ABSTRACT

The Timor and Arafura Seas extend over a substantial portion of the northern Australian continental margin. Exploration commenced in Australian waters in 1971, resulting in the discovery of the Greater Sunrise discovery and Evans Shoals gas accumulations, while the first significant discovery in Indonesian waters was the Abadi-1 gas discovery in 2000. The subject of this paper is the interpretation of a new seismic survey, the Matahari MC2D seismic survey, which links the Australian gas discoveries of Greater Sunrise and Evans Shoal with the Abadi accumulation and extends into open acreage within Indonesian waters to the north and east of Abadi.

Abadi and earlier Australian discoveries including Greater Sunrise, Evans Shoal and Lynedoch lie on the Sahul Platform, a peri-rift basement high, separated from the Australian craton by a failed Jurassic to Early Cretaceous rift. This rift is identified as the Malita Graben which extends east into the Calder Graben, providing key depocentres and an effective charge kitchen from mature Early to Middle Jurassic Plover Formation source rocks (mixed Type 2 to Type 3 kerogens), which are regarded as the origin of these gas-condensate accumulations. The latter are reservoired in Plover Formation paralic and shelfal sandstones.

To the north and northeast of the Abadi discovery, in open acreage, new seismic interpretation has revealed the existence of hitherto untested Paleozoic basins, especially on the southeastern margin of the Tanimbar Trough. Based on analogues with the Bonaparte Basin and Goulburn Graben of northern Australia, these Paleozoic Basins could contain high quality and mature oil-prone source rocks of Cambrian, Devonian and Carboniferous age. In addition, deeply buried Early Cretaceous source rocks may exist along the flanks of the Tanimbar Trough, with similar attributes to excellent quality Echuca Shoals Formation source rocks in the northern Bonaparte Basin, which charged oil discoveries such as the Elang Field in the East Timor Joint Development Area.

INTRODUCTION

While the geological literature on both the northern margin of Australia (essentially the North West Shelf) and South East Asia (including East Indonesia) is voluminous, the overlap of political and geological boundaries has tended to mask the common geology between the two regions (Longley et al., 2002). Tectonic elements of East Indonesia and the northern Australia continental margin are shown as Figure 1. This paper will present a revised interpretation of Paleozoic/Mesozoic/Cenozoic tectonic provinces immediately north of the Australian border west and south of Tanimbar Island and discuss the Early to Middle Jurassic Plover Petroleum System and potential for other oil-prone source rocks.

Exploration in the Australian sector began with the discovery of the Sunrise-Troubadour complex of gas-condensate fields (“Greater Sunrise” complex) on the
Sahul Platform during the early 1970s – appraisal of these fields was delayed until the late 1990s.

In the meantime, sporadic exploration continued throughout the 1980s and early 1990s, resulting in the discovery of the Evans Shoal and Lynedoch gas fields, reseroired in Mid/Late Jurassic sandstones of the Malita Graben, while a number of dry holes were drilled into Palaeozoic sediments in the Goulburn Graben (Figure 2).

Until recently, very little activity had occurred in the Indonesia sector, except for the drilling of the Koba-1 and Barakan-1 dry holes, during 1984 and 1995 respectively. Both these wells terminated in basement at relatively shallow depths. In 2000, Inpex discovered the large Abadi gas-condensate accumulation in Indonesian waters on the eastern extension of the Sahul Platform.

Future exploration of the area will be aided by a new MC2D 8,366km regional seismic survey acquired in 2002, linking under-explored Indonesian acreage (including the Abadi accumulation and the Barakan-1 well to the northeast) with Australian acreage to the south where six wells were tied including the gas discoveries of Greater Sunrise, Lynedoch and Evans Shoal (Figure 2). This survey (Matahari, MH02), together with the earlier 2,500km GP-ARI survey acquired in 1996, provides a regional grid of modern high quality seismic data with which to evaluate the overall hydrocarbon prospectivity of the general area. Additional control was provided by Geoscience Australia regional horizon mapping files for northwestern Australian waters (Geoscience Australia, 2001).

