Regional Geology of the Bonaparte Basin

Basin Outline

The Bonaparte Basin is located predominantly offshore (**Figure 1**) and covers an area of approximately 270,000 km^2 of Australia's northwest continental margin. The basin contains up to 15000 m of Phanerozoic marine and fluvial siliciclastics and marine carbonates. The regional geology, structural evolution and petroleum potential have been described by Laws and Kraus (1974), Gunn (1988), Lee and Gunn (1988), Gunn and Ly (1989), MacDaniel (1988), Mory (1988, 1991), Botten and Wulff (1990), Petroconsultants Australasia Pty Ltd (1990), Hocking et al (1994), Woods (1994), and summarised by Longley et al (2002) and Cadman and Temple (2004). Numerous papers on the petroleum geology of the region are presented in the Proceedings of the Timor Sea Symposium, Darwin, June 2003 (Ellis et al, 2004).

The Bonaparte Basin is bounded to the northwest by the Timor Trough, where water depths exceed 3000 m. In the northeast, beyond the limits of the Darwin Shelf, the basin adjoins the Arafura and Money Shoal basins. To the southwest, it is contiguous with the Browse Basin.

The Bonaparte Basin is structurally complex and comprises a number of Paleozoic and Mesozoic sub-basins and platform areas (**Figure 1**). The basin developed during two phases of Paleozoic extension, followed by Late Triassic compression, and then further extension in the Mesozoic that culminated in the breakup of Gondwana in the Middle Jurassic (O'Brien et al, 1993). Convergence of the Australia-India plate and Southeast Asian microplates in the Miocene to Pliocene resulted in flexural downwarp of the Timor Trough and widespread fault reactivation across the western Bonaparte Basin.

The Petrel Sub-basin is a northwest-trending Paleozoic rift in the eastern portion of the Bonaparte Basin. The sub-basin contains a thick section of mostly Paleozoic and thinner Mesozoic sediments, and is underlain by Proterozoic crystalline basement (dolerite in wells) and sediments of the Proterozoic Kimberley Basin (Colwell and Kennard, 1996). The eastern and southwestern margins of the sub-basin are flanked by platforms of relatively shallow basement and thin sediment cover. Sedimentation in the sub-basin commenced in the Cambrian, and northeast-trending rifting was initiated in the Late Devonian to Early Carboniferous. Offshore, the Petrel Sub-basin is orthogonally overprinted by a northeast-trending structural grain that resulted from Late Paleozoic and Mesozoic rifting.

The Malita Graben and Calder Graben form a major northeast-trending rift system that lies between the Petrel Sub-basin and the Sahul Platform. The graben contains a thick succession of Late Paleozoic, Triassic, Jurassic and Early Cretaceous sediments.

The Sahul Platform, which underlies most of the Joint Petroleum Development Area (JPDA), is an area of relatively shallow basement. The Permo-Triassic succession in this area was uplifted to form a structural high during Jurassic extension of the adjacent Malita and Calder graben.

The Vulcan Sub-basin is a major northeast-trending Late Jurassic rift depocentre in the western part of the Bonaparte Basin. It is flanked to the southeast and northwest by Permo-Triassic platforms; the Londonderry High and the Ashmore Platform, respectively.

The Sahul and Flamingo synclines are northwest-trending depocentres that link and offset the northeast-trending Vulcan Sub-basin, Malita Graben and Calder Graben rift systems. These synclines are separated by the Laminaria and Flamingo highs.

Basin Evolution and Tectonic Development

The Bonaparte Basin has a complex structural history. The Phanerozoic evolution of the region has been described by Gunn (1988), Gunn and Ly (1989), Veevers (1988), Pattillo and Nicholls (1990), O'Brien et al (1993, 1996a), AGSO NW Shelf Study Group (1994), Baillie et al (1994), Whittam et al (1996), Kennard et al (2002) and Peresson et al (2004). Neogene tectonism and its implications for petroleum exploration in the Bonaparte Basin are described by McCaffrey (1988), Shuster et al (1998), Keep et al (1998, 2002) and Longley et al (2002).

Key events in the evolution of the Bonaparte Basin include:

> Widespread volcanism and subsidence initiated deposition in the onshore portion of the Petrel Sub-basin in the Cambrian.

> Late Devonian to Early Carboniferous extension formed the northwest-trending Petrel Sub-basin.

> Extension in the Late Carboniferous to Early Permian overprinted the older trend with a northeast-oriented structural grain. The proto-Vulcan Sub-basin and Malita Graben developed at this time.

> A compressional event in the Late Triassic caused uplift and erosion on the Londonderry High, the Ashmore and Sahul platforms, and the southern margins of the Petrel Sub-basin.

> In response to Mesozoic extension, the Vulcan Sub-basin, Sahul Syncline, Malita Graben and Calder Graben became major Jurassic depocentres. This structuring coincided with the commencement of sea-floor spreading in the Argo Abyssal Plain to the west of the Browse Basin.

> With the onset of thermal subsidence in the Early Cretaceous (Valanginian), a thick wedge of fine-grained, clastic and subsequently carbonate sediments prograded across the offshore Bonaparte Basin throughout the Cretaceous and Cenozoic.

