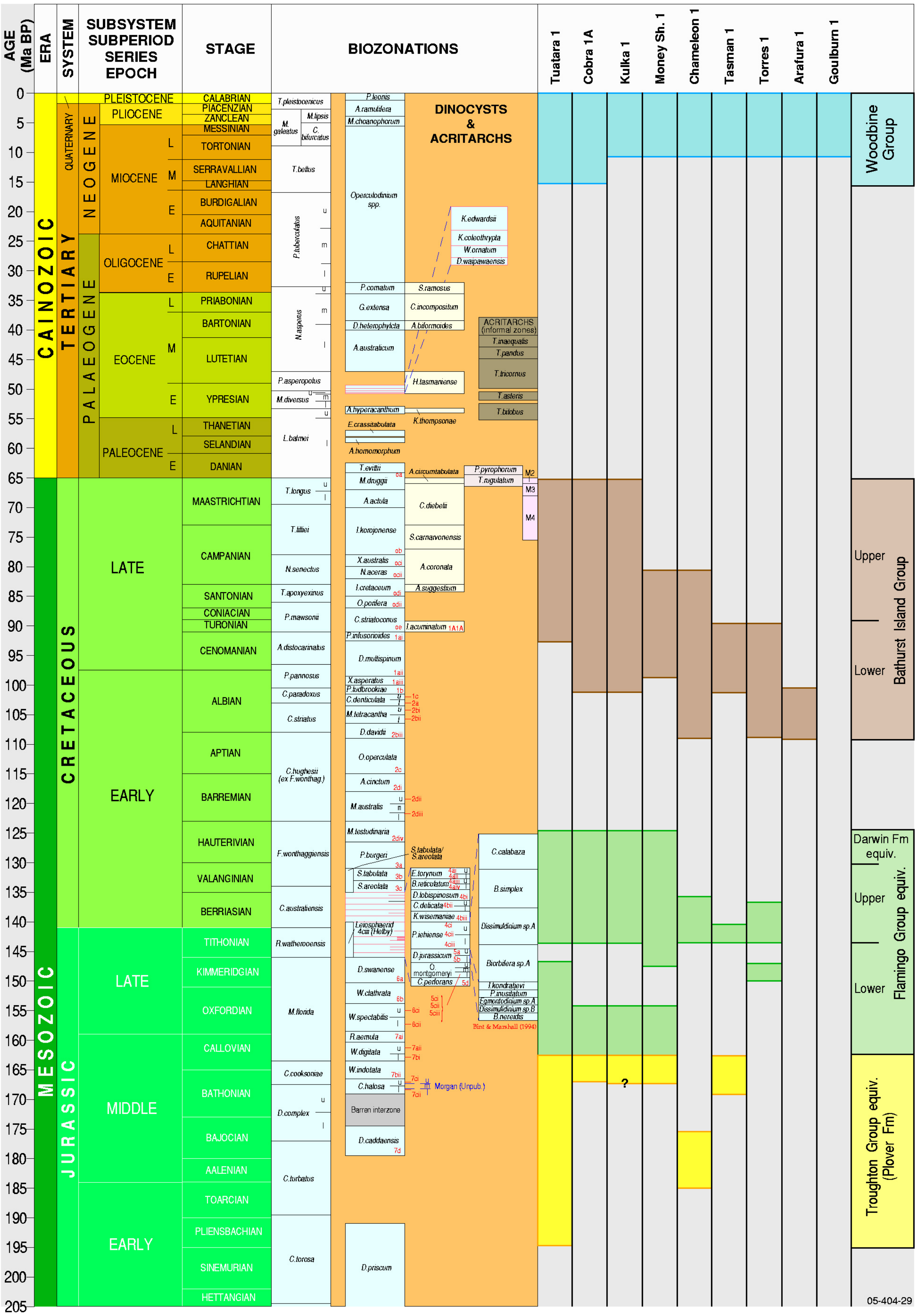

Figure 29: *Age and distribution of Money Shoal Basin sediments intersected in exploration wells of the Goulburn Graben.*

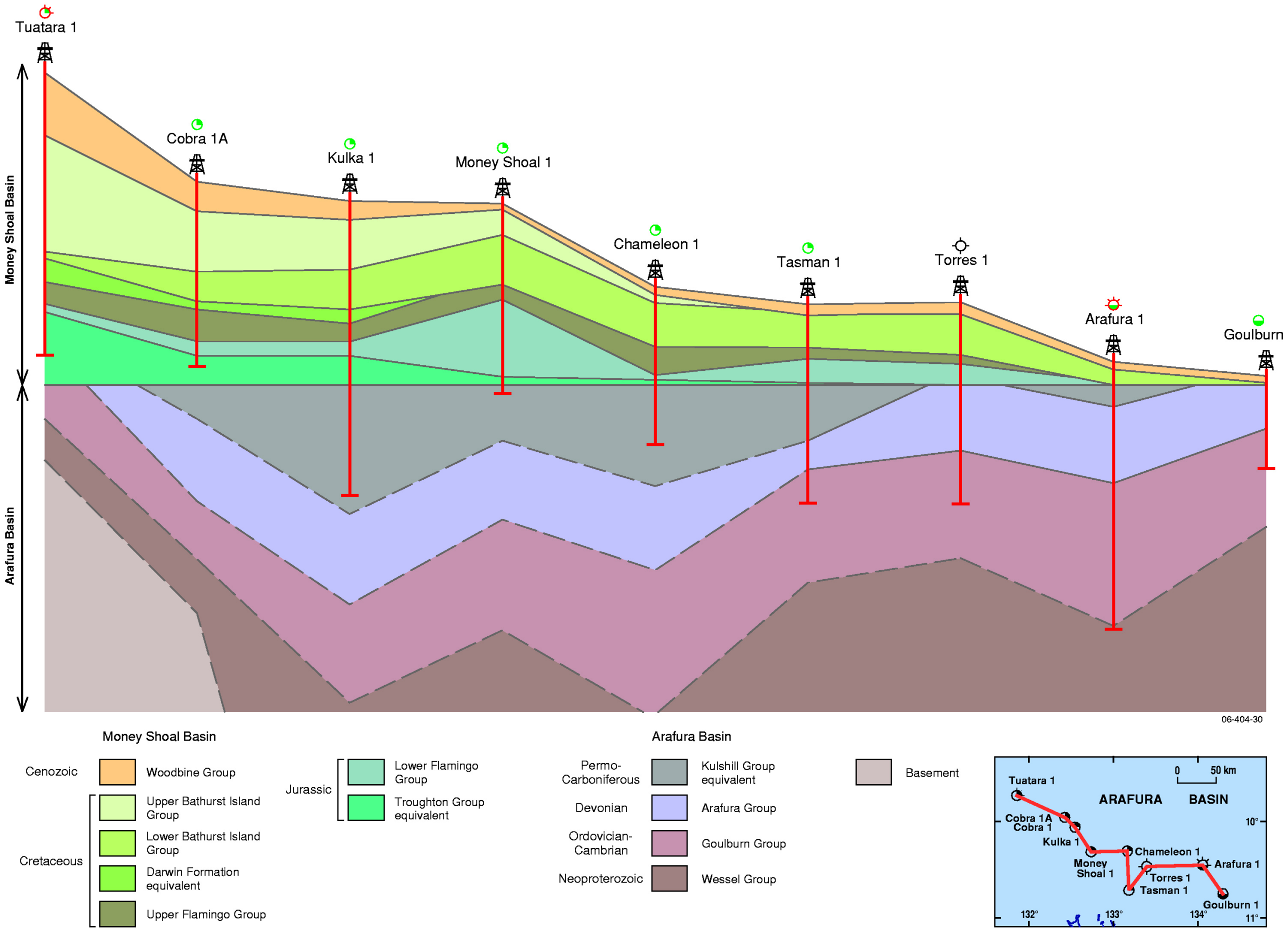

***Figure 30**: Stratigraphic well correlation flattened on Triassic unconformity (modified from Earl, 2006).*

TROUGHTON GROUP EQUIVALENT (PLOVER FORMATION)

In the study area, the Troughton Group is represented only by its youngest component, the Plover Formation, which directly overlies the Triassic regional unconformity. The oldest sediments, intersected at Tuatara 1 (Fig. 29), are of late Early Jurassic age (*C. torosa* to *C. turbatus* spore/pollen zone). The upper boundary of the unit is defined by the regional Callovian unconformity (cal). Deposition of the Troughton Group occurred mostly in the western Goulburn Graben region where it is up to 564 m thick at Tuatara 1. It thins rapidly to the north and east and is absent in wells of the eastern Goulburn Graben (Fig. 30).

The Plover Formation comprises fine- to coarse-grained sandstones with interbedded siltstones and claystones, and minor coal. A generally blocky to serrate gamma log character, the absence of marine microfossils and the presence of coal all indicate an overall fluvial depositional environment. Barber et al. (2003) suggest that a series of braided river systems fed into a wide, northeast–southwest trending marine shelf, with the Goulburn Graben the focus of one of these “trunk rivers”. Lowe-Young et al. (2004) postulated increasing marine influence in the upper Plover Formation in the Evans Shoal area to the west of the study area. Seismically, the Plover Formation is characterised by moderate to high amplitude, moderately continuous, parallel reflections (Fig. 27), but the sequence geometry often is below seismic resolution. Outside the western Goulburn Graben area, the reduced thickness of the Jurassic to Early Cretaceous succession does not allow mapping of individual units of this age.

FLAMINGO GROUP EQUIVALENT

The Flamingo Group ranges in age from Callovian (upper *W. digitata* dinoflagellate zone) to Hauterivian (*M. testudinaria* dinoflagellate zone). The unit is separated into a lower and upper group by a mid-Tithonian unconformity (mtith) (Fig. 26). The base of the Flamingo Group is defined by the Callovian unconformity (cal) which also marks the commencement of a minor extensional event. This is reflected in the clear increase in thickness of the lower Flamingo Group across a reactivated boundary fault of the Goulburn Graben (Fig. 27). A clastic unit of Hauterivian age, equivalent in age to the Darwin Formation, is here included in the Flamingo Group rather than the Bathurst Island Group as defined by Hughes (1978) and Mory (1991), because a major Barremian to Late Aptian hiatus observed in all wells of the Goulburn Graben (Fig. 29) is interpreted to represent the boundary between two major depositional cycles. In the Bonaparte Basin, the age equivalent of this unit is generally known as the Echuca Shoals Formation (e.g. Patillo and Nicholls, 1990; Whittam et al., 1996).

In the Bonaparte Basin, the Flamingo Group is characterised by a condensed section of open marine strata consisting mostly of mudstones (e.g. Longley et al., 2002). In the study area, the succession consists of mostly fine-grained, quartzose, partly glauconitic sandstones with interbedded mudstones and minor coals, deposited in fluvial, deltaic and shallow marine environments. At Tuatara 1, the westernmost well in the study area, the unit is mudstone-rich with a strong marine influence, but it becomes increasingly sand-prone towards the east. Similar to the Troughton Group, the Flamingo Group is thickest in the western Goulburn Graben region (up to 1230 m at Money Shoal 1), thins rapidly to the north and east and is absent in wells of the eastern Goulburn Graben (Fig. 30). A number of erosional surfaces and flooding surfaces can be identified within this unit (Fig. 27), however, due to significant channelling and rapid thinning, these are not regionally mappable on seismic data. A major feature of the Flamingo Group is a fluvial channel system along the northern edge of the Goulburn Graben (Fig. 27) that straddles the hanging wall of the reactivated graben-bounding fault system (Enclosure 4 of Miyazaki and McNeil, 1998). It is present along the entire length of the Goulburn Graben, but is most pronounced near Kulka 1. A distinct flooding surface (mtithflood) defines the upper limit of the channel fill and separates the fluvio-deltaic sediments of the lower Flamingo Group from the upper Flamingo Group. The lower Flamingo Group is characterised by more blocky to serrate gamma ray log signatures, compared with the distinctly upwards coarsening signatures of the upper Flamingo Group that represent prograding marine deltaic deposits (Fig. 31).

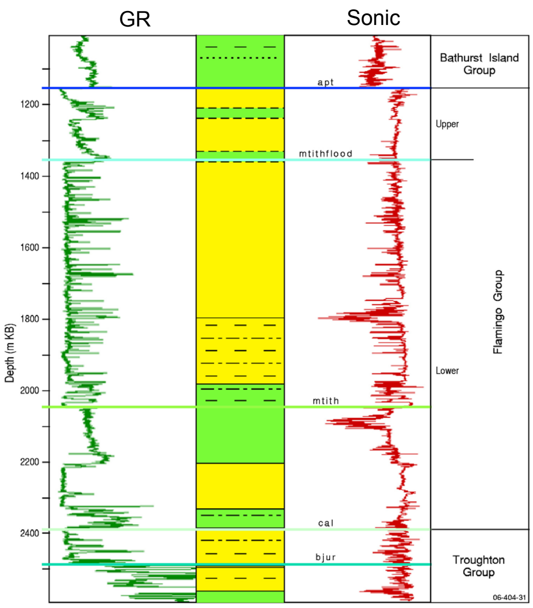

Figure 31*: Well log summary for the Jurassic to Early Cretaceous section in Money Shoal 1.*

BATHURST ISLAND GROUP

The Bathurst Island Group of the eastern Money Shoal Basin is Late Aptian (*D. davidii* dinoflagellate zone) to Maastrichtian in age. In the study area, the base of the group is defined by a major unconformity of Aptian age (apt), which forms the base of a series of thick prograding packages (Fig. 14). At the toe of the progrades, in the more distal parts of the basin, this unconformity merges with the overlying downlap surface. Overall, the unit consists of mostly fine-grained rocks including claystone, marl and siltstone with locally thick interbeds of mostly fine-grained sandstones. In the study area, it reaches a thickness of up to 2000 m (1400 ms two-way time), (Fig. 32), but seismic data show that it thickens further into the Calder Graben near Lynedoch 1.

The Bathurst Island Group consists of a series of stacked prograding units deposited in deltaic to open marine environments. The distribution of the group in the offshore Money Shoal Basin and the age of sediments mapped onshore (Hughes, 1978; Carson et al., 1999) suggest that the most far-reaching marine transgression occurred during the Aptian to Cenomanian (Fig. 29). The increasing presence of planktic foraminifera at Lynedoch 1 to the west of the study area suggests a westwards deepening marine environment.

Deeper water environments are also indicated by the presence of upward fining units suggestive of turbidites, particularly in the upper part of the Bathurst Island Group (Fig. 33). Submarine canyons and coeval deep-water deposits, such as slope fans and basin floor sands, occur in the western study area north and south of Tuatara 1. The fan systems are typically greater than 10 km in diameter and have an overall "gull-wing" geometry (Fig. 34) suggesting that they are mud-rich and likely to represent channel-levee systems containing channel overbank and fill deposits, and chaotic slumps and distal fine-grained turbidites (Emery and Myers, 1996).