Water depths in the survey area range from 100m in the south to over 500m along the northern Australian shelf, increasing to over 2500m in the present-day Tanimbar Trough (the eastern extension of the Timor Trough), before rising to shallower depths around the island of Tanimbar in the Banda Arc. Nearest major port facilities south of the Tanimbar Trough are at Darwin in the Northern Territory of Australia, some 350km from the Australian-Indonesia international boundary.

**GEOLOGICAL SETTING**

Eastern Indonesia lies within a complex tectonic zone formed as a result of Neogene collision and interaction of the Australian and Eurasian (Sundaland) continental plates and the Caroline and Philippine Sea oceanic micro-plates (Pacific Plate). The region has been likened to a giant jigsaw puzzle, consisting of a complex of small ocean basins separated by slivers or fragments of sometimes-thickened continental crust which seem ultimately destined to form part of a single complex terrane (Milsom, 1991; Metcalfe, 1998).

The geological evolution may be considered in terms of:

- Building blocks formed during Proterozoic and Palaeozoic times;
- Development of a Mesozoic mid-latitude passive margin on the eastern margin of Gondwanaland;
- Neogene collision of Australia and the Indonesian archipelago.

The present study is concerned primarily with the geology of the northern Australian continental margin and the complex geology of the eastern part of the Indonesian archipelago will not be considered here. The Australian margin has undergone a complex structural history, resulting in the development of several Palaeozoic and Mesozoic sub-basins, terraces and platforms. Regional structural elements are shown schematically as Figure 4 and an interpreted line across the collision zone is shown as Figure 5.

Structurally, the area of interest comprises a series of Palaeozoic basins (e.g. Barakan Basin, Arafura Basin) and Late Palaeozoic-Early Mesozoic elevated platform highs (e.g. Sahul Platform and Darwin Shelf), the latter separated from each other by Mesozoic depocentres such as the Malita and Calder Graben (Figure 4). To the northeast is the Banda Arc formed by collision of the leading edge of the Australia continental plate with the East Indonesia island arc system during the Neogene.

The overall chronostratigraphic succession in the region extends from the basal Cambrian to the present-day (Figure 3), reflecting a multi-phase extensional history during Late Palaeozoic and Mesozoic times, followed by Neogene compression. This has led to both orthogonal and curvilinear basin morphologies in the study area, as defined by the following extensional and compressional episodes:
• Palaeozoic NNW-SSE trends: Goulburn Graben, inverted during the Triassic (sometimes known as the Fitzroy Movement – Foreman and Wales, 1981).

• Mesozoic NE-SW trends: Malita and Calder Graben, formed during Triassic through Jurassic to Early Cretaceous rifting and continental breakup of the NW Shelf.

• Tertiary trends: Curvilinear Banda Arc accretionary prism and Timor Trench-Tanimbar Trough (Neogene Australian continental plate collision with the Indonesia arc system).

Although Early Palaeozoic rift trends and inherited underlying Proterozoic basement trends have a pronounced NW-SE structural orientation, the Late Carboniferous-Permian rifting episode, orthogonal to the earlier NW-SE grain, is the most important tectonic event on the northwestern Australian margin. It was the progenitor key rifting episode that led to subsequent progressive Mesozoic continental breakup of the continental plates of northern Gondwanaland and related thermal sag cycles. Over 500% of rift extension occurred during the Late Carboniferous-Permian extensional episode (Etheridge and O’Brien, 1995), followed by progressive breakup/drift of continental segments such as the Lhasa Block (Tibet) during the Late Triassic; West Burma blocks I, II, and III during the Sinemurian, Oxfordian and Kimeridgian respectively; and the Greater India microcontinent during the Valanginian (Longley et al., 2002). Block faulted structuring throughout the study area is related to these extensional episodes.