> Regional compression associated with the collision of the Australia-India plate and Southeast Asian microplates in the Miocene formed the Timor Trough and the strongly faulted northern margin of the adjacent Sahul Platform.

The stratigraphy of the basin is summarised in **Figure 2** after Cadman and Temple (2004). The stratigraphy of the Bonaparte Basin has been defined by Beere and Mory (1986) and Mory (1988, 1991), with many localised revisions since, such as those by Gorter (1998, 2006a, b); Gorter et al (2004, 2005); Whittam et al (1996) and Labutis et al (1998). Paleozoic sediments are largely restricted to the onshore and inboard portions of the Petrel Sub-basin, while Mesozoic and Cenozoic sequences are largely confined to the outboard portion of the Bonaparte Basin. Paleogeographic reconstructions of the Northwest Shelf region, including the Bonaparte Basin are provided by Bradshaw et al (1988) and Norvick (2001).

Volcanic and clastic sedimentation commenced in the onshore Petrel Sub-basin in the

Cambrian. This pre-rift sequence contains extensive evaporite deposits, but the precise age (Ordovician, Silurian or Devonian), lateral continuity and extent of these salt bodies is poorly known. Subsequent salt tectonics (flow, diapirism and withdrawal) has controlled the development of numerous structural and stratigraphic traps within the sub-basin (Edgerley and Crist, 1974; Gunn, 1988; Durrant et al, 1990; Lemon and Barnes, 1997).

Northeast-trending rifting was initiated in the Late Devonian, and clastic and carbonate sediments were deposited in shallow marine and non-marine environments within the Petrel Sub-basin. During the Carboniferous, a thick succession of marine and fluvio-deltaic (Bonaparte Formation to Point Spring Sandstone) and, finally, glacial sediments (Kuriyippi Formation and Treachery Shale) were deposited in response to post-rift subsidence and salt withdrawal.

The initial northwest-trending Late Devonian-Early Carboniferous rift-sag system (Petrel Sub-basin in the eastern Bonaparte Basin) was orthogonally overprinted in the Late Carboniferous to Early Permian by northeast-trending rifts to form the proto-Malita Graben and probably a proto-depocentre in the Vulcan Sub-basin (O'Brien, 1993; Baxter, 1996). A succession of northwest-thickening, shallow marine to fluvio-deltaic, Permian and Triassic sediments was then deposited across the Bonaparte Basin (Keyling to Cape Londonderry formations). Sandstones within this succession form the reservoir facies for the gas discoveries in the Petrel Sub-basin and on the Londonderry High.

Compression in the Late Triassic resulted in reactivation and inversion of the previous Paleozoic fault systems (O'Brien et al, 1993) and caused widespread uplift and erosion on the Ashmore Platform, Londonderry High and in the southern portion of the Petrel Sub-basin. Late Triassic-Early Jurassic fluvial sedimentation (Malita Formation) was followed by a thick, widespread succession of Early-Middle Jurassic fluvial and coastal plain deposits (Plover Formation) throughout most areas of the Bonaparte Basin except for the Ashmore Platform and the crest of the Londonderry High. The Plover Formation forms a major source and reservoir unit over much of the northern Bonaparte Basin.

The onset of rifting in the mid-Callovian resulted in a widespread marine transgression and the deposition of retrogradational deltaic sandstones (Elang and Montara formations), which form reservoir units in many of the commercial petroleum accumulations in the northern Bonaparte Basin. Continued rifting and rapid subsidence resulted in the deposition of a thick succession of marine mudstones (Vulcan Formation and Frigate Formation) within the Vulcan Sub-basin, Sahul Syncline, Malita Graben and Calder Graben. These marine sediments may contain good quality oil-prone source rocks; however, they are gas-prone within the Malita and Calder graben.

Mesozoic extension ceased with the onset of sea-floor spreading in the Valanginian and was followed by widespread thermal subsidence and flooding of the western Australian continental margin. Fine grained clastics and carbonates of the Bathurst Island Group were deposited across the Bonaparte Basin during this phase. At the base of the Bathurst Island Group, claystones of the Echuca Shoals Formation provide a regional seal for the hydrocarbon accumulations in the Vulcan Sub-basin and northern Bonaparte Basin. This unit thins onto the platform areas in the west (Ashmore and Sahul platforms) and in the Petrel Sub-basin to the east. The Late Cretaceous and Cenozoic sections typically comprise thick, prograding platform carbonates. Lowstand sandstones accumulated in the Maastrichtian (Puffin Formation) and Eocene (Grebe Sandstone Member).

Regional compression, associated with the collision of the Australia-India Plate and Southeast Asian microplates, reactivated Mesozoic faulting and breached many fault-dependent structures in the Vulcan Sub-basin and adjacent areas. This regional tectonism resulted in the loss of hydrocarbons from previous accumulations (O'Brien and Woods, 1995; O'Brien et al, 1999; Longley et al, 2002) and leakage to the sea floor that appears to have controlled the development and distribution of present-day biohermal mounds in the region (Bishop and O'Brien, 1998; O'Brien et al, 2002).