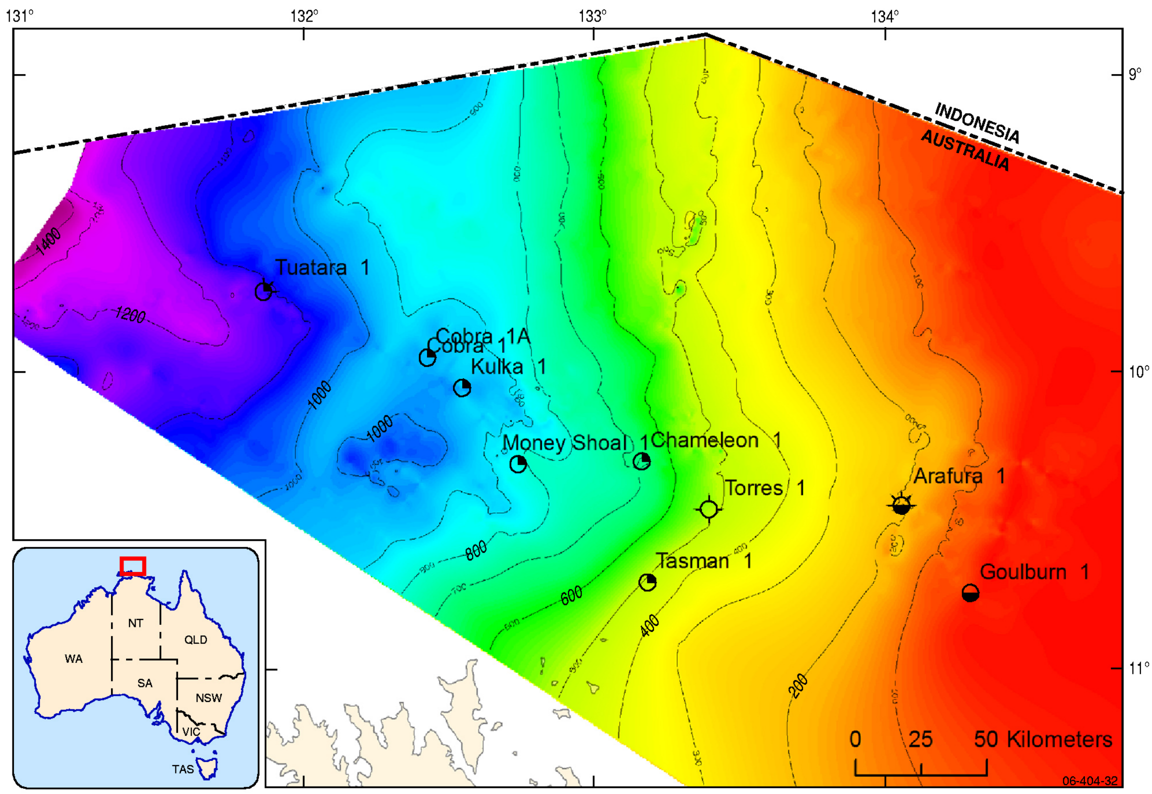

Figure 32: *Thickness (milliseconds two-way time) of the Bathurst Island Group in the eastern Money Shoal Basin.*

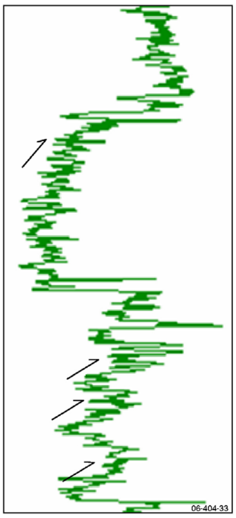

***Figure 33**: Example of upward-fining gamma log signature indicative of turbidites within the upper Bathurst Island Group at Kulka 1 (700-1010 m).*

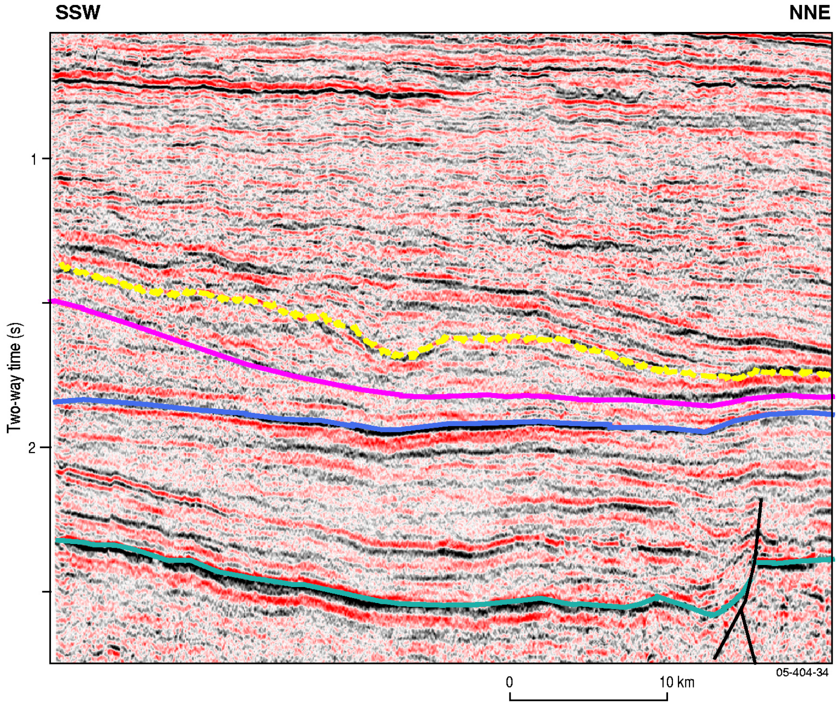

***Figure 34**: Seismic example showing gull-wing geometry of a fan system in the Bathurst Island Group. Seismic line courtesy Australian Seismic Brokers.*

WOODBINE GROUP

In the study area, sediments of the Woodbine Group are typically Late Miocene and younger in age and are generally less than 400 m thick. West of Kulka 1, where the unit includes Middle Miocene sediments, it thickens rapidly towards the Calder Graben, reaching about 800 m at Tuatara 1, and 1300 m at Lynedoch 1 to the west of the study area. Seismic data from the easternmost study area suggest that the unit also gradually thickens towards the Carpentaria Basin.

The Woodbine Group was sampled in a limited number of wells only. For example, at Cobra 1A, a lower unit of probable Lower to Middle Miocene, coarse, quartzitic sandstones with claystone interbeds and minor coal and dolomite is overlain by an upper unit of Late Miocene and ?younger calcareous claystone and marl with calcarenite interbeds (BHP Petroleum, 1993). This suggests initially localised, shallow marine to deltaic sedimentation followed by more widespread open marine environments in the Late Miocene.

In the study area, the Woodbine Group is generally unstructured. Exceptions to this are in the Money Shoal 1 area, where compressional reactivation is evidenced by the presence of a large anticline (Fig. 35). This is likely to have formed in the Late Miocene to Recent in response to northern margin collisional processes. Other structures associated with this are occasional steep, normal reactivation faults in the northern study area close to the Indonesian border (Fig. 36) and to the west of the study area in the northern Calder Graben.

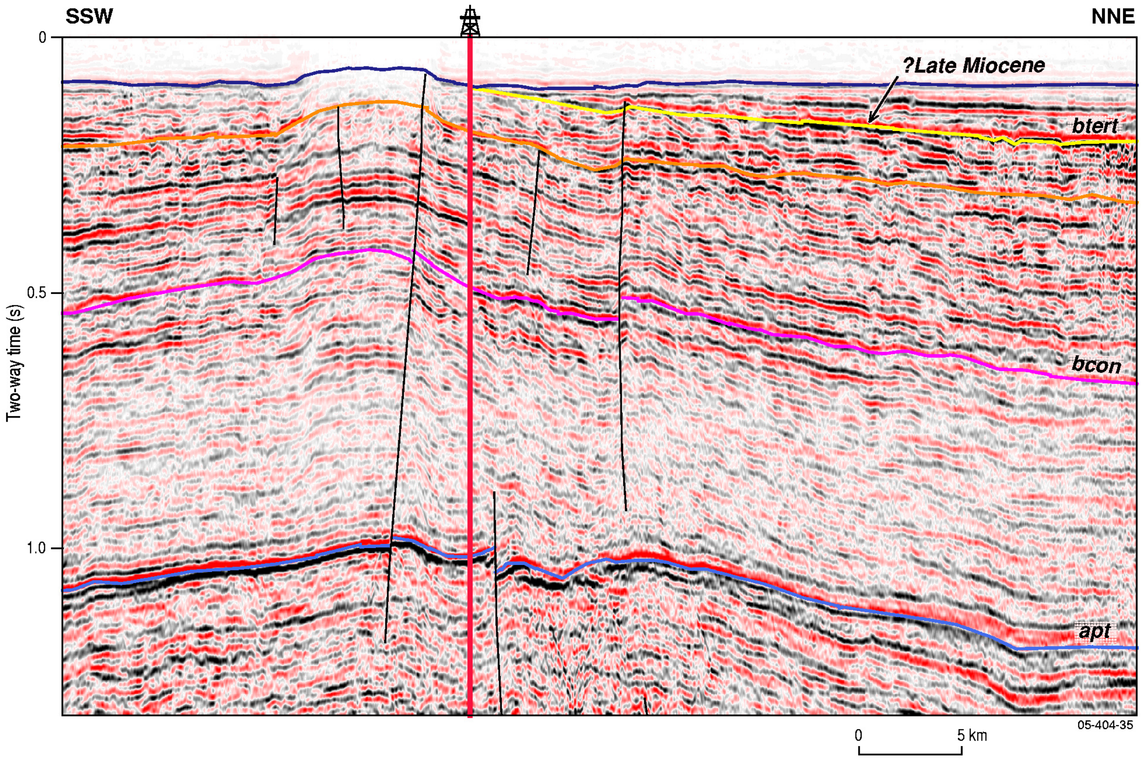

Figure 35*: Seismic example showing Cenozoic to Recent anticline near Money Shoal 1. Seismic line courtesy Australian Seismic Brokers.*

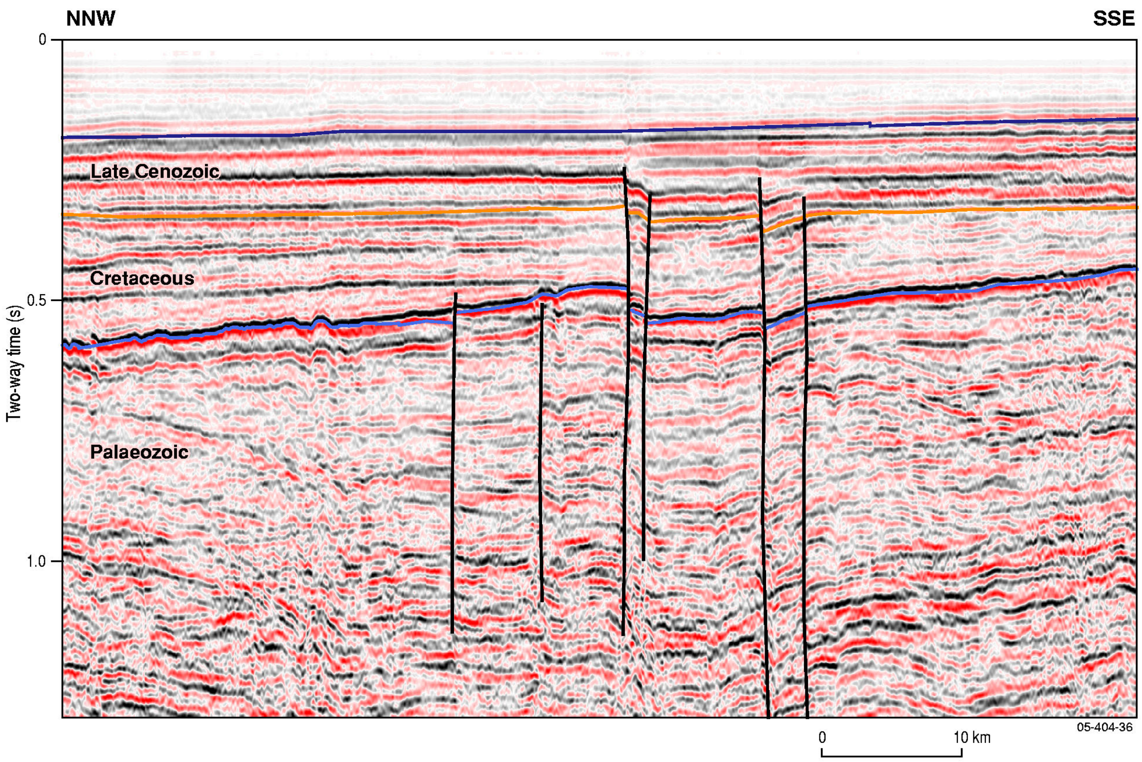

Figure 36*: Seismic example showing Cenozoic reactivation of small-scale Mesozoic or Palaeozoic faults.*

PETROLEUM SYSTEMS ELEMENTS

Heike I.M. Struckmeyer and Karen L. Earl

The Arafura and Money Shoal basins comprise a sedimentary succession that potentially contains all the necessary elements for the generation, expulsion, migration and preservation of hydrocarbons. Well data from the Arafura Basin indicate the presence of at least four potential source rock intervals; two further source rock units could be present based on regional correlations (Bradshaw et al., 1990; Edwards et al., 1997). Although limited, the available dataset strongly suggests that potential clastic reservoir rocks occur in both the Palaeozoic and Mesozoic successions, and that secondary porosity in Palaeozoic carbonate sequences could be important (Earl, 2006). Potential seal rocks are present throughout the succession, with potential regional seals present in the Devonian and Cretaceous sections.

To date, no commercial discoveries have been made in the Arafura Basin, but there are numerous hydrocarbon indications in wells drilled in the Goulburn Graben (Miyazaki and McNeil, 1998; Earl, 2006). Arafura 1 and Goulburn 1 had the most promising results with oil shows, and a gas show in Arafura 1. Chameleon 1, Cobra 1A, Kulka 1, Money Shoal 1, Tasman 1 and Tuatara 1 all contain oil indications in Mesozoic and Palaeozoic reservoirs. These, together with other, indirect hydrocarbon indications, strongly suggest that hydrocarbon generation and migration have occurred in the basin. The timing of generation and expulsion of hydrocarbons from potential source rocks in relation to major structural events and trap formation have been identified as a major exploration risk by previous studies (Bradshaw et al., 1990; Moore et al., 1996; Earl, 2006). This issue is addressed in the next chapter.

CHARACTER AND MATURITY OF POTENTIAL SOURCE ROCKS

As outlined by Bradshaw et al. (1990) and Totterdell (this volume), the Arafura Basin is underlain by the Palaeo- to Mesoproterozoic McArthur Basin. Crick et al. (1988) and Jackson et al. (1988) described two major potential source rock units from the onshore McArthur Basin, the lacustrine Barney Creek Formation of the McArthur Group and the marine Velkerri Formation of the overlying Roper Group. A live oil show was reported from the latter during drilling of the BMR Urapunga 4 stratigraphic hole. The sediments contain Type I and II kerogens comprising mostly lamalginite and bitumen and have TOC values of up to 7%. Maturation levels range from marginally mature to overmature for oil generation. It is likely that these potentially excellent source rocks are also present in the section underlying the Arafura Basin and it is conceivable that hydrocarbon generation and expulsion from these rocks occurred. An assessment of the timing of generation in relation to Arafura Basin deposition is difficult with the limited datasets, although Crick et al. (1988) suggested that the Velkerri Formation may have passed through the oil window during the Palaeozoic.

Potential source rocks are probably also present within the Neoproterozoic Wessel Group, however, no geochemical or organic petrological data are available for this section. For example, onshore, the Raiwalla Shale and Elcho Island Formation contain thick, fine-grained sediments deposited in shallow marine environments (Carson et al., 1999). The type of organic matter is likely to be similar to that for the Mesoproterozoic, i.e. Type I/II algal/bacterial organic matter.

Both organic geochemical and organic petrological open file data are available for Palaeozoic and Mesozoic sediments intersected in the Arafura and Money Shoal basins. These are available online in Geoscience Australia's petroleum databases. Additionally, results from analyses carried out for the present study were compiled in Struckmeyer

(2006). These analyses focused mainly on the Palaeozoic to improve understanding of both source rock maturity and quality in this section (Boreham, 2006; Sherwood et al., 2006). A summary diagram (Fig. 37) showing RockEval TOC values plotted against age for samples from the Arafura and Money Shoal basins illustrates the presence of fair to very good source rocks within the sedimentary succession. Vitrinite reflectance data for samples from the study area are presented in Figure 38, indicating that sediments which are mature for oil and gas generation are present.