The next major tectonic episode of significance is the Pliocene collision of the Australian Plate with the Banda Arc around 5Ma. This resulted in the breaching of some traps and leakage of hydrocarbons to the sea floor in the Vulcan Basin and parts of the northern Bonaparte Basin. Re-structuring at the Greater Sunrise and Abadi complex of fields resulted in a late gas and gas condensate charge (Longley et al., 2002).

**Palaeozoic Basins**

The only area in the study area where the Early Palaeozoic succession has been penetrated by several wells is the Goulburn Graben and as such forms a key analogue for elucidating the potential of Palaeozoic petroleum systems. The Goulburn Graben, which contains up to 10km of section, and forms part of the larger Arafura Basin (Cambrian to Permian). It has a multi-phase tectonic history with indicated changes in direction of tectonic stress over time and hence does not fit a simple graben tectonic model, (Moore et al., 1996). Initial Goulburn Graben development began during Late Carboniferous-Early Permian crustal extension of the northwest continental margin (Etheridge and O’Brien, 1994; Longley et al., 2002), probably along a former hinge line marking the southern margin of the Arafura Basin. This was followed by extensional strike-slip and finally transpressional strike-slip during the Late Triassic (Fitzroy Movement of Forman and Wales, 1981), creating negative flower and inversion structures within the graben. Bradshaw et al. (1990) estimated that up to 5km of section were removed from the crests of the some of the rising anticlines.

In the study area, interpretation of the new seismic data below the Near Base Jurassic unconformity has revealed the presence of several large basin-scale inliers believed to represent rocks of Palaeozoic age, cradled between elevated Proterozoic basement areas such as the Barakan Terrace and the Money Shoals Platform (Figure 6).

Of particular interest is the Barakan Basin, a previously unknown Paleozoic depocentre, located opposite the island of Tanimbar, on the Australian continental margin side of the Tanimbar Trough (Figure 6). This basin appears to be a remnant of a much larger Palaeozoic basin, the flanks of which were severely eroded prior to the onset of base Jurassic sedimentation. Of note is the pronounced Paleozoic horst and graben terrain in the Barakan Basin. As the Australian plate collided with the Indonesian arc system during Late Tertiary times, numerous faults in the Barakan Basin were rejuvenated, vertically propagating upward into overlying Mesozoic and Early Tertiary succession.

Except for an elevated remnant of Early Cambrian rocks drilled by the Barakan-1 well, virtually all the Barakan Basin succession remains untested. Based on seismic jump correlations with calibrated seismic data in the Goulburn Graben, much of the Barakan Basin succession is believed to comprise of Cambro-Ordovician to Late Devonian-Early Permian rocks. While the jump correlation is some 200km, much of the known Palaeozoic succession along the north
Australian margin comprises platform sediments, resulting in parallel-bedded stratal geometry patterns over an extensive area, engendering cautious optimism for the proposed correlations indicated in Figure 8.

Based on drilling and seismic correlations in the Goulburn Graben, the Palaeozoic succession in the Baraklan Basin is likely to be over 2–4km-thick, composed of Middle Cambrian and Ordovician shallow-marine carbonates and occasional clastics, separated from overlying Late Devonian-Carboniferous to Early Permian sediments by a major disconformity (the Rodingan orogenic event of Central Australia). The latter sediments mainly comprise continental and shallow-marine carbonates and siliciclastics.

Mesozoic-Cenozoic Basins

Sedimentation patterns from the Permian continued into the Triassic albeit with increased subsidence within newly formed Triassic depocentres. A maximum of 2200m of siliciclastics and carbonates were deposited in marine and non-marine environments, as heralded by basal Mount Goodwin Formation marine shales, which were in turn successively overlapped by shoreface, fluviodeltaic and later continental sedimentary rocks that make up the Osprey, Cape Londonderry, Pollard, and Malita Formations. This progressive change from marine to continental facies was reflected by a 500km migration of the palaeo-shoreline northwards, culminating in inversion and uplift of the Goulburn Graben area, along with concurrent block faulting and erosion throughout the northern margin. On seismic profiles, the end of this episode is marked by the Near Base Jurassic unconformity.