Petrel Sub-basin

The Petrel Sub-basin is an asymmetric, northwest-trending Paleozoic rift that contains a succession of thick Paleozoic and thinner Mesozoic sediments. The eastern and western faulted margins of the sub-basin converge onshore to form a southern termination. To the south and east of the Petrel Sub-basin, extensions of the Halls Creek-Fitzmaurice Mobile Zone separate this sub-basin from the Precambrian Victoria River Basin and Pine Creek Geosyncline. Extensive basement shelves overlain by a thin cover of Phanerozoic sediments lie on the eastern, western and southern margins of the Petrel Sub-basin. To the east, the Kulshill Terrace and Moyle Platform extend to the north-northeast into the Darwin Shelf. In the southwest, the Berkley Platform has been sub-divided into several, smaller southeast-trending horst (Lacrosse Terrace and Turtle-Barnett High) and graben (Cambridge Trough) structures.

Sediments within the Petrel Sub-basin dip regionally to the northwest about a northwest-plunging synclinal axis, resulting in exposure of Early Paleozoic sediments in the southern onshore area, and in the progressive subcropping of Late Paleozoic, Mesozoic and Cenozoic sediments offshore. The Late Paleozoic-Mesozoic section exceeds 15000 m in thickness in the central and northern Petrel Sub-basin.

Vulcan Sub-basin

The Vulcan Sub-basin is a northeast-trending Mesozoic extensional depocentre in the western Bonaparte Basin (**Figure 1**). The sub-basin comprises a complex series of horsts, graben and marginal terraces, and abuts the Londonderry High to the east-southeast and the Ashmore Platform to the west-northwest. The structurally significant and proven hydrocarbon source provinces of the Swan Graben and Paqualin Graben die out to the northeast beneath the younger (Neogene) Cartier Trough. The Montara Terrace flanks the Swan Graben to the east, while the Jabiru Terrace borders the eastern margin of the Cartier Trough. The southern boundary of the Vulcan Sub-basin with the northern Browse Basin is somewhat arbitrary. O'Brien et al (1999) considered that the boundary is marked by a fault relay zone that overlies a major northwest-trending Proterozoic fracture system.

The Vulcan Sub-basin developed as part of an upper plate rift margin (O'Brien, 1993).

The rift margin developed as a linked array of northwest-trending accommodation zones orthogonal to northeast-trending normal faults (Etheridge and O'Brien, 1994; O'Brien et al, 1996b, 1999). Thermal sag phase sedimentation continued until the Neogene, resulting in over 10000 m of sediment-fill in the deeper graben (Baxter et al, 1997).

Ashmore Platform

The Ashmore Platform is an extensive, elevated and highly structured block. It borders the Vulcan Sub-basin to the east, the northern Browse Basin to the south and deepens into the Timor Trough to the west. On the platform, up to 1500 m of flat-lying Cretaceous and Cenozoic strata overlie up to 4500 m of heavily faulted and folded Permo-Triassic sediments. Rifting through to the Late Jurassic breakup of the Argo margin to the south led to tilted fault-block development prior to widespread peneplanation, subsidence and burial in the Cretaceous-Cenozoic. The Ashmore Platform has been subjected to fault reactivation due to the Miocene-Pliocene convergence of the Australia-India Plate and the Southeast Asian microplates.

Londonderry High

The Londonderry High is characterised by a highly faulted sequence of Paleozoic and Triassic rocks that acted as a major sediment source for adjacent depocentres during the Late Jurassic rifting (Whibley and Jacobsen, 1990; de Ruig et al, 2000), overlain unconformably by a relatively unfaulted, Late Jurassic and younger succession. Although most faulting terminates at the top of the Triassic sequence, some faults show evidence of Miocene reactivation. On higher parts of the Londonderry High the Triassic section is deeply eroded. Uplift and erosion are less pronounced on the eastern and northern flanks where the unconformity is underlain by progressively younger sediments.

Northern Bonaparte Basin

The northern Bonaparte Basin, as defined by Whittam et al (1996), encompasses the area to the northwest of the Petrel Sub-basin that contains a thick Mesozoic and Cenozoic succession. Two major depocentres of Late Jurassic to Early Cretaceous age are recognised in the northern Bonaparte Basin; the northeast-trending Malita and Calder graben, and the northwest-trending Sahul Syncline, including its western extension, the Nancar Trough. These depocentres are flanked to the north by the Sahul Platform and to the south by the Londonderry High (**Figure 1**).

The stratigraphy and geological history of the northern Bonaparte Basin has been described by Mory (1988), Mory and Beere (1988), Gunn (1988), MacDaniel (1988), Veevers (1988), Pattillo and Nicholls (1990), O'Brien et al (1993), Whittam et al (1996), Labutis et al (1998) and Shuster et al (1998) and is summarised by Cadman and Temple (2004).

The present day configuration of the northern Bonaparte Basin results from the intersection and superimposition of three cycles of rifting: an initial northwest-trending Late Devonian rift extending outboard from the Petrel Sub-basin, northeast-trending Carboniferous-Permian rifting, and Jurassic rifts in the Malita and Calder graben and Vulcan Sub-basin. The pre-existing Paleozoic structural grain had considerable influence on the distribution and thickness of the Mesozoic and Cenozoic succession on the western part of the Sahul Platform (particularly during the Triassic), and is expressed in the northwest trend of both the Sahul and Flamingo synclines (Whittam et al, 1996).