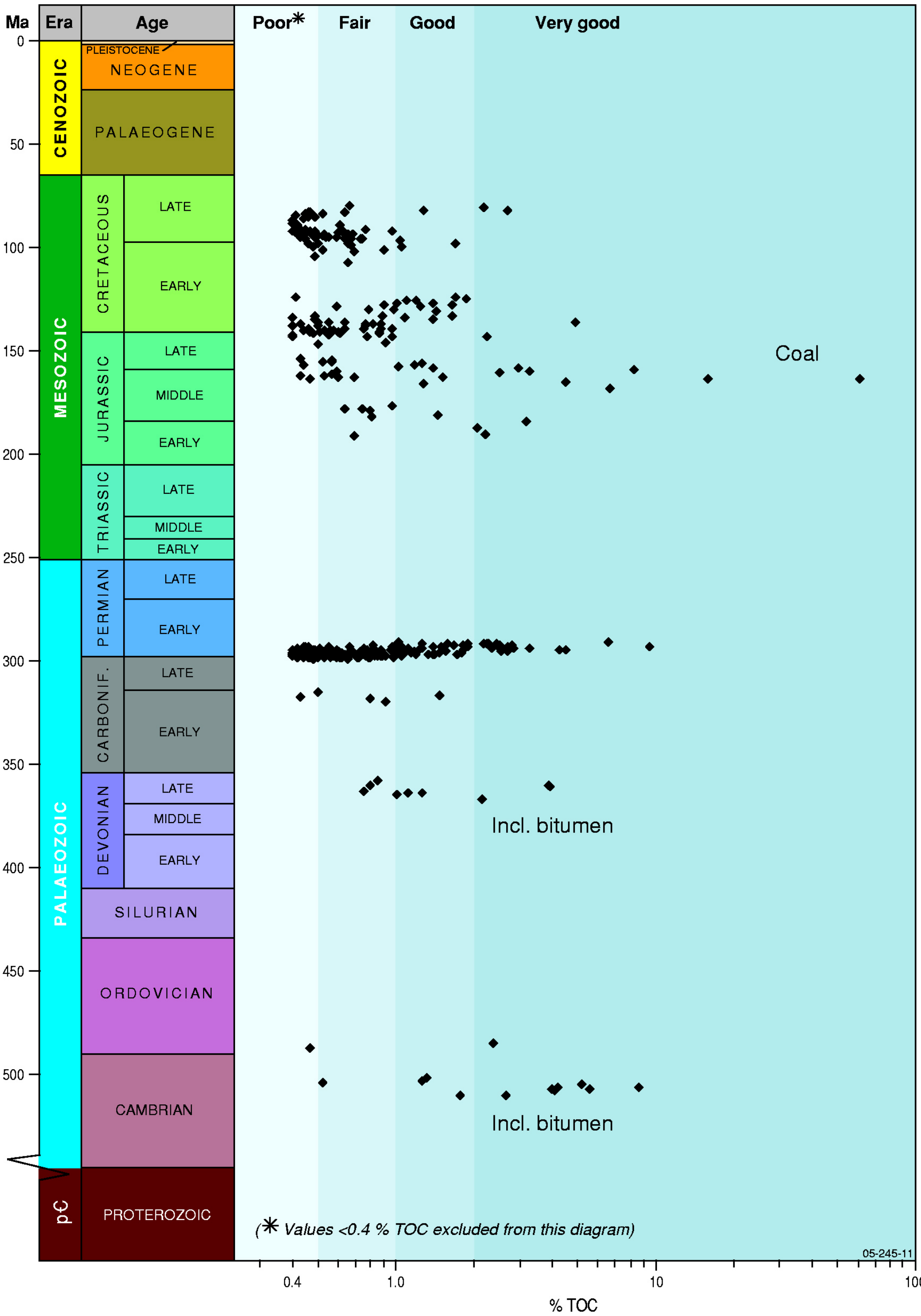

***Figure 37**: RockEval TOC (Total Organic Carbon) content plotted against age for samples from the Arafura and Money Shoal basins.*

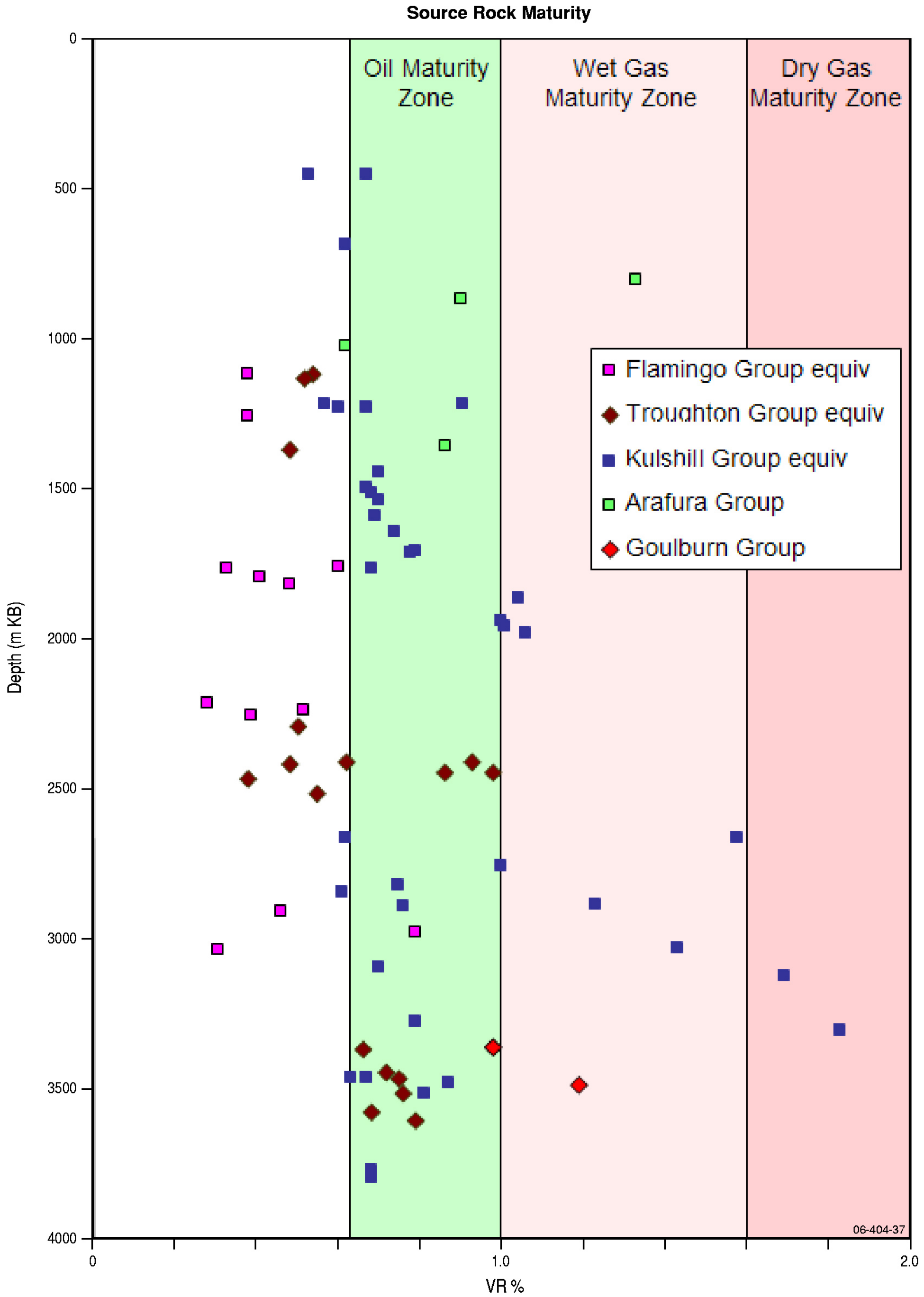

***Figure 38**: Vitrinite reflectance data plotted against depth for samples from the Arafura and Money Shoal basins).*

The Cambro-Ordovician ***Goulburn Group*** was intersected in four wells and samples from this succession contain up to 8.6% TOC (Fig. 37). However, the higher values represent migrated oil and solid bitumen (Fig. 39) (Keiraville Konsultants, 1984; Sherwood et al, 2006), rather than dispersed organic matter as reported in previous publications (Bradshaw et al, 1990, Edwards et al, 1997). A recent oil-source correlation study in the Georgina Basin (Boreham and Ambrose, in press) identified three Middle to Late Cambrian petroleum systems related to source rocks of algal/bacterial origin. One of these, the Early Middle Cambrian Thorntonia(!) petroleum system, has similar geochemical and isotopic

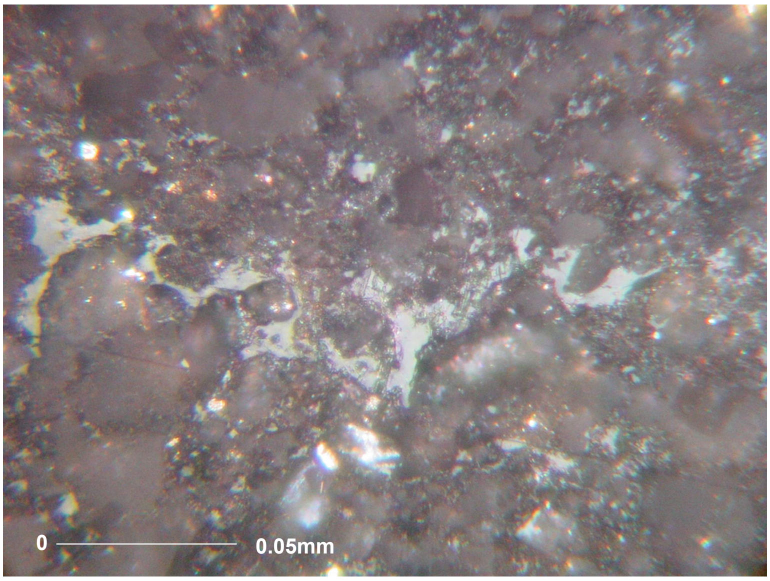

***Figure 39**: Cambrian carbonate with interstitial and finely disseminated bitumen (from Sherwood, 2006).*

characteristics to oil stains in Early Palaeozoic rocks at Arafura 1 and Goulburn 1 (Boreham and Ambrose, in press). This suggests that the effective source rock in the Arafura Basin is likely to occur in the Jigaimara Formation, which is an age equivalent of the Thorntonia Limestone in the Georgina Basin. The presence of abundant interstitial bitumen in association with oil stains in Early Palaeozoic samples is indicative of a multi-charge history from a prolific source nearby (Sherwood et al, 2006).

Thus, although not intersected in wells from the Arafura Basin, the most likely, most prolific potential source rock sequence is considered to be middle Cambrian in age, based on geochemical correlation from oil stains and solid bitumens (see also Boreham, 2006). Boreham and Ambrose (in press) suggest that the Jigaimara Formation was part of the Early Palaeozoic Larapintine petroleum supersystem, which occurs in onshore northern Australia, across the Arafura Sea into the island of New Guinea, and in the Early Palaeozoic basins of the North West Shelf. It correlates with source rocks of similar age in the onshore Amadeus, Georgina and Officer Basins in Australia (Boreham and Ambrose, in press), and globally, with organic-rich black shales of Middle–Late Cambrian age, deposited during a time of high sea-level in euxinic conditions.

The maturity of the early Palaeozoic succession is difficult to assess due to the absence of organic material derived from higher plants. As part of the present study, Sherwood et al. (2006) evaluated thermal maturity using a combination of FAMM (fluorescence alteration of multiple macerals) and conventional organic petrological analyses from several wells in the Arafura Basin. These are complemented by new analyses of organic geochemical maturity parameters by Geoscience Australia (Boreham, 2006). Based on a combination of these datasets, Cambro-Ordovician sediments in the Arafura Basin are presently mature to overmature for oil generation.

A limited number of samples from the Devonian ***Arafura Group*** suggests a generally poor source potential for this section; however, one sample at Arafura 1 contains 0.85% TOC that consists predominantly of lamalginite (Sherwood et al, 2006). This confirms that potentially fair source rocks are present within Devonian marine calcareous mudstones. High TOC values in other samples reflect the presence of bitumen (Fig. 37). Vitrinite reflectance data suggest that the sediments are early mature to mature for oil generation (Fig. 38).

Good to very good potential source rocks with Type II/III kerogen (Fig. 40) are also present in the Permo-Carboniferous ***Kulshill Group*** equivalent. The typical TOC range is

<0.4 to 3%; several samples contain up to 9% TOC (Fig. 37), comprising land plant-derived organic matter such as vitrinite, sporinite and liptodetrinite (Sherwood et al., 2006) (Fig. 41). The Kulshill Group is immature to mature for oil generation, with maturity dependent on the thickness of the Money Shoal Basin overburden.

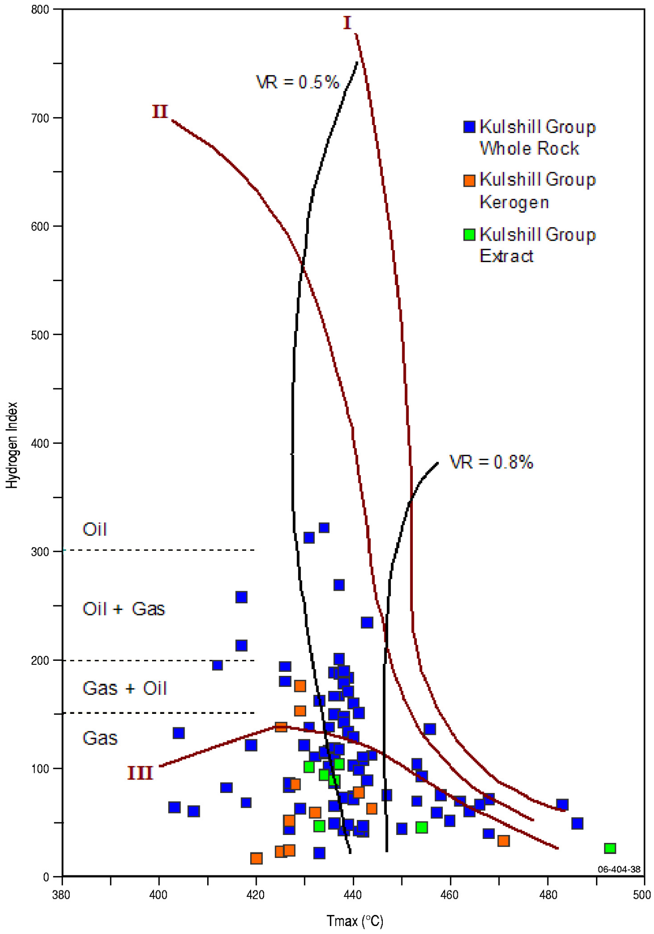

***Figure 40**: RockEval pyrolysis plot for samples from the Kulshill Group equivalent.*

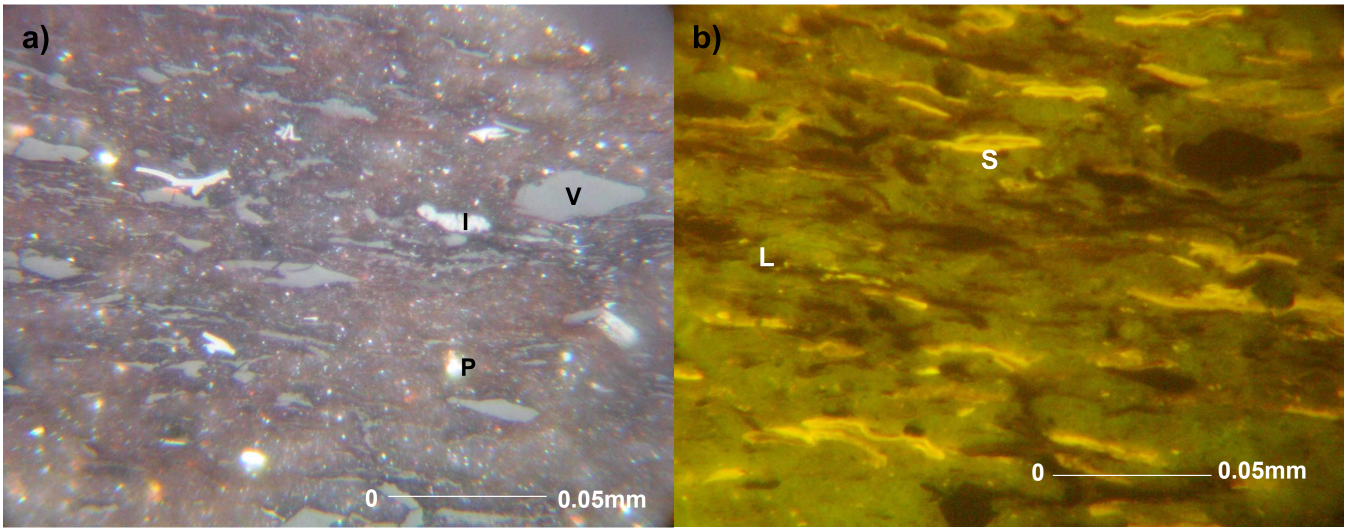

***Figure 41**: Permian mudstone (450-460 m, Arafura 1) containing a) abundant vitrinite (V) and inertinite (I) with disseminated pyrite (P) (reflected white light photomicrograph), and b) abundant sporinite (S) and liptodetrinite (L) (fluorescence mode photomicrograph); from Sherwood et al. (2006).*

Preston & Edwards (2000) and Longley et al. (2002) suggested that the **Troughton Group** (**Plover Formation)** provides a source for many of the hydrocarbon accumulations of the Bonaparte Basin. In the study area, apart from thin coal layers, the unit contains considerable amounts of Type II/III kerogen as dispersed organic matter (Fig. 42a). TOC values range from less than 0.5 to 8% (Fig. 37), indicating fair to very good source potential. Sediments of this age reach maturity for oil generation in the westernmost Goulburn Graben area, where they could provide the source kitchen for a range of potential traps in the Mesozoic section.

RockEval pyrolysis data suggest that the **Flamingo Group** contains oil-prone Type II/III kerogen (Fig. 42b). Total organic carbon values in samples from the Flamingo Group range from less than 0.5 to 4.9% (Fig. 37), indicating that some intervals have very good source potential. Although these sediments are generally immature in the study area, they could reach oil maturity in the deepest depocentres. This is supported by data from Money Shoal 1, where the base of the Flamingo Group yielded a vitrinite reflectance value of 0.79. Therefore, Flamingo Group organic-rich rocks could provide a source for a range of potential traps in the Mesozoic section of the western Goulburn Graben area.

RockEval pyrolysis data suggest that the **Bathurst Island Group** contains oil-prone Type II/III kerogen. Total organic carbon values range from less than 0.5 to 2.7% (Fig. 37), indicating that some intervals have fair to good source potential. Although these sediments are immature for hydrocarbon generation in the study area, vitrinite reflectance values higher than 0.5% at Tuatara 1 indicate that the unit could reach oil maturity in the deepest depocentre between Tuatara 1 and Lyndoch 1.