The interpreted Base Jurassic sub-crop map of the region (Figure 6) reveals a multitude of truncated rocks ranging in age from Precambrian to Triassic. It is interesting to note that much of the subcropping succession east of the Abadi High pre-dates the Permian, while towards the west over much of the Sahul Platform, Permo-Triassic sediments subcrop the Base Jurassic unconformity.

Continental to shelfal marine sedimentation continued throughout Early–Middle Jurassic times, leading to deposition of the Malita Formation red beds and overlying Plover Formation fluviodeltaic sediments up to 1500–2000m thick, prior to West Burma block-Australia continental breakup during the Oxfordian. Litholog characteristics in conjunction with biostratigraphic control (Helby et al., 1987) indicate that sedimentation patterns during Plover Formation times were dominated by a series of widespread braided trunk river systems feeding a relatively narrow wave-dominated coastline and beyond, a wide marine shelf. The most prominent preferential river system was that entrenched along a line of weakness provided by the axis of the former Goulburn Graben (Figure 7). Plover (including Laminaria and Elang) shoreface deposits form the main reservoir facies in the Greater Sunrise and Abadi complex of fields.

In response to southwest to northeast diachronous breakup (Callovian to Oxfordian), local depocentres such as the Malita and Calder Graben developed, heralded by a marine transgression (Laminaria/Elang Formation sands). The shoreline was initially in the same position as the preceding Plover succession but began to move inboard as basinal deepening and related sediment starvation continued, the sands being replaced by condensed shales (Frigate Shale). Further subsidence continued in these depocentres during latest Tithonian to early Cretaceous times (Barremian), with deposition of over 500–1500m of marine shales and turbidite sands of the Upper Flamingo Group. By this time, the palaeo-shoreline had receded some 120km towards the craton, inducing starved argillaceous facies over much of the area, excepting for occasional turbidite sand debouchment during eustatic lowstands (Figure 8). These sands were derived from the continually flowing Goulburn Graben axial trunk river system, as observed by pronounced incised channeling of late Tithonian age on seismic sections and tested by the Chameleon-1 (BHP, 1992) which penetrated channel-fill clays. The final stage of starved sedimentation in the Upper Flamingo led to the preservation of enriched marine organic shales in condensed sequences of the Echuca Shoals Formation, a potential oil-prone source rock in the study area.

The succeeding intra-Valanginian unconformity marks the beginning of the final post-breakup subsidence phase and commencement of pronounced thermal sag and passive margin cooling. The succession is characterized by deposition of fine-grained clastics of Mid to Late Cretaceous age, deposited in an aggradational to progradational shelf-slope environment, interrupted by occasional
lowstand events especially in the Late Campanian, sands being derived from the Goulburn Graben proto-river trunk stream.

During the succeeding Cenozoic era, up to 2km of carbonate-shelf ramp stratal geometries dominated sedimentation patterns in the northern and northwestern part of the basin.

**PETROLEUM SYSTEMS**

Despite the discovery of several large gas and gas-condensate accumulations, the northern Australian continental margin covered by the Matahari survey is still grossly under-explored by world standards, with only some 20 exploration wells drilled to date. Consequently, in evaluating the prospectivity of the area, analogue Palaeozoic petroleum system models, such as from the Goulburn Graben, have been invoked to demonstrate prospectivity for undrilled section. In particular, these analogues have been employed within the newly recognised Barakan Basin along the southeastern margin of the Tanimbar Trough (Figure 4). The Barakan Basin is of inferred Palaeozoic age, with sediments ranging in age from Cambrian to Early Permian.

These Palaeozoic source analogues are in addition to the more traditional and well-known Mesozoic source rock systems of the North West Shelf, such as found within the Middle Jurassic Plover Formation and the Late Jurassic Flamingo Group (Figure 3). Location of key source, reservoir intervals, and related mapping horizons are indicated on the chart.