This northwest-trending structural grain is cross-cut by a series of Jurassic faults, the strike of which varies from northeast-southwest in the area adjacent to the Londonderry High, through north-northeast to south-southwest at the western end of the Malita Graben, and to east-west in the area of the Flamingo and Laminaria highs. Woods (1992) attributes this latter east-west-trend to Tithonian tectonism.

Whittam et al (1996) concluded that the geological history in the northern Bonaparte Basin and Vulcan Sub-basin are broadly similar, but there are significant differences recognised in the northern Bonaparte Basin:

- The strong influence of the Permo-Carboniferous rifting event in the distribution and thickness of the Triassic succession.
- The tectonic event at the Triassic-Jurassic boundary, which marks the onset of extension during the Mesozoic.
- The relative unimportance of the Callovian phase of tectonism that initiated subsidence in the Vulcan Sub-basin.
- The Tithonian extensional event resulted in the development of east-trending horsts and graben that characterise the structure of the Sahul Syncline and Flamingo Syncline region, which have proven to be the most prospective structural traps in the area.
- The identification of the base-Aptian disconformity as a regional seismic marker that is the principal structural mapping horizon in the region and the most reliable indicator of regional structure at the top of the Callovian reservoir section.

These differences have important implications for petroleum exploration in the region. Variations in the subsidence history and timing of tectonic events between the two regions influenced the distribution and preservation of potential reservoir and source rocks (Whittam et al, 1996). For example, it is considered unlikely that deposition of the Elang (Laminaria) Formation reservoir sandstones would be widespread on the Laminaria and Flamingo highs and Sahul Platform if the major Callovian extension that affected the Vulcan Sub-basin had occurred on the western part of the Sahul Platform. Similarly, differences in subsidence history and in the thickness of the mid-Cretaceous to Cenozoic succession had a major impact on the timing of hydrocarbon generation, and on the extent to which later episodes of faulting affected the integrity of Jurassic traps.

The Permian to Cenozoic Sahul Platform is a structural element of the Bonaparte Basin located offshore on Australia's northwestern margin in water depths of 50 to 1500 m.

Most of the Sahul Platform lies within the JPDA between Australia and Timor Leste, with the northern-most part located in Australian and Indonesian waters (**Figure 1**). The Sahul Platform is an area of relatively shallow basement. It is divided into the Troubadour High in the east, where basement is approximately 3000 m deep, and the Kelp High in the west, where basement is interpreted to be significantly deeper (Whittam et al, 1996). The Troubadour High is also referred to as the Sunrise High (Longley et al, 2002). Sediment thicknesses vary from 3000 m on the Troubadour High to more than 5000 m on the Kelp High. The Troubadour Terrace is an area of relatively shallow basement that is arbitrarily separated from the Sahul Platform. The southern boundary of the Sahul Platform is marked by northeast-trending Mesozoic normal faults showing displacement down into the Malita and Calder graben creating a series of prominent blocks and terraces. The Heron Terrace is a perched, down-faulted block covering an extensive area adjacent to the Troubadour Terrace.

The Sahul Platform was originally part of a broad, northeast-trending Late Paleozoic sag basin. Following Early Jurassic rifting, the platform became a depocentre for non-marine and marginal to shallow marine clastics in the Early to Middle Jurassic. Subsequent breakup in the Callovian produced a series of narrow, confined depocentres (Malita Graben and Sahul Syncline) to the south and west of the elevated Sahul Platform. Late Jurassic and Early Cretaceous sediments are mainly confined to these depocentres, and both consist of thin, condensed marine mudstones across the Sahul Platform and Troubadour Terrace or are absent. Late Miocene to Pliocene convergence of the Australia-India Plate and the Southeast Asian microplates resulted in flexural down-warp of the Timor Trough to the north, and generation of the Kelp High and Troubadour High faulted anticline structures. The Late Cretaceous to Cenozoic sediments consist predominantly of marine carbonates.

Hydrocarbon discoveries on the Sahul Platform include the Greater Sunrise and Evans Shoal gas fields and the gas accumulation at Chuditch 1. Recent drilling has encounter gas accumulations at Heron 2 and Blackwood 1. The Indonesian Abadi gas field is located on what is thought to be the northeastern extension of the Sahul Platform.

Middle Jurassic Plover Formation sediments contain the main reservoir and source rock units. There is also additional, but limited, reservoir potential in Permian to Triassic sediments; gas flowed on test from the Hyland Bay Subgroup at Kelp Deep 1. A regional seal is provided by Late Jurassic and Cretaceous mudstones. The main exploration targets are complex, faulted anticlines with hydrocarbons trapped at the apex of large, regional structural closures.

The Sahul Syncline (and its western extension, the Nancar Trough) is a prominent Paleozoic to Mesozoic northwest-trending trough located between the Londonderry and Flamingo highs in the northern Bonaparte Basin. It is the primary source kitchen for petroleum accumulations discovered on the adjacent Laminaria and Flamingo highs.