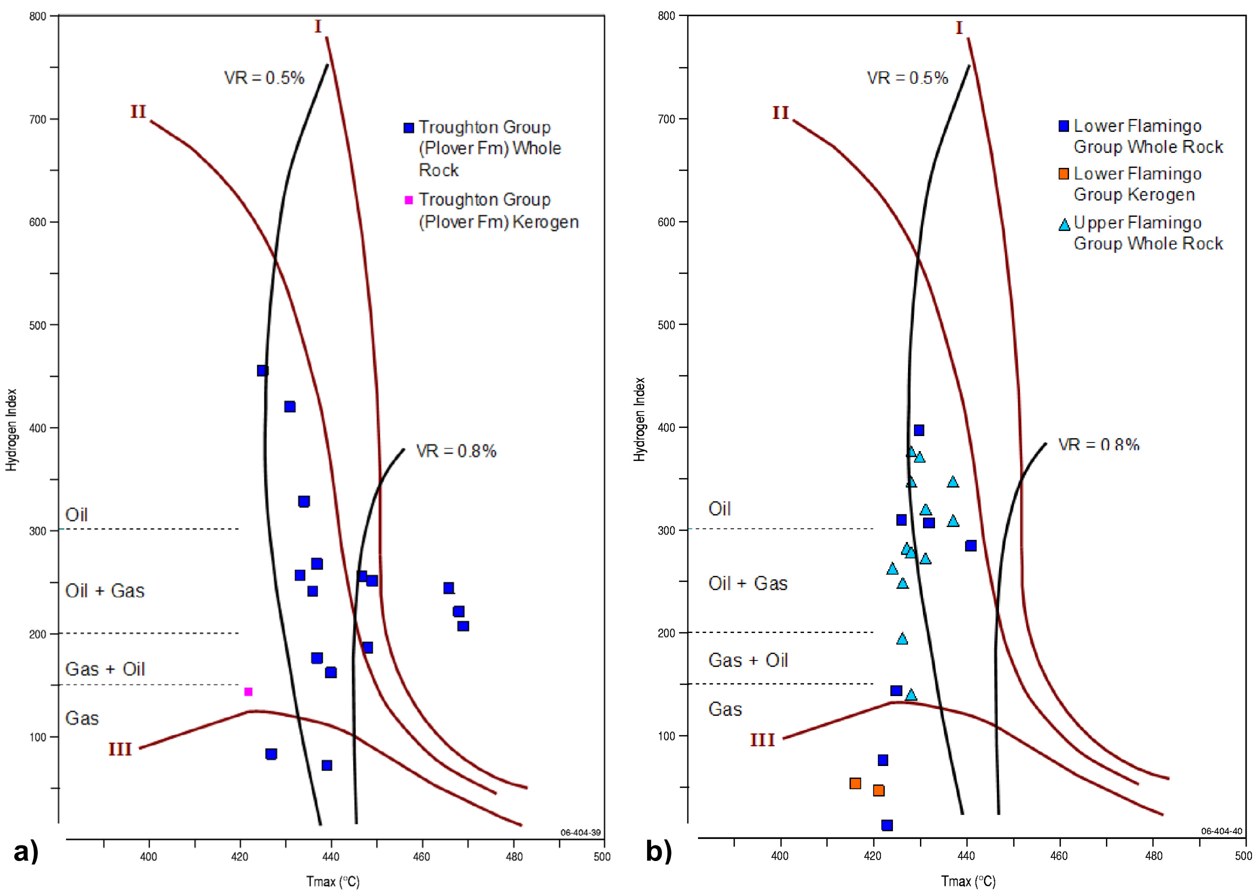

***Figure 42**: Rock Eval pyrolysis plots for samples from the (a) Troughton and (b) Flamingo groups.*

RESERVOIR AND SEAL ROCKS

Potential reservoir rocks in the Arafura Basin (Fig. 43) include shallow marine limestones and dolomites of the Cambro-Ordovician Goulburn Group, and terrestrial to fluvio-deltaic interbedded sandstones and mudstones of the Devonian Arafura Group and Permo-Carboniferous Kulshill Group equivalent. The Goulburn Group dolomite is an important potential reservoir in the region, hosting an oil and gas show in Arafura 1 and oil indications in Goulburn 1. The unit has a maximum porosity of 7.7%, but averages about 2% in intervals lacking significant secondary porosity (Fig. 43). Permeability values are also generally low. As a result, reservoir quality in this unit relies on the development of secondary porosity through features such as vugs and fractures. These features are common, as evidenced by repeated mud losses, increases in drilling rates, variable caliper logs and drilling breaks (Earl, 2006). Movement of fluid into and through the unit is facilitated by these secondary features, as indicated by the numerous associated oil occurrences. A risk associated with this unit is cementation reducing secondary porosity. Apart from deep burial, the cementation is probably partly related to Triassic contraction and uplift. The reduced impact of this event in the northern Arafura Basin implies that this may be a less important risk in this area as compared with the Goulburn Graben. Shales interbedded with the carbonates of the Goulburn Group could provide intraformational seals, but the predominant carbonate lithologies within this unit suggest that a range of diagenetic seals and traps could also be present.

Siltstones and sandstones of the Arafura Group form another important reservoir in the basin, hosting oil shows at both Arafura 1 and Goulburn 1. The unit has a maximum porosity and permeability of 19% and 7.83 mD at Goulburn 1, but averages 9.6% porosity with a large standard deviation (Fig. 43). A significant proportion of the primary porosity has been destroyed by diagenetic effects, including silica overgrowths and carbonate cementation. Similar to the Goulburn Group, this is likely to be of less importance in the northern part of the basin, where these potential reservoirs generally occur at shallower depths, and have not undergone as much burial or uplift. Relatively thick shale intervals (up to 400 m at Torres 1) within the upper part of the Devonian succession suggest that at least intraformational seals and possibly a regional seal could be present. This is supported by the pattern of hydrocarbon shows at Arafura 1 (Earl, 2006), where all reported shows occur below this interval, apart from a fault-associated show in the Permian section.

The Kulshill Group equivalent generally has poor reservoir quality, with porosities averaging 5.5%. However, the upper parts of this unit generally have better than average porosities (Fig. 43) with a maximum of 17.7% at Tasman 1. Carbonate cements are sporadic throughout the unit but there is evidence of multiple fracture sets (such as at Chameleon 1), which could enhance the overall permeability and porosity. Potential seals within the Kulshill Group are likely to be intraformational.

In the eastern Bonaparte Basin, the upper Plover Formation provides the reservoir for the gas accumulations at Evans Shoal (Lowe-Young et al., 2004), Lynedoch/ Sunrise/Troubadour (Whittam et al, 1996; Seggie et al., 2000; Longley et al., 2002) and Abadi (Barber et al., 2004). In the study area (Fig. 44), the average porosity of the Plover Formation equivalent is variable and ranges from less than 5% to 27% (Earl, 2006), depending on the proportion of fine-grained clastics and depth of burial. These values indicate the potential for favourable reservoir properties in the region. Seals could be provided by up to 50 m thick claystone-rich intervals in the lower part of the Lower Flamingo Group, and by the Bathurst Island Group in the eastern part of the basin.

Samples from the Flamingo Group have an average porosity of 18.5%, with a maximum of 32% at Tasman 1, suggesting good to excellent reservoir potential (Fig. 44). Major hydrocarbon accumulations occur in sediments of similar age in the Bonaparte Basin (e.g. Bayu Undan, Laminaria) and Browse Basin (Brewster). Seals could be provided by interbedded mudstone intervals, particularly associated with condensed sections and, regionally, by the Bathurst Island Group.

Due to its overall fine-grained character, the Bathurst Island Group forms a regional seal to Early Cretaceous reservoirs in the Bonaparte and Money Shoal basins. In the eastern part of the study area, mudstones of Aptian to Cenomanian age directly overlie Palaeozoic rocks of the Arafura Basin. Very little is known about the reservoir qualities of the deltaic and turbiditic sandstones of the Bathurst Island Group, but samples from Tuatara 1 yielded porosities of 13–33 %, with an average of 20%.

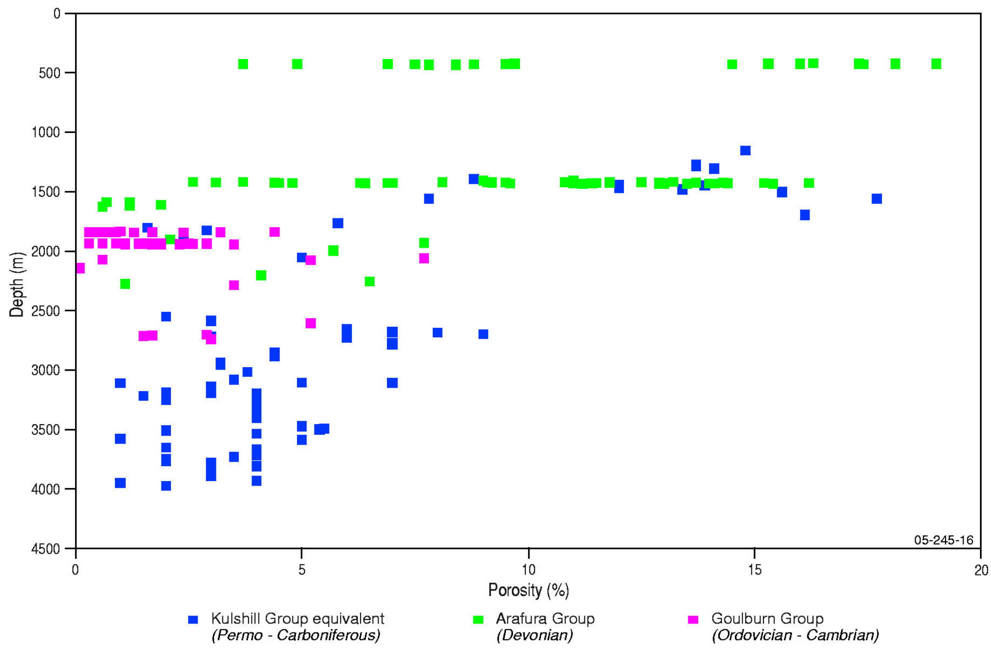

Figure 43: *Porosity data for samples from the Arafura Basin (from Earl, 2006).*

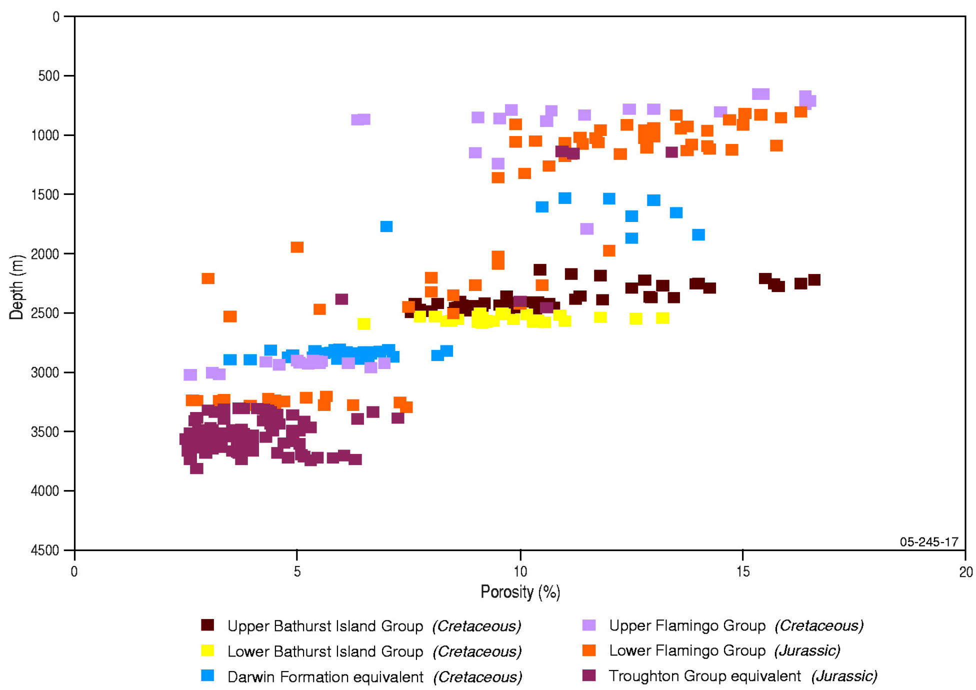

Figure 44: *Porosity data for samples from the Money Shoal Basin (from Earl, 2006).*

TIMING OF HYDROCARBON GENERATION AND EXPULSION

Heike I.M. Struckmeyer

Moore et al. (1996) concluded that oil generation and migration from potential Palaeozoic source rocks in the Goulburn Graben, where all exploration wells are located, pre-dates the Triassic structural event and thus potential trap formation. The area to the north of the Goulburn Graben was suggested to have an increased chance of hydrocarbon preservation as a result of later generation and migration.

To test this hypothesis within the context of new structural and stratigraphic interpretations of well and seismic data and the resulting tectonostratigraphic model of the region (Totterdell, this volume), geohistory modelling of all exploration wells and several 'pseudo-well' sites in the northern Arafura Basin (Fig. 45) was carried out for this study using WinBury^{TM} and FobosPro software. Pseudo-well sites were selected to represent varying sediment thickness and degrees of Triassic uplift and erosion in order to model burial history in different structural settings of the basin (Fig. 46). All wells and pseudo-wells were modelled to the interpreted base of the Arafura Basin thus providing a consistent model across the basin.