While the primary play in the region has been hydrocarbons sourced from Lower to Middle Jurassic sediments, reservoir in Mesozoic sands in a structural trap (e.g. Greater Sunrise complex – Seggie et al., 2000), it is considered that both younger and older oil-prone source rock successions may have generated hydrocarbons in the region.

**Plover Petroleum System**

The Greater Sunrise, Evans Shoal and Abadi discoveries lie on the Sahul Platform, a peri-rift basement high, separated from the Australian craton by a failed Jurassic to Early Cretaceous rift, the Malita Graben. This graben extends east into the Calder Graben, providing key depocentres and an effective charge kitchen from mature Early to Middle Jurassic Plover Formation source rocks (mixed Type 2 and Type 3), which are regarded as the origin of gas-condensate accumulations on the Sahul Platform and adjoining structural highs (e.g. Bayu-Undan – Brooks et al., 1996). The latter are reservoired in Elang and Plover Formation paralic and shelfal sandstones.

This petroleum system has been fully discussed in numerous publications, particularly those of Geoscience Australia and will not be further considered here.

**Echuca Shoals Petroleum System**

Deeply buried Early Cretaceous source rocks may exist along the flanks of the Tanimbar Trough, with similar attributes to excellent quality Echuca Shoals Formation source rocks in the northern Bonaparte Basin, which charged a number of oil discoveries such as Elang and Kakatua Fields in the East Timor-Australia Joint Development Area. Available well data (e.g. Tuatara-1) indicates that Echuca Shoal Formation TOC values generally exceed 1% and may reach 4%. Rock Eval pyrolysis yields (S1+S2) are generally at least fair (>2 mg/g rock) and may be very good (<14 mg/g rock) and Hydrogen Index in the range 100-400 mg HC/g TOC indicates that the unit is able to generate both liquid and gaseous hydrocarbons.

Present-day maturity trends in the survey area indicate that over much of the study area, the Echuca Shoals Formation lies within the oil generative window (>0.55% Ro) except over shallow portions of the Barakan Terrace and the Money Shoals Platform (Figure 9). There is a clear increase in maturity to the west, with late mature values around the Abadi area. While the current study has not addressed issues of timing of maturation and expulsion, the Echuca Shoals has the potential to charge structures throughout the study area, especially reservoirs in the younger section that have not been targeted during previous drilling campaigns.

An Echuca Shoals play is recognized in Australian waters (NT/P58, 59) by Nexen Petroleum Australia, involving Mid-Upper Cretaceous basin-floor and slope fans within, and sealed by, the Wangarlu Formation, and sourced by the underlying Echuca Shoals Formation.
**Palaeozoic Petroleum System**

To the north and northeast of the Abadi discovery, open Indonesian acreage is virtually unexplored and there is a necessity to rely on analogues to invoke possible petroleum system models for undrilled section, especially within the Tanimbar Basin (inferred Palaeozoic Basin with sediments ranging in age from Cambrian to Early Permian). Based on analogues with the Bonaparte Basin and Goulburn Graben to the south, these Palaeozoic basins (Figure 4) could contain high quality and mature oil-prone source rocks of Cambrian, Devonian and Carboniferous age.

Numerous oil, bitumen and gas shows have been documented from the Palaeozoic succession in the graben, notably at Arafura-1, Goulburn-1, Kulka-1 and Tasman-1, the most significant being at Arafura-1, where live oil was recovered over a 425m interval within fractured Ordovician dolomites and upper Devonian dolo-siltstones (Edwards et al., 1997). The latter shows have been typed by biomarkers to oil-mature Mid-Cambrian Jigaimara Formation organic rich shales, which exhibit mean TOC’s of 3% and a HI of 149.