Botten and Wulff (1990) considered that the Sahul Syncline formed in the Late Triassic to Middle Jurassic, whereas Durrant et al (1990) believe it formed as part of the Late Devonian rift system in the Petrel Sub-basin. O'Brien et al (1993) and Robinson et al (1994) described the Sahul Syncline as a'sag' feature, and suggested that the latest

Carboniferous to earliest Permian extension reactivated pre-existing, northwest-trending fault zones (such as the Sahul Syncline) as transfer faults.

Subsidence in the Permian and Triassic led to the deposition of a thick sedimentary succession in the region between the Londonderry High and Sahul Platform (including the present day Sahul Syncline, Flamingo High and Flamingo Syncline). Tectonic compression in the Late Triassic resulted in uplift and erosion of the Flamingo High, but deposition continued within the Sahul Syncline where a thick section of the Plover Formation was deposited.

Further subsidence, as a result of minor Callovian and then more pronounced Tithonian extension, controlled the deposition of the Late Jurassic to Early Cretaceous clastic sequences (Elang Formation, Frigate Formation and Sandpiper Sandstone).

In axial areas of the syncline, the sandstones of the Plover and Elang formations lie too deep to constitute valid exploration objectives, but these units form good quality reservoirs on the Laminaria and Flamingo highs and Sahul Platform. Following continental breakup in the Valanginian, a thick Cretaceous-Cenozoic thermal sag section accumulated across the Sahul Syncline.

The Malita and Calder graben form a major, northeast-trending rift system that contains a significant thickness of Late Paleozoic, Triassic, Jurassic and Early Cretaceous sediments. These graben are bounded by northeast to east-northeast-trending faults that show large displacement. Mesozoic and Cenozoic sediments are probably up to 10000 m thick in the graben and are underlain by a considerable section of Late Carboniferous-Permian sediments. Key features of the stratigraphic succession deposited in these areas are:

> Early-Middle Jurassic Plover Formation sediments thicken markedly into the graben, and may include good quality source rocks.

> Mudstones of the late Middle Jurassic-Early Cretaceous Flamingo Group may have some source potential in the area.

> Tithonian turbiditic sandstones (which were intersected in Heron 1) may provide valid exploration targets in the graben.

> The Early Cretaceous Echuca Shoals Formation may provide additional source potential in the graben.

> The Cretaceous-Cenozoic section exceeds 4000 m in thickness in the central Malita Graben.

Exploration in the Malita and Calder graben has resulted in the discovery of the Barossa (Lynedoch) and Caldita gas accumulations.

Regional Hydrocarbon Potential

Hydrocarbon Families and Source Rocks

Hydrocarbon families and their postulated source rocks have been extensively documented within the Bonaparte Basin. Recent papers on the detailed geochemistry of oils and source rocks from the Petrel Sub-basin are by Edwards et al (1997, 2000), Gorter et al (2004, 2005) and Gorter (2006a). Geochemical studies of Vulcan Sub-basin oils include those by Carroll and Syme (1994), George et al (1997, 1998, 2004a), van Aarssen et al (1998a, b), Edwards et al (2004) and Dawson et al (2007). In the northern Bonaparte Basin appraisal of the hydrocarbon potential of the Jurassic-Early Cretaceous source rocks has been undertaken by Brooks et al (1996a, b) and Preston and Edwards (2000). Gas studies were undertaken by AGSO and Geotech (2000). Oil-oil and oil-source rock correlations in the northern Bonaparte Basin have been made by Gorter and Hartung-Kagi (1998) and Preston and Edwards (2000), while George et al (2002a, b, 2004a, b and c) carried out oil-fluid inclusion oil correlations.

Oil-oil and gas-condensate/oil comparisons have been made throughout the Bonaparte Basin by Edwards and Zumberge (2005) and Edwards et al (2006), respectively, from which much of the following text is taken. **Figure 3** shows the hydrocarbon families of the Bonaparte and Browse basins and their interpreted origin after Edwards et al (2004).

In the Petrel Sub-basin, an oil family comprising the Barnett, Turtle and Waggon Creek oils was recognised (**Figure 3**), of which the offshore oils at Barnett and Turtle have undergone biodegradation. This oil family was generated from anoxic marine mudstones. Such source rocks have been located at 208 m depth in the onshore NBF-1002 mineral hole (McKirdy, 1987; Edwards and Summons 1996; Edwards et al 1997), and were postulated as being within the Carboniferous (late Tournaisian-Visean) Milligans Formation. However, reappraisal of the Petrel Sub-basin stratigraphy by Gorter et al (2004, 2005) and Gorter (2006a) assigned these sediments to the early-middle Tournaisian Langfield Group.

Most of the gas discoveries reservoired in the Late Permian Hyland Bay Subgroup in the outboard Petrel Sub-basin and on the Londonderry High are attributed to Permian source rocks within the Hyland Bay Subgroup and/or Keyling Formation (Edwards et al, 1997, 2000; Edwards and Zumberge, 2005); however there are no proven gas-source correlations in the literature. This hydrocarbon family is represented in **Figure 3** by condensate recovered from the Petrel gas accumulation. The stable carbon isotopic signatures of the gases recovered from the Petrel, Tern and Blacktip accumulations indicate that at least two source units generated these gases (Edwards et al, 2006). The biomarker signature of the recovered condensates from the Petrel and Tern accumulations are consistent with derivation from land-plant material.