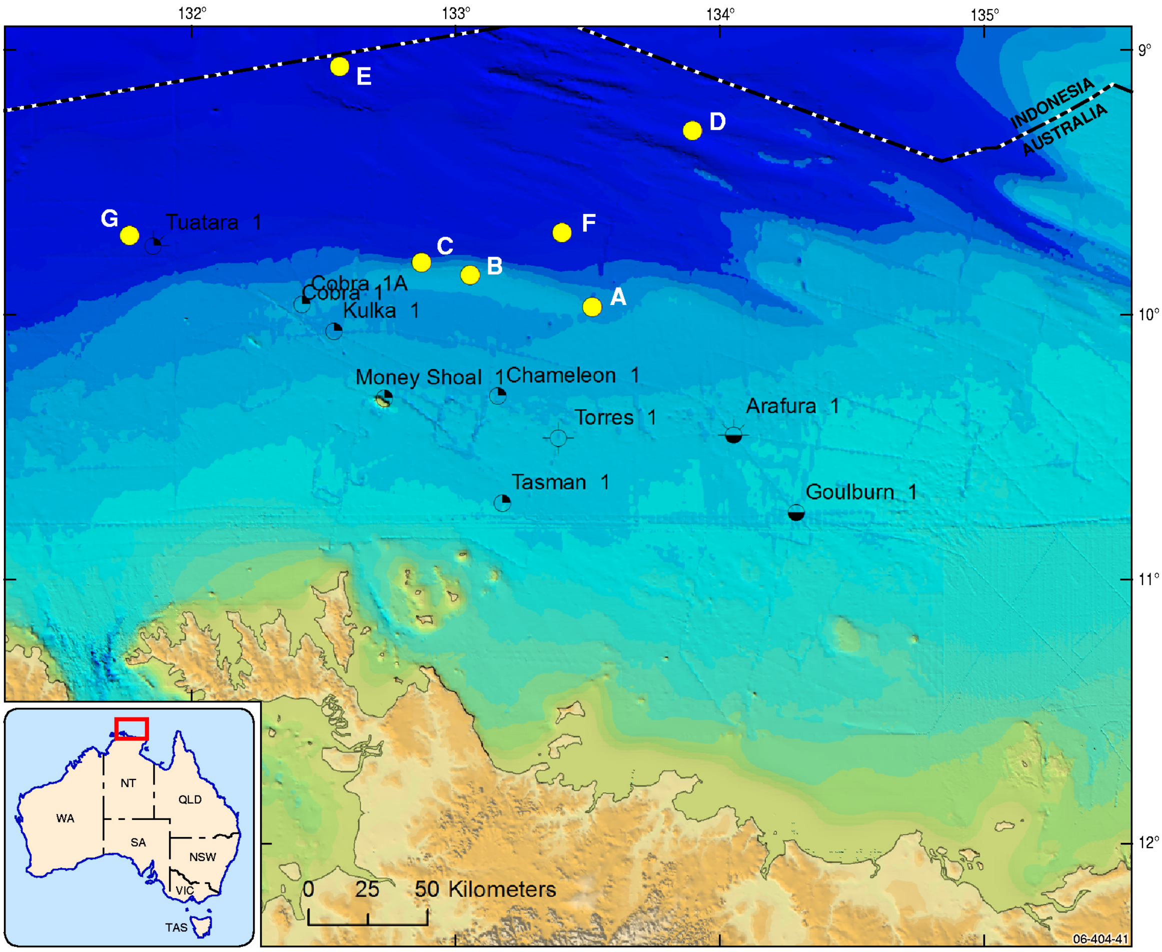

***Figure 45**: Map showing location of modelled exploration wells and pseudo-well sites.*

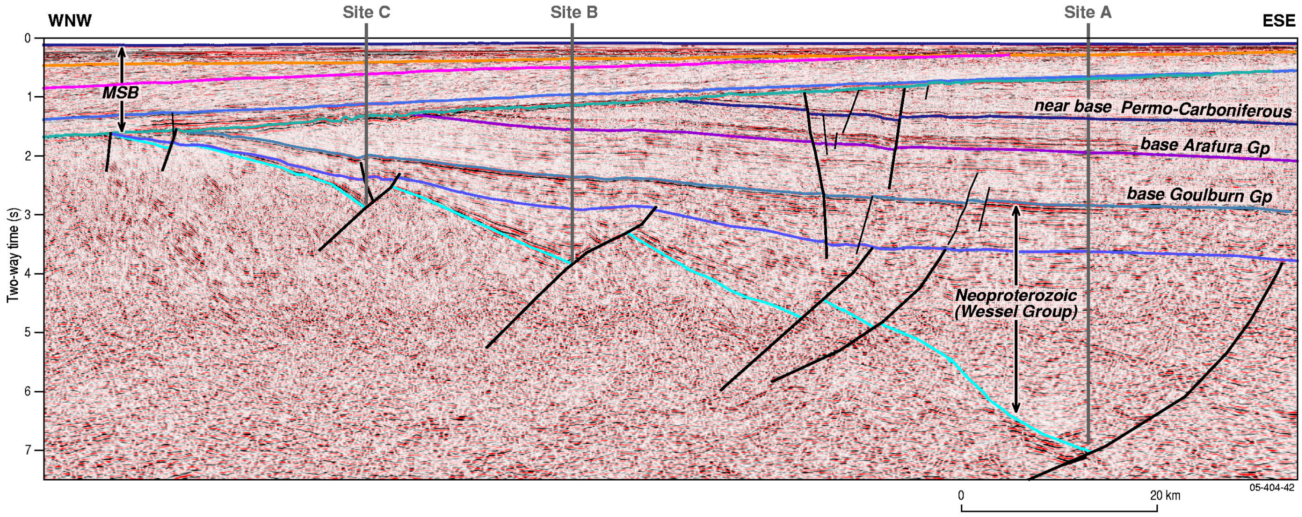

***Figure 46**: Location of pseudo-well sites A, B and C on seismic transect (courtesy Veritas DGC). For geological setting of sites D to G see Struckmeyer et al. (2006).*

Basic geohistory models and input parameters that underpin models of generation and expulsion discussed in this section, are provided in Struckmeyer et al. (2006). Present-day heatflow was calculated in WinBury™ from extrapolated bottom-hole-temperatures, estimated seafloor temperatures and thermal conductivities of end-member lithotypes of intersected lithologies. Present-day heatflow values range from 52 mW/m^2 at Tuatara 1 to 70 mW/m^2 at Chameleon 1 and Goulburn 1. This is considerably lower than values of 80 mW/m^2 given by Cull and Conley (1983) for the Arafura Sea, however, their map was produced prior to much of the drilling in the region and was based on the assumption of shallow basement throughout the area of interest.

Modelled palaeo-heatflow was constrained by vitrinite reflectance and FAMM (fluorescence alteration of multiple macerals) data from open file sources and new analyses (Sherwood et al., 2006). In addition, geochemical maturity parameters such as RockEval Tmax and newly generated data from aromatic biomarkers (Boreham, 2006) were taken into account. Following initial modelling in WinBury™, the palaeo-heatflow values were adjusted in FobosPro using whole lithosphere parameters of heat, thermal conductivity and stretching, which take into account the blanketing effect of the sediment pile above basement. In general, high maturity values for the Early Palaeozoic sections are indicative of high palaeo-temperatures during Palaeozoic burial. Together with significant amounts of erosion (up to 3.5 km) in the Goulburn Graben and along the margins of the basin, these maturity values suggest high palaeo-heatflows of up to a maximum of 100 mW/m^2 during the Cambrian to Devonian.

Palaeotemperatures are the key modelling factor for the timing of generation and expulsion from various source rock units. The complex subsidence history of the basin (Fig. 10) included several phases of rapid subsidence and differential uplift and erosion that vary greatly between the modelled sites. This in turn resulted in the modelled source rock units reaching maximum burial and thus maximum temperatures at different times in different parts of the basin. For the majority of the modelled sites, maximum temperatures were reached in the Palaeozoic, either associated with the Cambro-Ordovician or Permo-Carboniferous subsidence phases. However, there are locations in the basin where maximum temperatures were attained as a result of Cretaceous to Recent burial.

Basin-wide mulit-1D source rock models were generated for seven potential source rock units using the parameters listed in Table 1. Apart from the Wessel Group, the parameters are based on averaged data from individual well sections and projected into the northern basin for the pseudo-well sites. The value for initial HI represents an assessment of the HI before generation has taken place and thus reflects the richness of the modelled source rock. Kerogen kinetic data for the Wessel Group and Jigaimara Formation are based on analyses of samples from Cambrian rocks of the Georgina Basin (C. Boreham, pers. comm.), whereas kinetic data for the remaining units are based on standard Kerogen Types IB to IIIB as defined by Burnham and Sweeney (1992). A transformation plot for kerogen types used for this study is given in Fig. 47 showing that the Cambrian source rock has characteristics close to a Type IIB kerogen.

Table 1: *Parameters used for modelling hydrocarbon generation and expulsion from potential source rock units (TOC = total organic carbon; HI = Hydrogen Index).*

Potential source rock unit	Kerogen type	TOC (%)	Initial HI (mgHC/gTOC)	Modelled bulk thickness (m)
Wessel Group	I/II, algal bacterial	4	600	300
Jigaimara Formation	I/II algal bacterial	5	600	40-150
Djabura Formation	II	2	600	50-100
Darbilla formation	II	1.5	400	30-150
Kulshill Group	II/III	2-5	200-450	200-500
Plover Fm/ Flamingo Gp	II/III	5	400	150

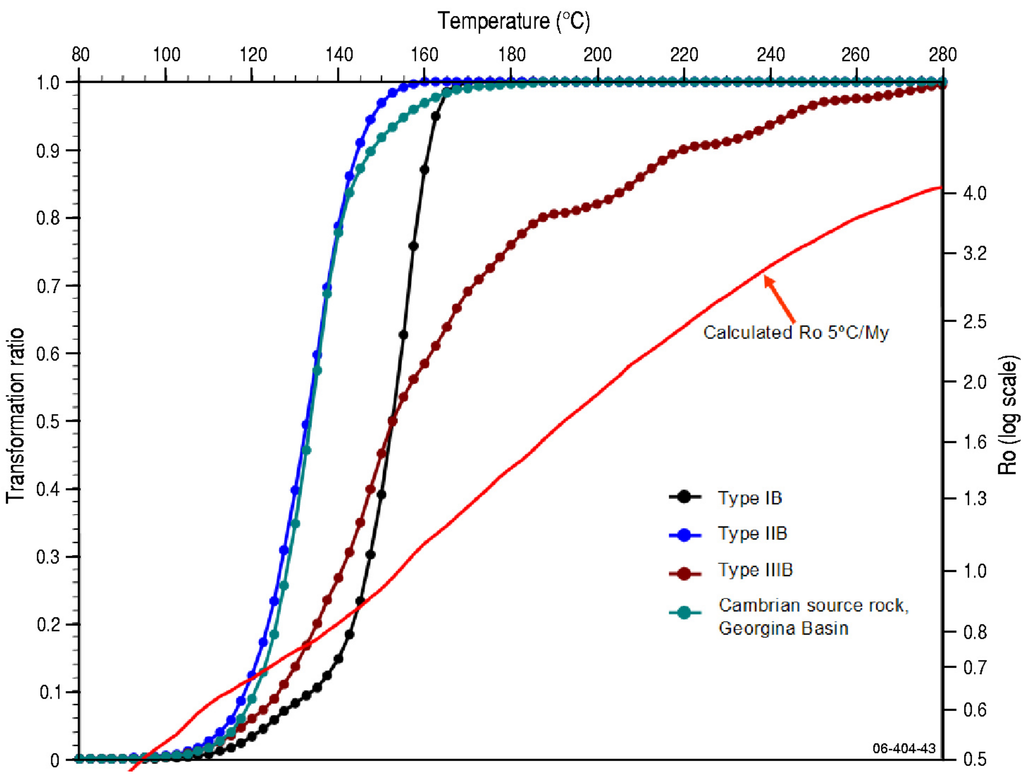

Figure 47*: Transformation plot of kerogen types used to model hydrocarbon generation and expulsion. Cambrian source rock from Boreham pers.comm.*

Wessel Group

Modelling of hydrocarbon generation and expulsion from a hypothetical source unit in the upper Wessel Group (Table 1) suggests that most sediments of this age would have passed through the oil window during the Ordovician to Carboniferous. The relatively low activation energies of the modelled Cambrian-type kerogens (Fig. 47) imply that relatively low temperatures (125–145ºC) would have been required to generate oil and gas from this unit. Figure 48 shows that expulsion of light oil and gas probably occurred in three major phases. Very early expulsion in the deepest parts of the basin occurred in the Late Cambrian to Ordovician, followed by further phases of expulsion of both oil and gas in the Late Devonian and Late Carboniferous to Early Permian in response to the major loading events. The models also indicate that minor late expulsion of oil and gas may have occurred at Tasman 1, Money Shoal 1 and Tuatara 1 during the Late Cretaceous to Recent. These wells are all located in the southern part of the Arafura Basin, where Palaeozoic loading was relatively low. Thus, any remaining potential for generation and expulsion of oil and gas from rocks of the Wessel Group would be located in the southern parts of the basin.

All modelling for the Wessel Group is based on an assumed Neoproterozoic (Ediacaran) age of about 550 to 590 Ma. Should this unit be older (Cryogenian), as suggested by Totterdell (this volume), then early phases of generation and expulsion would have occurred early in the depositional history with a very low likelihood of any hydrocarbons being preserved.

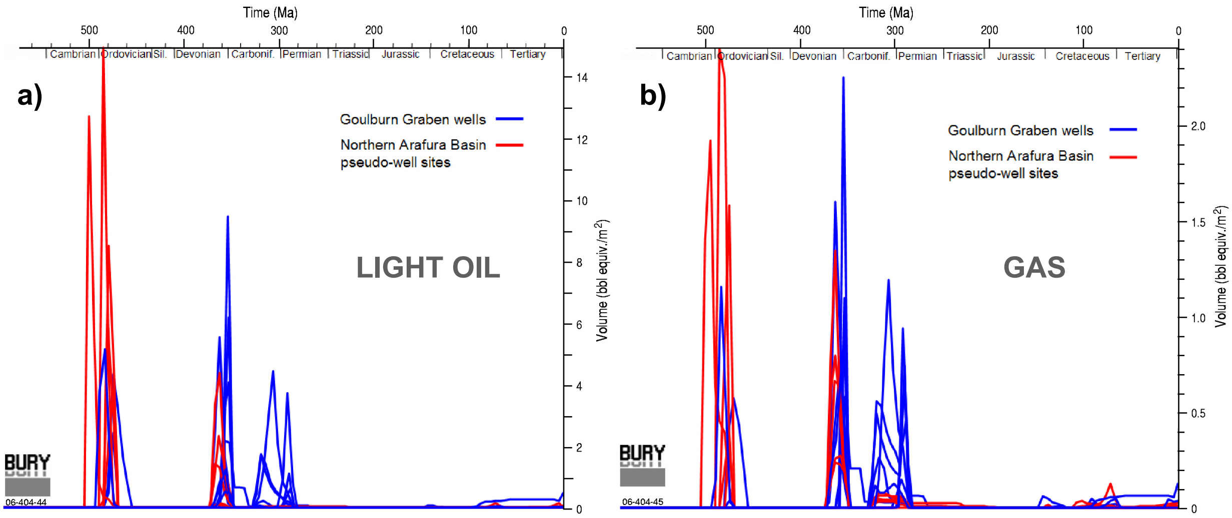

Figure 48: Hydrocarbon generation and expulsion models for a hypothetical source unit in the upper Wessel Group, showing a) rate of expulsion of light oil, and b) rate of gas expulsion.

Goulburn Group

As outlined in the previous chapter, mudstones and calcareous mudstones of the Jigaimara Formation of the lower Goulburn Group are regarded as the major potential source rock in the Arafura Basin. Modelling suggests that sediments of this age entered the oil window over a time span ranging from the Late Ordovician to the Early Permian. The relatively low activation energies of the modelled Cambrian-type kerogens (Fig. 47) imply that relatively low temperatures (125–145ºC) would have been required to generate oil and gas from this unit. Thus, expulsion commenced early (Late Cambrian to Ordovician) in the thickest parts of the basin (e.g. Sites A, D and F). However, the major phase of expulsion of both light oil and gas in both the Goulburn Graben and northern basin occurred in response to Devonian and Permo-Carboniferous subsidence (Figs 49 to 51).

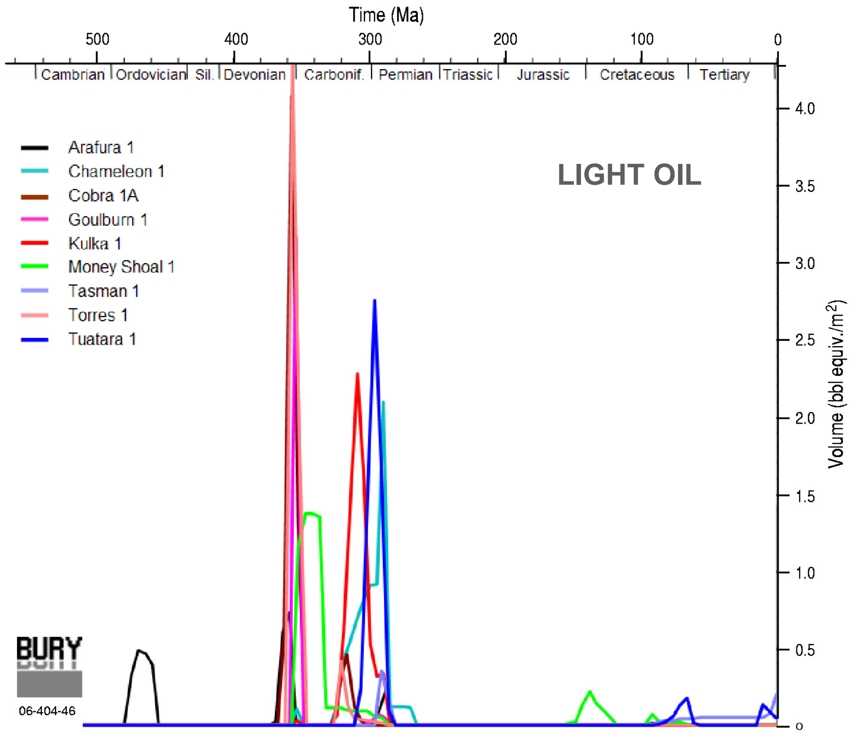

Figure 49: *Hydrocarbon generation and expulsion models for the Jigaimara Formation (lower Goulburn Group), showing rate of expulsion of light oil at well locations in the Goulburn Graben.*

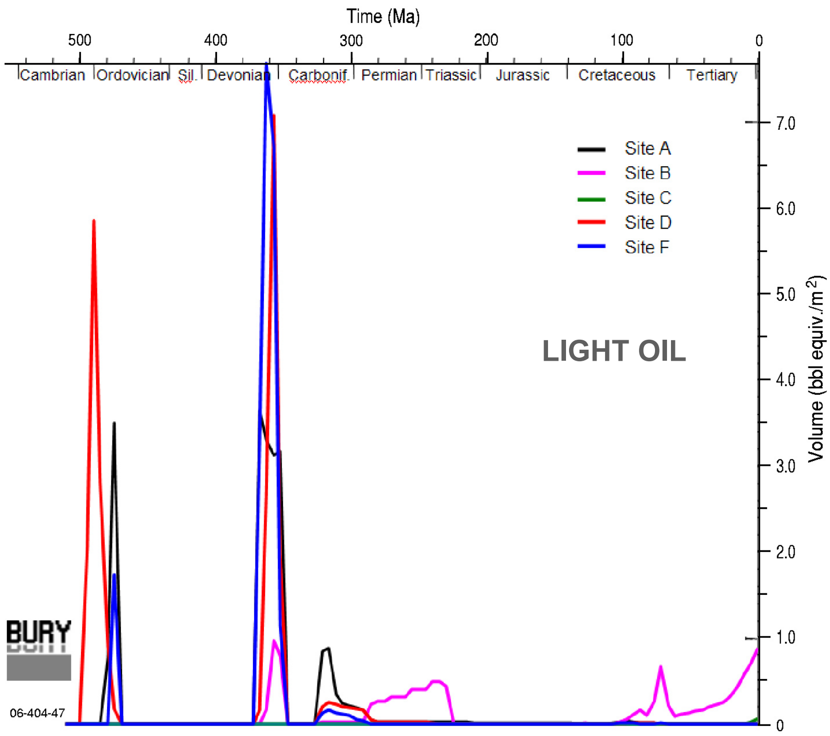

Figure 50: *Hydrocarbon generation and expulsion models for a Jigaimara Formation source rock unit (lower Goulburn Group), showing rate of expulsion of light oil at pseudo-well sites in the northern Arafura Basin.*