Organic rich sediments of Late Devonian age were also penetrated in Arafura-1 (TOC: 3.86%: Moore et al., 1996) and although immature at the well location, are inferred to be mature down-dip and may have contributed to some of the migrated oil found in the Upper Devonian (op cit.). While not directly calibrated in the Arafura wells, from Petrel Basin analogues, it is expected that oil-prone source rocks can be expected along the northern Australian margin in the Lower Carboniferous Milligans Formation and also deltaic sequences in the Permian.

Burial history modelling (Moore et al., 1996) has shown that at Arafura-1, Cambrian Jigaimara source rocks in the Goulburn Graben may have reached peak expulsion during the Late Carboniferous-Permian extensional episode (Etheridge and O’Brien, 1995) on the northern Australian margin when over 500% plate stretching and related high heat flow occurred. This expulsion episode is inferred to have peaked prior to, and/or coincident with trap formation associated with inversion of the graben, thus predating migration or, if traps were in place at time of migration, suffering biodegradation of oil during the post-Triassic to pre-Jurassic erosional event. The validity of high heat flows in the Palaeozoic however, have been questioned by Miyazaki and McNeil (1998), who implied more recent maturation, although they provide no independent calculations. Moreover, no sudden step offsets can be observed in vitrinite reflectance profiles from the Palaeozoic to Mesozoic section in Goulburn Graben wells. Moore et al. (1996) suggested that post-Triassic to present-day burial has now reached former heat-flow levels, thus explaining the lack of offset reflectance profiles.

Notwithstanding the above discrepancies, published modelled synthetic burial history profiles based on seismic profiles of the postulated Palaeozoic rocks in the northern Arafura Basin (Moore et al., 1995) and by inference, the Barakan Basin, suggests that the prospectivity of these areas for liquid hydrocarbons is enhanced by the possibility of a much later expulsion episode than that which is indicated to have occurred during the Late Palaeozoic in the Goulburn Graben. In this instance, late maturation is related to Mesozoic and Tertiary subsidence, post-dating structuring. Trap formation would have occurred either during Triassic inversion or Late Jurassic breakup of the continental margin.

**CONCLUSIONS**

This paper suggests possibilities for a new oil play from Palaeozoic and Early Cretaceous oil-prone source rocks, either within indigenous and/or updip and supercrop reservoir section. This is in addition to more ‘traditional’ Early–Mid Jurassic Plover reservoir targets, filled with gas and gas-condensate from source rocks of the same age, as discovered at the Abadi and Greater Sunrise accumulations.

The existence of Palaeozoic oil source rocks is based on analogues from the Goulburn Graben and other Palaeozoic basins, with charge to either interbedded reservoirs of the Palaeozoic age, or reservoirs in the overlying and updip Base Jurassic supercrop section. At higher levels, the Early Cretaceous Echuca Shoals oil source is in the peak oil window over much of the survey area, invoking charge into Late Cretaceous reservoirs.

**ACKNOWLEDGEMENTS**

This paper is the result of an interpretation project carried out by Isis Petroleum Consultants on the Matahari and GP-ARI MC2D datasets. We thank
REFERENCES


Figure 1 – East Indonesia and the northern Australia continental margin regional tectonic elements, with Matahari Survey study area indicated by dashed red rectangle.
Figure 2 – Seismic database with individual surveys indicated – MH02 (red), GP-ARI (blue) MC2D lines and AGSO regional lines (green) together with wells, field outlines and bathymetry.
Figure 3 – Late Palaeozoic to Recent regional stratigraphy, Bonaparte Basin.
Figure 4 – Survey area structural elements; line A-A’ indicates position of Figure 5.
Figure 5 – Interpreted seismic line A-A’ (location indicated on Fig. 4) showing margin of Australian Plate and collision zone with Banda Arc.
Figure 6 – Interpreted Base Jurassic sub-crop map.
Figure 7 – Upper Plover Formation palaeogeography.
Figure 8 – Flamingo Group palaeogeography.
Figure 9 – Top Echuca Shoals Formation present-day maturity map.