In the Vulcan Sub-basin, two oil families are recognised; a marine oil family comprising oils from the Birch, Cassini, Challis, Jabiru, Puffin, Skua, Talbot and Tenacious accumulations, and waxy terrestrial oils from the Bilyara, Maret and Montara accumulations (**Figure 3**). The majority of the oil accumulations (including all produced oils) throughout the sub-basin are sourced from the Late Jurassic lower Vulcan Formation (Edwards and Zumberge, 2005). Their source rocks comprise marine mudstones that contain variable amounts of terrigenous organic matter (Carroll and Syme, 1994; Edwards et al, 2004; Dawson et al, 2007). The most likely source of the waxy oil family is from fluvio-deltaic to marginal marine mudstones, possibly within the Plover Formation, which contains a greater terrestrial component than the lower Vulcan Formation (Edwards et al, 2004). The oils from Oliver 1 and Puffin 3 are mixtures of the two sources and hence plot separately from the other Vulcan Sub-basin families (**Figure 3**).

In the central northern Bonaparte Basin (Laminaria and Flamingo highs), oils reservoired within the Jurassic Plover and Elang formations, which include all the commercial accumulations, have been divided into two end-member families by Preston and Edwards (2000). As shown in **Figure 3**, one family includes the strongly land plant-influenced marine oils in the northwestern part of the area (Bluff, Buffalo, Corallina, Jahal, Krill and Laminaria accumulations), and the other family includes the marine oils/condensates to the southeast (Elang, Hingkip, Kakatua, Kakatua North, Trulek, Bayu and Undan accumulations).

While none of the oils can be uniquely correlated with a single source unit, Preston and Edwards (2000) concluded that all of the accumulations in this area are sourced predominantly from the Plover Formation, with additional contributions from the Elang Formation and overlying sealing units: the land-plant-rich, Frigate Formation in the northwest, and the marine-dominated, Flamingo Group in the southeast.

In the central northern Bonaparte Basin, a separate oil family is found comprising the non-commercial oils reservoired in the younger Early Cretaceous Darwin Formation from Elang West 1, Layang 1 and Kakatua North 1 wells (Preston and Edwards, 2000). These oils are believed to originate from the Sahul Syncline that contains post-rift, organic-rich marine sediments in the Early Cretaceous Echuca Shoals Formation. The oil from Elang West 1 has a similar composition to oils sourced from the Early Cretaceous (e.g., Caswell 2) in the Browse Basin (**Figure 3**).

Recent geochemical studies of the gases from accumulations on the northern Sahul Platform, and in the Malita and Calder graben indicate that they are sourced from the Plover Formation in the main depocentres and on the Heron and Troubadour terraces (Longley et al, 2002; Edwards et al, 2006;)

Regional Petroleum Systems

Numerous petroleum systems of various ages have been documented within the Bonaparte Basin (Bradshaw et al, 1994, 1997; Colwell and Kennard, 1996; McConachie et al, 1996; Kennard et al, 1999, 2000, 2002; Edwards and Zumberge, 2005);

- A Late Devonian-sourced petroleum system (Larapintine 3),
- An Early Carboniferous-sourced petroleum system (Larapintine 4)
- A Permian-sourced petroleum system (Gondwanan 1),

- An Early-Middle Jurassic-sourced petroleum system (Westralian 1),
- A Late Jurassic-sourced petroleum system (Westralian 2), and
- An Early Cretaceous-sourced petroleum system (Westralian 3).

Barrett et al (2004), following the nomenclature proposed by Magoon and Dow (1994), defined seven petroleum systems in the offshore Bonaparte Basin, consisting of three Jurassic, three Permian and one Permo-Carboniferous systems;

Jurassic

- Elang-Elang(!) Petroleum System (Sahul Syncline and Flamingo High)
- Plover-Plover(.) Petroleum System (Malita Graben and Sahul Platform)
- Vulcan-Plover(!) Petroleum System (Vulcan Sub-basin)

Permian

- Hyland Bay-Hyland Bay(?) Petroleum System (Kelp High)
- Hyland Bay/Keyling-Hyland Bay(.) Petroleum System (central Petrel Sub-basin)
- Permian-Hyland Bay(?) Petroleum System (Londonderry High)

Permo-Carboniferous

- Milligans-Kuriyippi/Milligans(!) Petroleum System (southern Petrel Sub-basin)

The distribution of these petroleum systems are shown in **Figure 4**, and are presented in montage format by Earl (2004). As noted earlier, the source of the Permo-Carboniferous system in the southern Petrel Sub-basin is now believed to be the Langfield Group (Gorter et al, 2004, 2005; Gorter, 2006a), rather than the Milligans Formation, so this system requires redefinition and re-mapping.