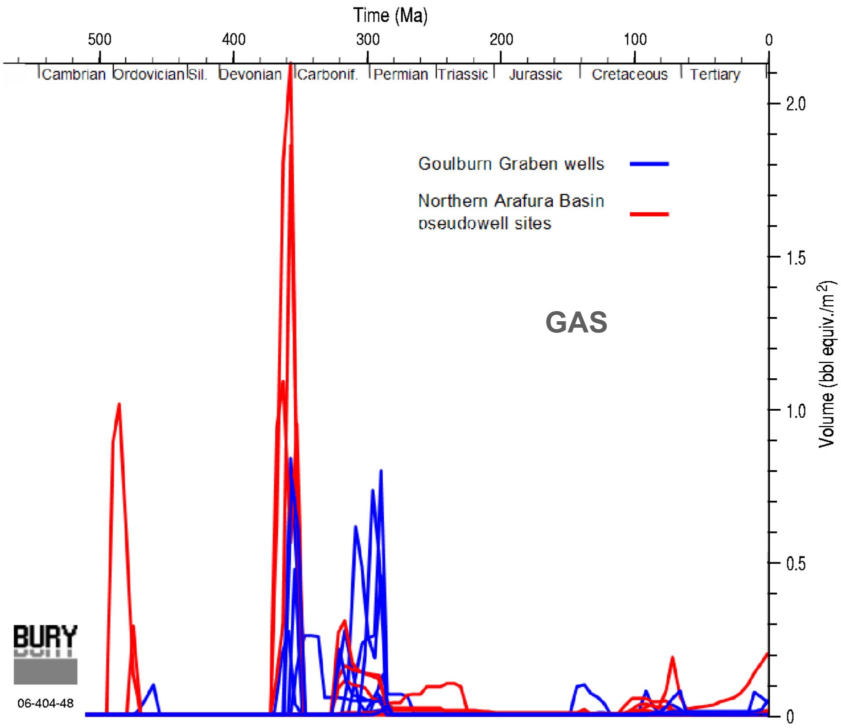

Figure 51*: Hydrocarbon generation and expulsion models for a Jigaimara Formation source rock unit (lower Goulburn Group), showing rate of expulsion of gas at modelled sites in the Arafura Basin.*

Importantly, expulsion models for the Jigaimara Formation also suggest that a second, late phase of expulsion occurred at several modelled sites. For example, expulsion of light oil and gas probably occurred at Site B and at Tasman 1, Money Shoal 1 and Tuatara 1 during the Late Cretaceous to Recent (Figs 49 to 51) in addition to possible earlier expulsion from the same source unit. These sites experienced moderate Palaeozoic burial, but significant Mesozoic burial. Importantly, geohistory models also indicate that there may be areas in the basin where the unit has entered the oil window in the past 5 to 10 million years, conceivably resulting in the generation and expulsion of oil and gas.

In summary, the postulated Cambrian source rock is likely to have expelled oil over several phases of deposition rather than in just one event, however, the bulk of expulsion occurred before the Triassic Fitzroy movement. In the Goulburn Graben area, where this event was most pronounced, much of the early generated and expelled oil and gas would have been lost (Fig. 52). This scenario is supported by the observed presence of bitumens and oil shows in Arafura 1 and Goulburn 1; two generations of bitumen (Keiraville Konsultants, 1984; Sherwood et al., 2006) in Cambrian and Ordovician carbonates are likely to reflect the Palaeozoic expulsion phases, whereas oil shows in Devonian siltstones may reflect remaining Late Cretaceous to Recent generation and expulsion from this source. This late expulsion phase may indicate increased hydrocarbon potential for some areas of the Goulburn Graben (Fig. 52).

In the northern Arafura Basin the Fitzroy movement was significantly less pronounced and it is here suggested that early generated and expelled oil and gas could be preserved in this region (Fig. 52), where large structures were not breached. Additionally, a late expulsion phase from the Cambrian source rock was more significant in the northern basin and could have resulted in accumulations in areas of moderate Palaeozoic burial.

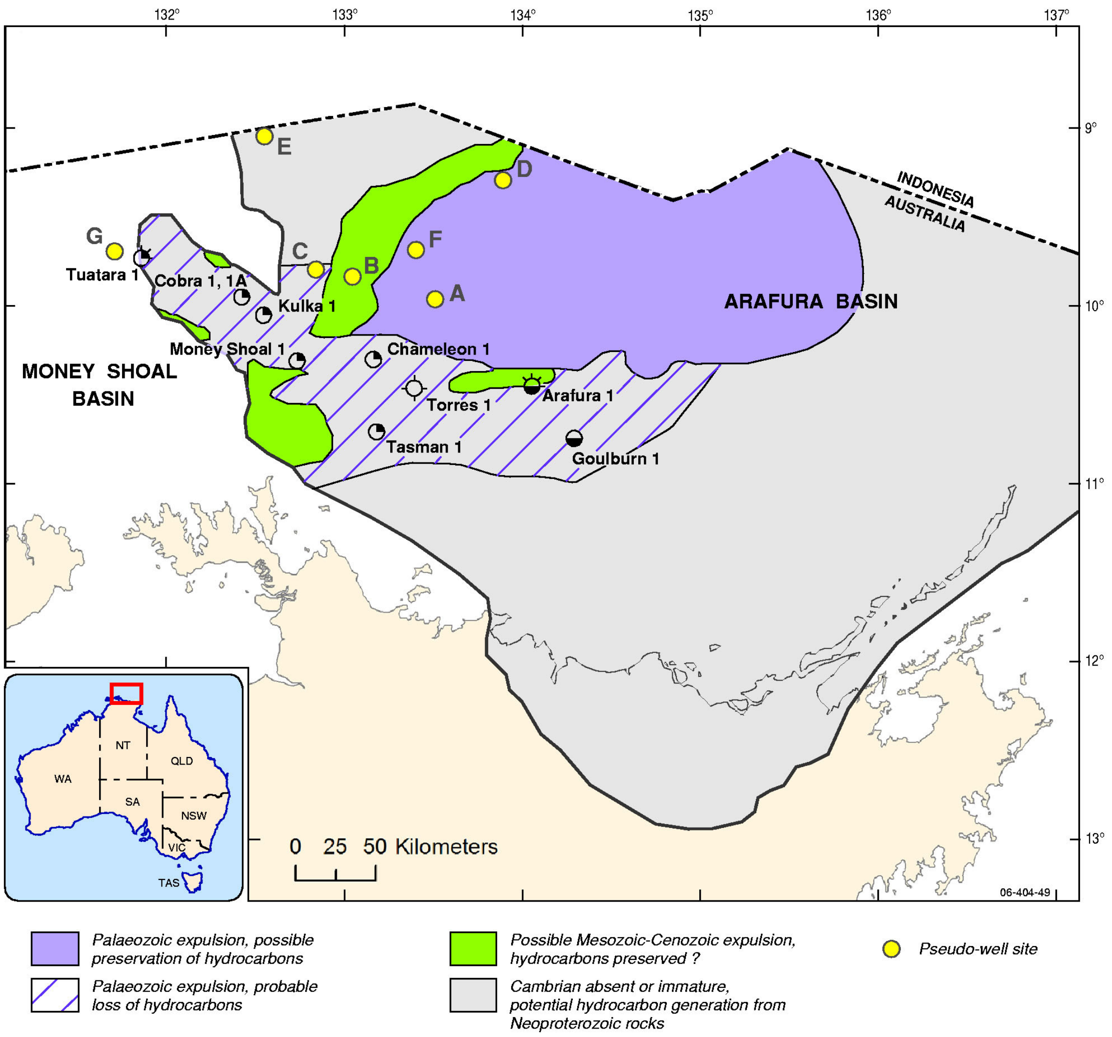

Figure 52: *Areas of potential expulsion and preservation of hydrocarbons sourced from a postulated Cambrian source rock, based on geohistory models and regional seismic interpretation.*

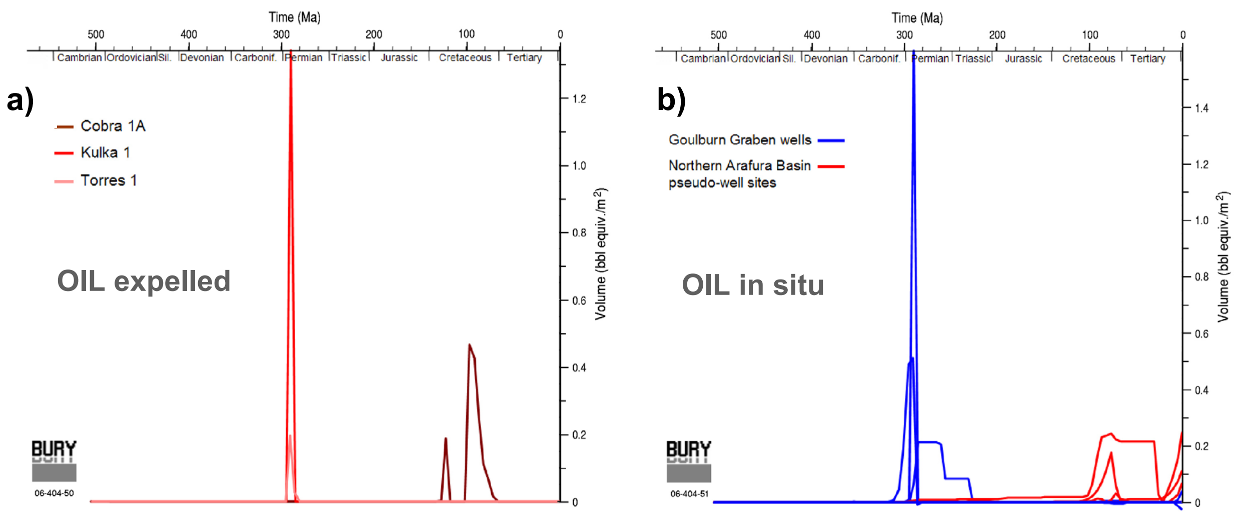

Figure 53: *Hydrocarbon generation and expulsion models for the Arafura Group, showing a) rate of expulsion of oil, and b) rate of generation of oil remaining in situ.*

Arafura Group

Potential source rocks were modelled for both the Djabura and the Darbilla formations (Table 1). These units are mature in several locations and modelling suggests that oil was potentially generated in both the Goulburn Graben (Fig. 53a) and in the northern basin. However, the models also indicate that oil expulsion only occurred where this unit was buried to an approximate depth of 4 km, either during its early burial history (e.g. at Kulka 1) or as a result of Money Shoal Basin subsidence (e.g. at Cobra 1 A). At most other locations in the basin, any generated oil has remained in situ (Fig. 53b). Areas where potential Devonian source rocks could have expelled hydrocarbons are shown in Figure 54.

Kulshill Group

In most parts of the Arafura Basin, potential source rocks of the Kulshill Group are immature for oil generation. Thus, although the unit reaches significant thickness in the northern basin, there does not appear to be enough overburden for hydrocarbon generation and expulsion to have occurred. Only the western part of the basin experienced enough Money Shoal Basin loading for the Kulshill Group to reach the oil window during the Late Cretaceous to Recent (Fig. 54). Modelling of wells in the western Goulburn Graben suggests that a burial depth of about 3 km is required for this unit to generate and expel oil. At Cobra 1 A, where these conditions are met, oil generation and expulsion is modelled to have occurred during the past 10 million years (Fig. 55a), whereas at Kulka 1, where the potential source rock unit of the upper Kulshill Group is present at a depth of 2.5 to 2.7 km, some generation may have occurred, but hydrocarbons are unlikely to have been expelled. Modelling of this unit is extremely sensitive to the amount of erosion assumed for various locations. Although constrained by both well and seismic interpretations, variations in the model of the amount of erosion by just a few 10s of meters, can make the difference between hydrocarbons being expelled or remaining in situ. Therefore, various scenarios should be tested when conducting a more detailed study of the generation and expulsion history from this source rock. The lack of an accumulation at Cobra 1 has been attributed to a seal issue rather than source and reservoir problems (Earl, 2006) and the time structure map for the Kulshill Group (Fig. 17b) suggests that wells drilled in the eastern Goulburn Graben may not have been valid tests for this petroleum system.

Troughton Group

Potential source rocks of the Plover Formation are typically immature in all wells in the Goulburn Graben and are unlikely to have generated hydrocarbons in the greater part of the study area. At Tuatara 1, in the westernmost study area, the unit reaches oil maturity and has probably generated some oil, but expulsion is unlikely to have occurred. However, at pseudo-well site G, to the west of Tuatara 1, a thicker Money Shoal overburden (about 4 km) is present and modelling suggests that oil expulsion has occurred at this site during the Late Cretaceous to Recent (Fig. 55b). When using these geohistory models in conjunction with the Jurassic–Cretaceous thickness map (Fig. 28), it appears likely that a Plover Formation source rock would have expelled hydrocarbons in the undrilled southwestern Goulburn Graben and in the western Money Shoal Basin towards the Calder Graben of the Bonaparte Basin, where hydrocarbon accumulations sourced from this unit are present.

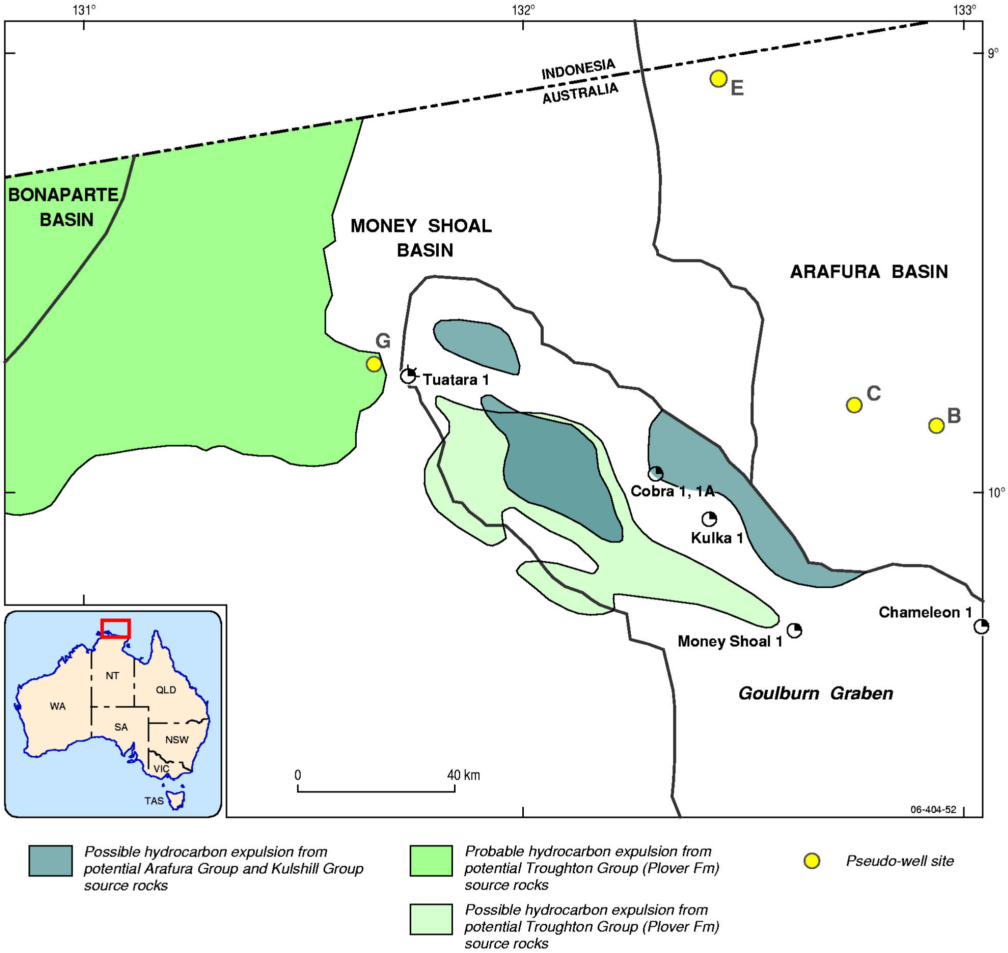

***Figure 54**: Map of the western Arafura Basin and eastern Money Shoal Basin showing interpreted areas of hydrocarbon expulsion from potential Devonian (Arafura Group), Permo-Carboniferous (Kulshill Group) and Jurassic (Troughton Group) source rocks.*

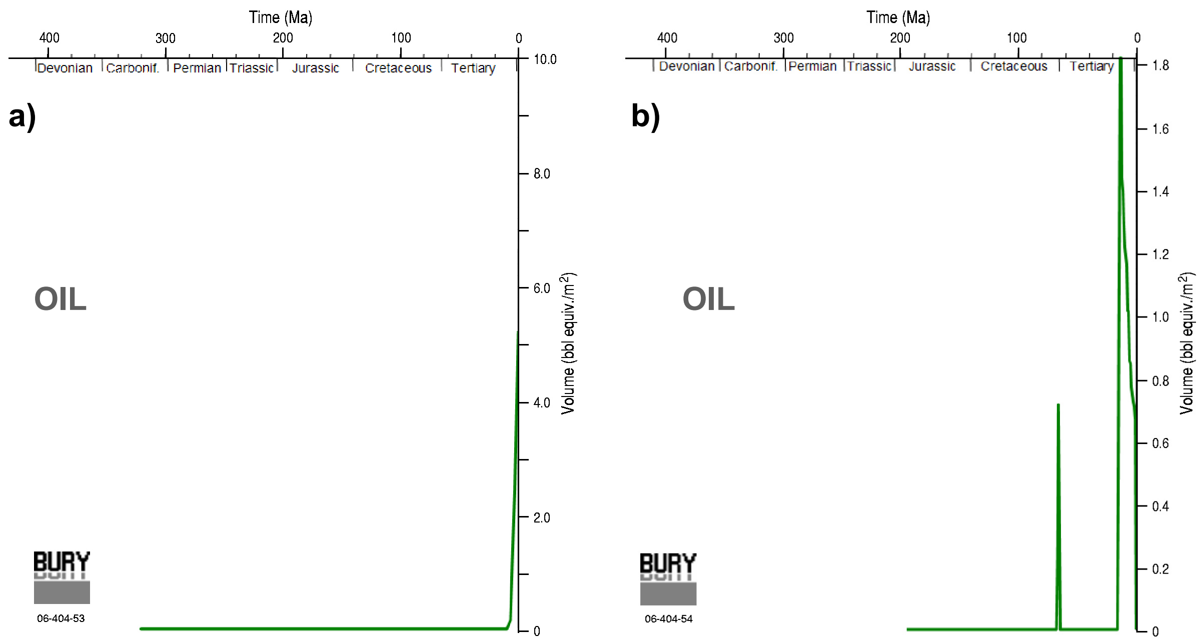

***Figure 55**: Hydrocarbon generation and expulsion models for a) Kulshill Group source rocks at Cobra 1A and b) Troughton Group (Plover Formation) source rocks at pseudo-well site G, showing rate of oil expulsion.*

POTENTIAL PLAY TYPES AND EVIDENCE FOR HYDROCARBONS

Heike I.M. Struckmeyer

A conceptual model of the distribution of petroleum systems elements in the northern Arafura Basin is overlain onto a regional seismic section in Figure 56, illustrating the hydrocarbon potential for this region. Potential source, reservoir and seal rocks are potentially juxtaposed and a variety of potential play types are present. These include large faulted anticlines and fault blocks that could provide traps at several stratigraphic levels (Figs 56 to 58). Sub-unconformity plays below the Triassic regional unconformity are present (Figs 57 to 59) within Neoproterozoic, Cambro–Ordovician, Devonian and Permo–Carboniferous strata. These occur at increasingly shallow depths towards the northeast (Fig. 58), thus reducing reservoir risk. Inversion anticlines formed during the Triassic compressional deformation provide large-scale potential traps. This play type was unsuccessfully tested in several wells (eg Torres 1, Kulka 1) in the Goulburn Graben.

Due to the decreased intensity of the event, inversion anticlines in the northern basin are more subtle and did not experience the significant erosion observed in the Goulburn Graben. Remigration of early generated hydrocarbons or late expulsion of hydrocarbons from a Cambrian source rock could form significant accumulations in these trap types. The late Triassic to Early Jurassic reactivation faulting on the Triassic structures (see Totterdell, this volume) could also have provided additional traps within the Palaeozoic section. Diagenetic traps and other stratigraphic traps within the Cambro–Ordovician and Devonian carbonate successions are a strong possibility in this region, but are as yet untested and insufficient stratigraphic information is available to allow a detailed assessment.

The Mesozoic Money Shoal Basin succession offers a variety of stratigraphic and combined structural/stratigraphic plays for hydrocarbons sourced from underlying Palaeozoic sediments and from mature Late Palaeozoic and Mesozoic source kitchens in the westernmost part of the basin. Onlap plays (Figs 57 and 59) associated with the Triassic unconformity occur within increasingly younger strata to the east, thus providing numerous potential targets within Middle Jurassic fluvial sandstones and/or Late Jurassic to Early Cretaceous fluvio-deltaic clastics in lowstand, transgressive and highstand settings. Plays associated with these deposits also include drape closure over Triassic topography, fluvial channel plays, lowstand wedge plays and fault block plays (Fig. 59).

One of the main features of the Money Shoal Basin section is a Tithonian channel system (Fig. 27) that runs along the major bounding faults of the Goulburn Graben (BHP Petroleum, 1993; Miyazaki & McNeil, 1998; Barber et al, 2004). The northern channel system was assessed by BHP Petroleum (1993) to be at least 225 km long and, on average, 10 km wide. There are numerous untested stratigraphic and structural traps within channel fills and associated erosional features. The mid– to Late Cretaceous prograding shelf and contiguous slope and basin deposits provide numerous potential plays (Figs 57 to 59), particularly within lowstand wedge deposits such as slope fans, channel-levee systems and basin floor fans.

Direct evidence that hydrocarbon generation and expulsion have occurred in the Arafura Basin is provided by oil shows/indications and gas indications in the majority of wells drilled (Earl, 2006), and the presence of interstitial solid bitumens in many samples (Sherwood et al, 2006; Fig. 39). A study investigating hydrocarbon charge in the Goulburn Graben (Kempton and Fenton, 2005) confirmed the presence of oil inclusions and provides further evidence for a working petroleum system in the basin. Bright amplitudes on

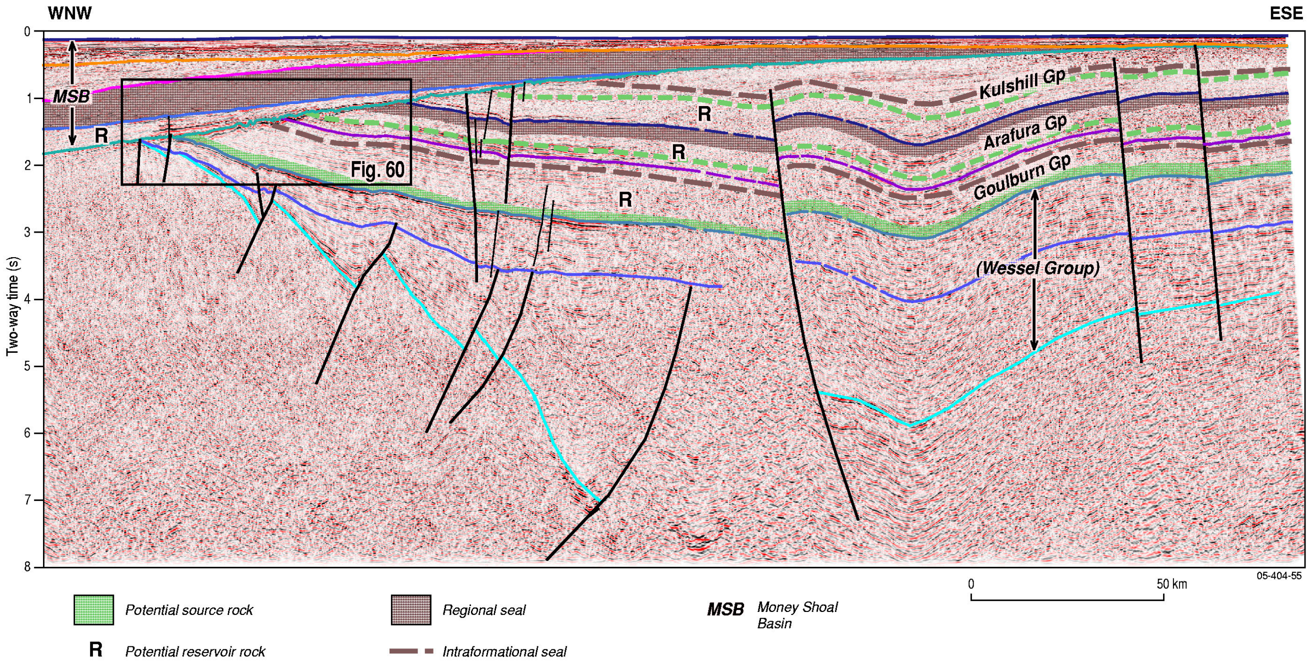

***Figure 56**: Distribution of potential petroleum systems elements in the northern Arafura Basin. Seismic line courtesy Veritas DGC.*

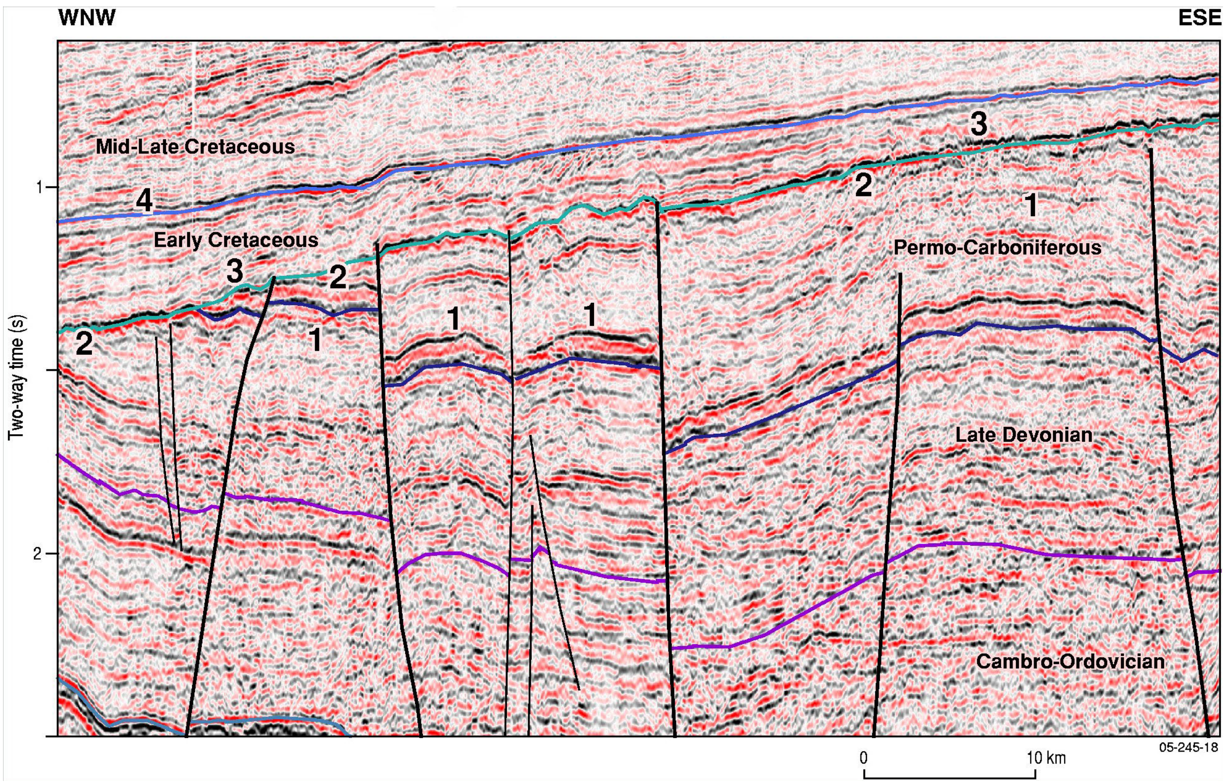

***Figure 57**: Potential play types in the northern Arafura Basin: faulted anticlines (1) and sub-unconformity plays (2) in Palaeozoic strata, onlap/pinchout (3) in Early Cretaceous strata, and lowstand plays (4) in mid- to Late Cretaceous strata.*

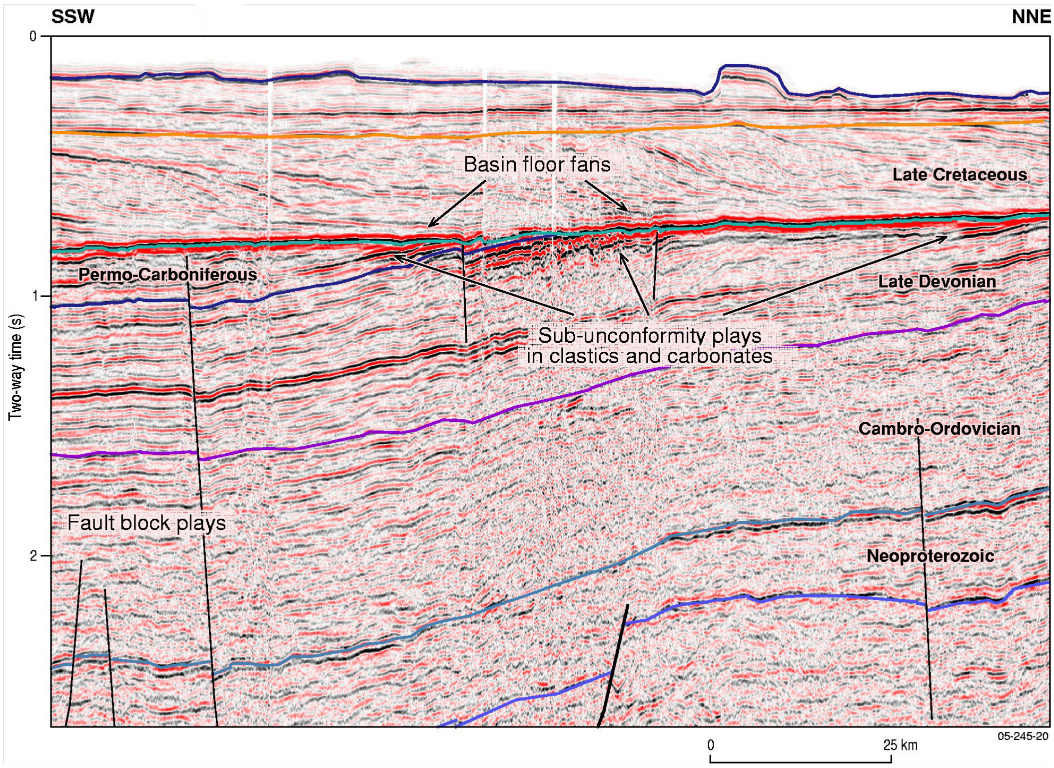

Figure 58: *Potential play types in the northern Arafura Basin, including fault block plays in Palaeozoic strata, sub-unconformity plays in Palaeozoic clastics and carbonates, and lowstand (basin floor fan) plays in Late Cretaceous strata.*

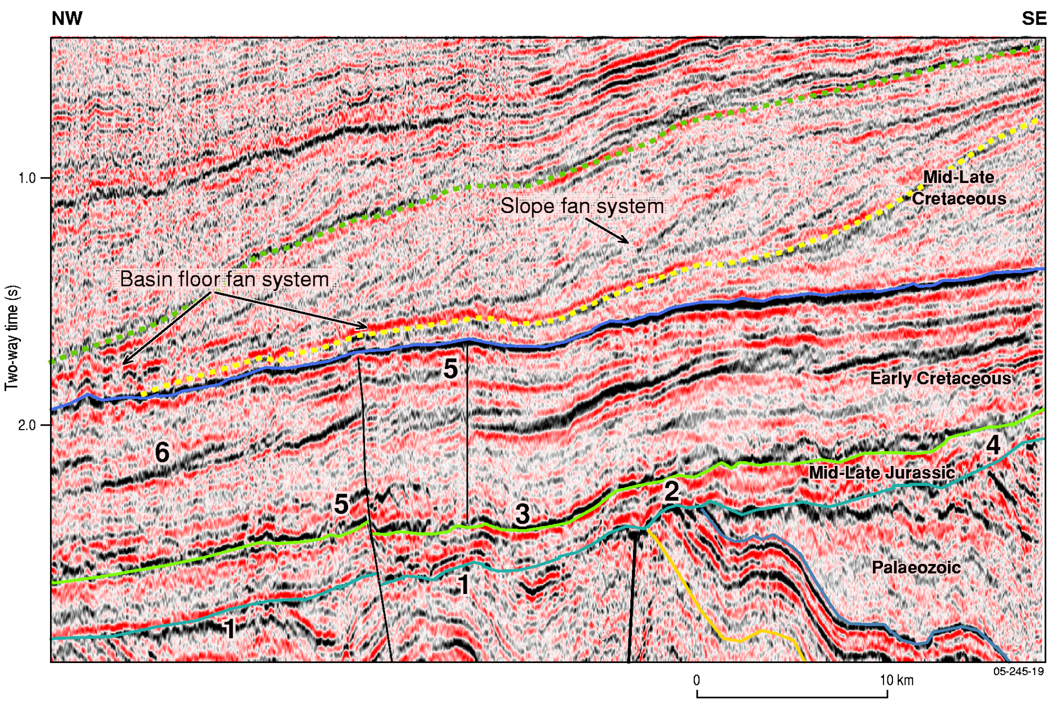

Figure 59: *Potential play types in the Money Shoal and northern Arafura basin: sub-unconformity plays (1) below the regional Triassic unconformity; drape closure (2) over topography, fluvial channels (3) within Middle to Late Jurassic strata, onlap/pinchout (4) onto the Triassic unconformity, fault blocks (5) within Jurassic to Early Cretaceous strata, and lowstand plays (6) in Early Cretaceous strata. Numerous lowstand plays are also present in the overlying Late Cretaceous section. Seismic line courtesy Australian Seismic Brokers.*

seismic data at various stratigraphic levels may also indicate hydrocarbons in the section. For example, Figure 60 shows bright amplitudes in Jurassic to Early Cretaceous strata above the sub-cropping Goulburn Group, between the western basin margin and the sub-cropping potential Arafura Group regional seal. In the same area, along the western margin of the basin, bright amplitudes occur in Cretaceous strata above reactivated Neoproterozoic faults (Fig. 61). Together with results from geohistory models suggesting Late Cretaceous to Recent expulsion from a Cambrian source rock in this area (Fig. 52), these indicators provide supporting evidence for the presence of hydrocarbons.