Exploration History

Offshore exploration of the Bonaparte Basin commenced in 1965 when regional aeromagnetic data were acquired. This was supplemented by regional seismic coverage acquired between 1965 and 1974. The first offshore exploration wells in the basin, Ashmore Reef 1 and Sahul Shoals 1, located on the Ashmore Platform, were drilled as stratigraphic tests. Although these wells failed to encounter hydrocarbons, they indicated that the Jurassic section is either thin or absent and that Triassic sandstones form potential petroleum reservoirs over much of the Ashmore Platform.

Between 1969 and 1971, seven wells were drilled in the offshore Petrel Sub-basin. This drilling campaign resulted in the discovery of the Petrel and Tern gas accumulations reservoired within the Late Permian Hyland Bay Subgroup, which constitutes a primary exploration target in the outboard Petrel Sub-basin.

In the early 1970s, exploration expanded beyond the limits of the Petrel Basin into the Vulcan Sub-basin and onto the Londonderry High and Sahul Platform. Between 1971 and 1975, 24 wells were drilled; a further five in the Petrel Sub-basin, two on the Sahul Platform, seven in the Vulcan Sub-basin, five on the Londonderry High, three on the Ashmore Platform and two in the Malita Graben. Several significant petroleum discoveries were made during this period including the Puffin (oil), Troubadour (gas) and Sunrise (gas) accumulations.

Between 1975 and 1982 relatively low levels of exploration drilling took place in the offshore Bonaparte Basin (a total of eight wells) due to a dispute over sovereignty of the sea-bed boundary.

The discovery in 1983 of economic oil in Jabiru 1A (which tested a Jurassic horst block in the Vulcan Sub-basin) stimulated further exploration in the offshore part of the Bonaparte Basin, and 21 exploration wells were drilled in the next three years (1984 to 1986). Of these wells, 12 were located in the Vulcan Sub-basin and on the western flank of the Londonderry High. This phase of exploration resulted in the discovery of a further three commercial oil accumulations in the Vulcan Sub-basin (Cassini, Challis and Skua). Oil production from the Jabiru, Skua, Challis and Cassini fields is via Floating Production Storage and Offloading facilities (FPSOs). Production ceased at Skua in 1997.

During the mid 1980s, two non-commercial discoveries of oil were made in stacked reservoirs within the Milligans and Kuriyippi formations at Turtle 1 (1984) and Barnett 1 (1985) in the inboard Petrel Sub-basin.

After a brief downturn in 1987, levels of offshore exploration drilling in the Bonaparte Basin accelerated. Between 1988 and 1990, 31 exploration wells were drilled in the Vulcan Sub-basin. Drilling results from these wells proved disappointing, although several oil and gas discoveries were made. In the northern Bonaparte Basin, Evans Shoal 1 (1988) intersected a significant gas accumulation within the Jurassic Plover Formation. However, it was 10 years before this discovery was appraised with the Evans Shoal 2 well (1998).

Resolution of the territorial dispute between Indonesia and Australia in 1991 established the Zone of Cooperation (ZOC) and allowed exploration on the Sahul Platform and adjacent areas to resume. Between 1992 and 1998, the focus of exploration in the offshore Bonaparte Basin shifted to this area. Of the 73 exploration wells drilled here during this period, 43 were located either on or adjacent to the Sahul Platform, Laminaria High and Flamingo High. The first commercial petroleum success in the area resulting from this phase of exploration occurred in 1994, when Elang 1 discovered liquid hydrocarbons and identified a new oil play on the Flamingo and Laminaria highs. Shell and Woodside carried out appraisal drilling of the Troubadour (Bard 1) and Sunrise (Loxton Shoals 1, Sunrise 2, Sunset 1, Sunset West 1) discoveries. Elsewhere at this time, the only significant oil discovery was at Tenacious 1 (1997) in the Vulcan Sub-basin (Woods and Maxwell, 2004).

In 1999, Timor-Leste was granted independence by Indonesia . This created a climate of uncertainty with regard to petroleum exploration in the Zone of Cooperation (ZOC). In that year, only one exploration well (Jura 1) was drilled in the former ZOC Area A; now known as part of the Joint Petroleum Development Area (JPDA). During 2002-2003, drilling on the Laminaria High and Flamingo High was focussed on the development of the accumulations at Buffalo, Kuda Tasi, Laminaria and Bayu/Undan. Of the few recent exploration wells that have been drilled in this area, Firebird 1 (2005) discovered gas and Kitan 1 (2008) discovered oil.

Exploration drilling on the Londonderry High in 2000 identified numerous gas accumulations within the Hyland Bay Subgroup at Prometheus 1, Rubicon 1, Ascalon 1A and Saratoga 1.

Two wells (Sandbar 1 and Blacktip 1) were drilled during 2001 in the inboard portion of the Petrel Sub-basin. No hydrocarbons were encountered in Sandbar 1, but Blacktip 1 was completed as a gas discovery (Leonard et al, 2004). Further drilling in the Petrel Sub-basin resulted in limited success, with Shakespeare 1 and Weasel 1 recording only minor oil and gas indications. Polkadot 1 (2004) encountered non-commercial gas in the Hyland Bay Subgroup, but the recently drilled well Blacktip North 1 (2006), which also targeted gas in this formation, was dry. Appraisal drilling of the Blacktip structure was carried out by Blacktip 2 (2009). The latest exploration wells to have been drilled in this sub-basin were Marina 1 (2007) and Sidestep 1 (2008).