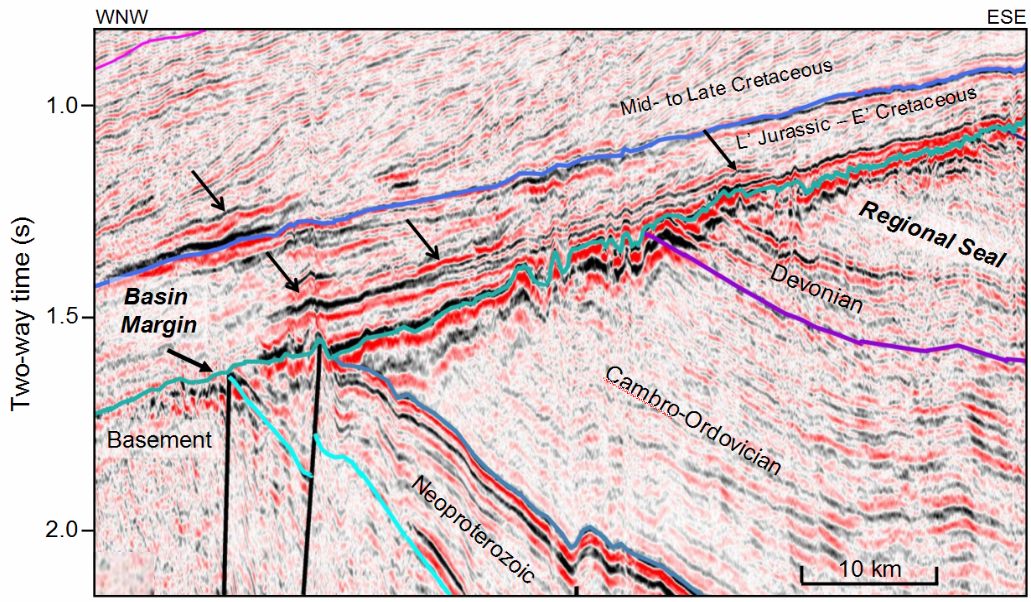

Figure 60*: Bright amplitudes in Late Jurassic to Cretaceous onlapping strata overlying potential source rocks of the Cambro-Ordovician Goulburn Group. Seismic line courtesy Veritas DGC.*

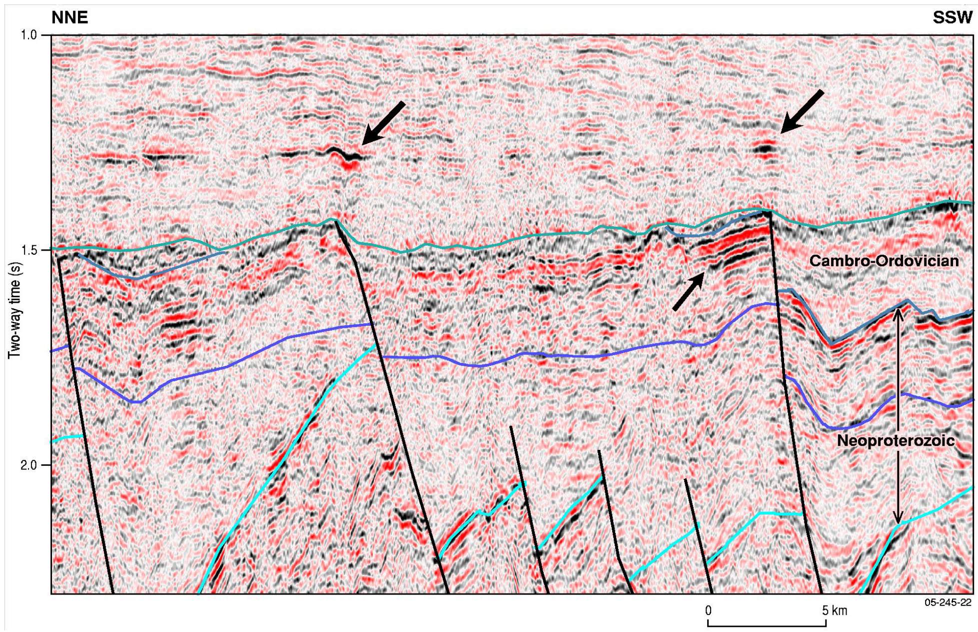

Figure 61*: Portion of seismic line showing bright amplitudes in mid-Cretaceous and Neoproterozoic strata associated with reactivated Neoproterozoic faults. Seismic line courtesy Veritas DGC.*

A survey conducted by Geoscience Australia (Survey S282) in May 2005 investigated potential hydrocarbon seepage in the northern Arafura Basin (Logan et al, 2006). A range of datasets was collected, including sub-bottom profiles, side-scan sonar and echosounder data. These, together with available deep-seismic data, show a range of features that are indicative of the presence of hydrocarbons in the northern Arafura Basin. For example, high amplitudes near the tips of Cenozoic reactivation faults that extend through Palaeozoic strata correspond to low frequencies in seismic data, indicating the possible presence of gas. Enhanced reflections with reversed polarity and low frequency indicative of shallow gas were observed on sub-bottom profiles (Logan et al., 2006). Echosounder data revealed a possible active gas plume (Fig. 62a) similar in character to a confirmed plume on the Yampi Shelf in the Browse Basin (Rollet et al., 2006). Sidescan sonar data showed extensive pockmark fields (Fig. 62b) coincident with an areally extensive poor seismic data zone (Fig. 62c), which may be due to the presence of shallow gas.

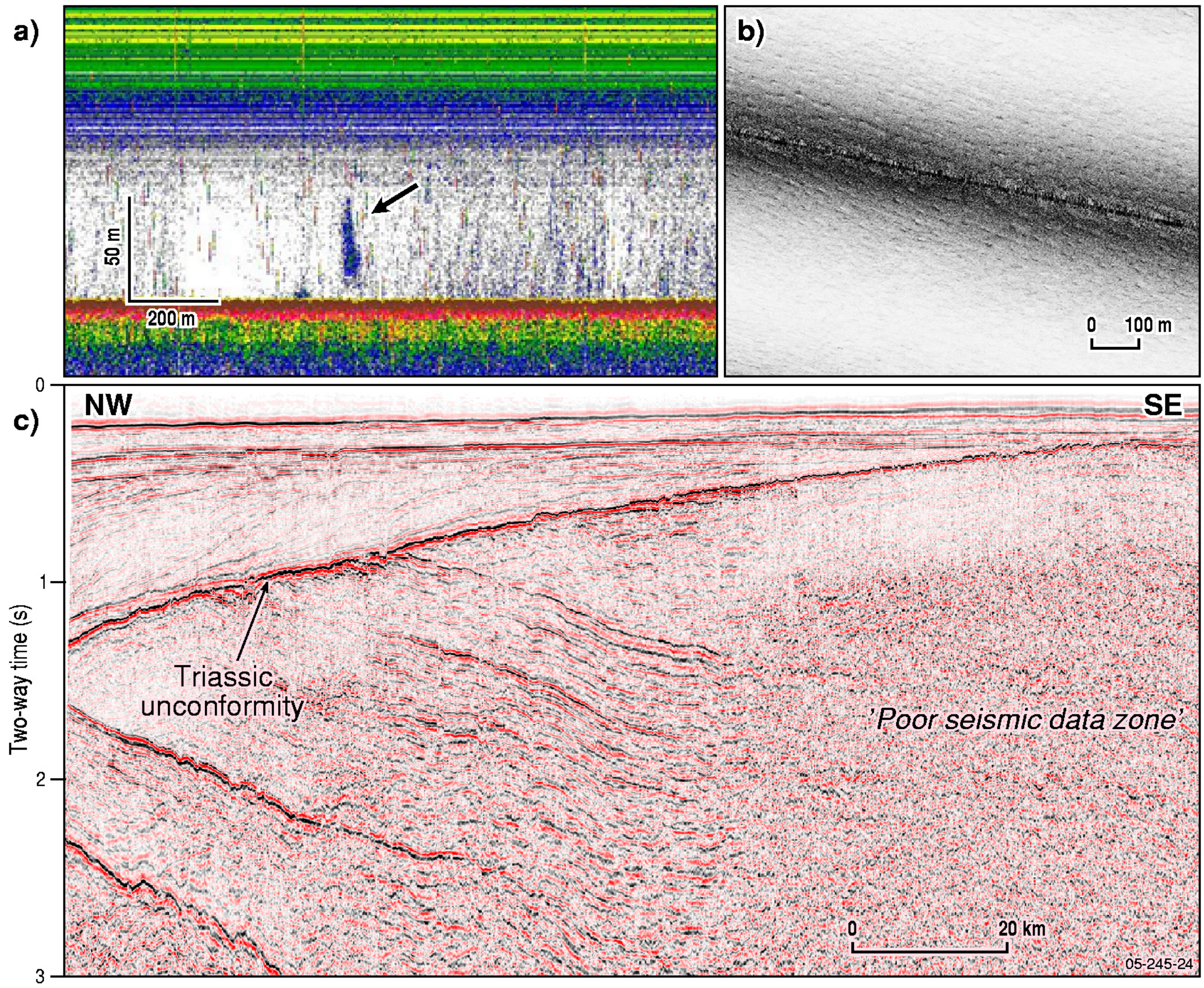

***Figure 62**: Possible indications for the presence of gas in the northern Arafura Basin (modified from Logan et al., 2006); a) echosounder image of possible active gas plume; b) Sidescan sonar image showing extensive pockmarks near poor seismic data zone, and c) portion of seismic line showing poor seismic data zone in the eastern part of the northern Arafura Basin.*

Further evidence for hydrocarbons is provided by Synthetic Aperture Radar (SAR) data which revealed a number of anomalies across the northeastern part of the northern Arafura Basin (INFOTERRA Global Seeps Database). Figure 63 shows that these anomalies align along a depocentre associated with a major Neoproterozoic half graben. The extensional fault would have influenced deposition into the Cambrian when the potential source rock accumulated, and it experienced Triassic and probably Neogene to Recent mild reactivation. The interpreted hydrocarbon seepage occurs in the same area shown in Figure 62, characterised by poor seismic data and by rapid eastward thinning of the regional seal of the Bathurst Island Group (Fig. 63).

Although the occurrence of individual indicators for hydrocarbons in the northern Arafura Basin is not necessarily conclusive by itself, the coincidence of several indicators is significant. The hydrocarbon indicators described above and in Logan et al. (2006), together with interpreted source rocks and modelled hydrocarbon expulsion based on a re-evaluation of the geological history of the basin provides strong cumulative support for the presence of an active petroleum system.

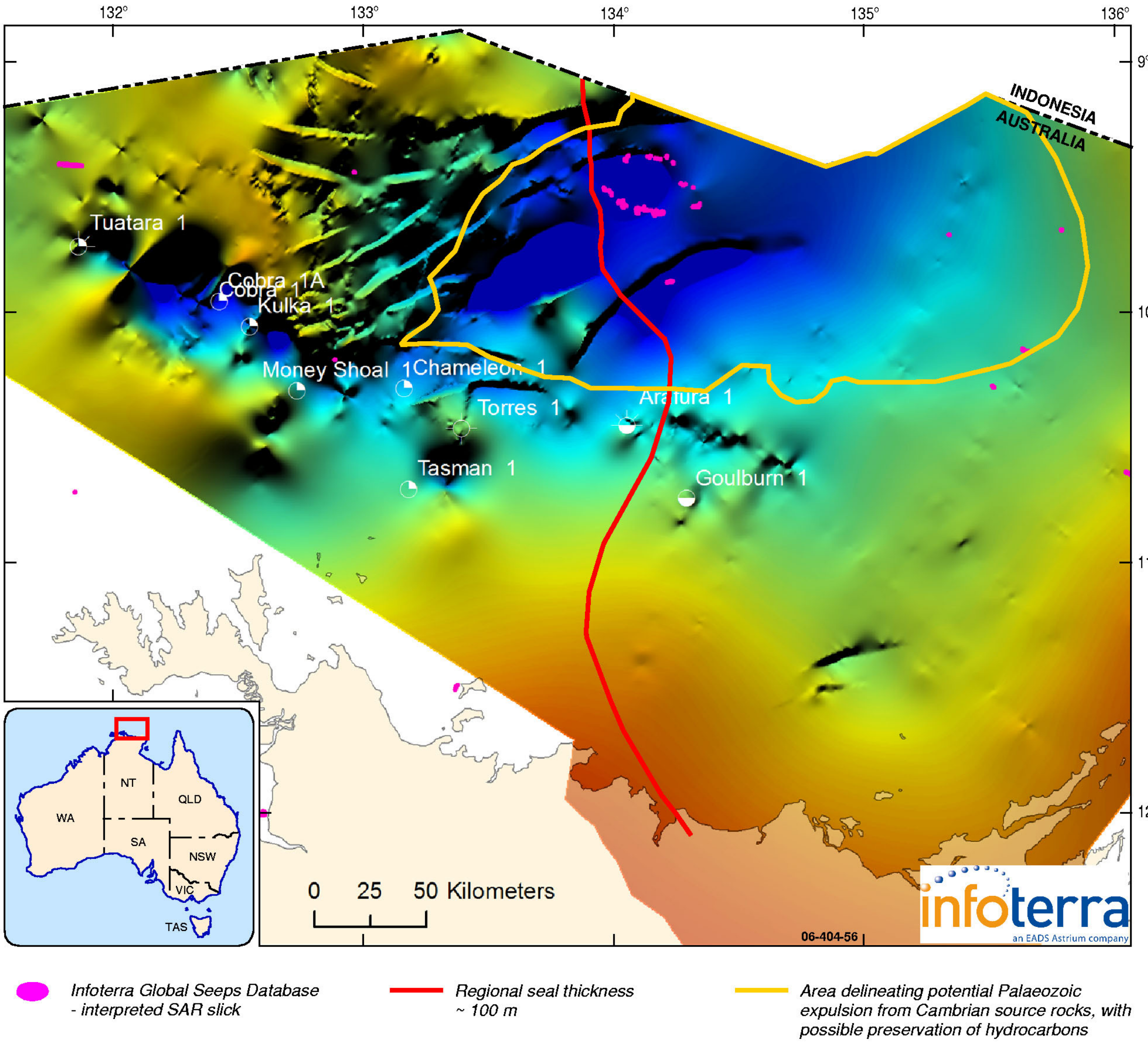

***Figure 63**: 3D image of depth to basement (milliseconds two-way time) showing correlation between Neoproterozoic basin-forming structures, potential Palaeozoic expulsion from Cambrian source rocks, hydrocarbon seeps interpreted from SAR data and thickness of the Cretaceous regional seal. SAR interpretation courtesy INFOTERRA Global Seeps Database (details available from www.infoterra.co.uk/ogm.htm).*

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