In January 2001 oil in was discovered in Audacious 1 in the Vulcan Sub-basin (Maxwell et al, 2004). Although drilling continued in the Vulcan Sub-basin throughout 2001-2003, no further commercial discoveries were made. From 2004 to 2005, there was a revival in exploration success in this sub-basin with Katandra 1A and Vesta 1 discovering both oil and gas (Woods, 2004). Development and extension drilling at Puffin continued (Puffin 7-12; 2006-2008), and production via FPSO commenced in October 2007. Extension/appraisal wells successfully discovered more oil at Swift North 1 ST1 and Swallow 1, with the results of Swift 2 to be released. Development drilling of the Montara-Skua-Swift/Swallow oil accumulations has commenced with production to be via FPSO.

Exploration has been active in the northern Sahul Platform and Malita and Calder graben region since the mid-2005, with the gas discovery at Caldita 1 (2005) and appraisal drilling at Evans Shoal South 1 (2006), Barossa 1 ST1 (2006), Caldita 2 (2007) and Heron 2. The most recent well drilled was Blackwood 1 ST1 (2008) by MEO Australia Ltd. This revival of exploration in the northern Bonaparte Basin is partly due to gas now becoming an economically exploitable commodity and also the commissioning of the Wickham Point LNG plant near Darwin.

In summary, 282 exploration wells and 100 extension/appraisal wells have been drilled in the Bonaparte Basin, of these wells, 64 are hydrocarbon discoveries, giving a technical success of 23%.

Updated information on drilling successes, permit histories and reserves can be found in'Oil and Gas Resources of Australia, 2005' (Geoscience Australia, 2005) and from Western Australia's Department of Mines and Petroleum web site (**www.dmp.wa.gov.au/371.aspx**) and the Northern Territory Department of Regional Development, Primary Industry, Fisheries and Resources web site (**www.nt.gov.au/d/Minerals_Energy/**) and publications (NT DPIFM, 2007).

Hydrocarbon Reserves

Table 1: Initial hydrocarbon reserves for Bonaparte Basin

Field	Oil	Condensate	Gas	Gas	Source
	MMbbl	MMbbl	Bcf	MMboe1	
Audacious - Audacious-1 area only	3.1		0.0	0.0	RDPIFR
Barnett	2.7		0.0	0.0	RDPIFR
Barossa			2700.0	459.0	RDPIFR
Blacktip			957.2	162.7	DMP
Buffalo	20.6		0.0	0.0	DMP
Caldita			2900.0	493.0	RDPIFR
Cash/Maple		34.2	1650.0	280.5	RDPIFR
Challis and Cassini	59.9		0.0	0.0	RDPIFR
Corallina	97.5		0.0	0.0	RDPIFR
Evans Shoal			8300.0	1411.0	RDPIFR
Evans Shoal South			74.0	12.6	RDPIFR
Greater Sunrise		243.0	5440.0	924.8	RDPIFR
Jabiru	112.4		0.0	0.0	RDPIFR
Katandra	1.2		0.0	0.0	RDPIFR
Laminaria	103.0		0.0	0.0	RDPIFR
Montara, Bilyara, Tahbilk, Padthaway *	20.8	20.8	363.3	61.8	RDPIFR
Oliver *	20.4	20.4	345.1	58.7	RDPIFR
Petrel		5.9	970.0	164.9	RDPIFR
Prometheus/ Rubicon			197.0	33.5	DMP
Puffin	14.3		0.0	0.0	RDPIFR
Skua	20.2		0.0	0.0	RDPIFR

Swan		5.0	70.0	11.9	RDPIFR
Talbot	1.8		0.0	0.0	RDPIFR
Tenacious	4.6		0.0	0.0	RDPIFR
Tern		5.7	468.1	79.6	DMP
Turtle	7.7		0.0	0.0	DMP
Vesta	14.2		0.0	0.0	RDPIFR
Weaber			4.5	0.8	RDPIFR

*Liquids include crude oil and condensate, [1]Conversion factor for gas (Tcf to MMboe) is 0.17x1000.

All reserves are P50. All developed field resources from DMP have been compiled using the remaining reserves plus the cumulative production as of December 2007. All other fields are reserves as of 31st December 2007.

DMP - Department of Mines and Petroleum, Western Australia

www.dmp.wa.gov.au/documents/PWA_September_2008.pdf (last accessed 8 Jan 2008)

RDPIFR - Department of Regional Development, Primary Industry, Fisheries and Resources, Northern Territory.

Figures

Figure 1:	Structural elements map of the Bonaparte Basin showing location of the 2009 Release Areas and petroleum accumulations.
Figure 2:	Stratigraphic summary of the Bonaparte Basin (after Cadman and Temple, 2004).
Figure 3:	Oil family dendrogram from hierarchical cluster analysis showing origin of major petroleum accumulations in the Bonaparte and Browse basins (after Edwards et al, 2004).
Figure 4:	Distribution of the petroleum systems of the offshore Bonaparte Basin (after Barrett et al, 2004; Earl, 2004).

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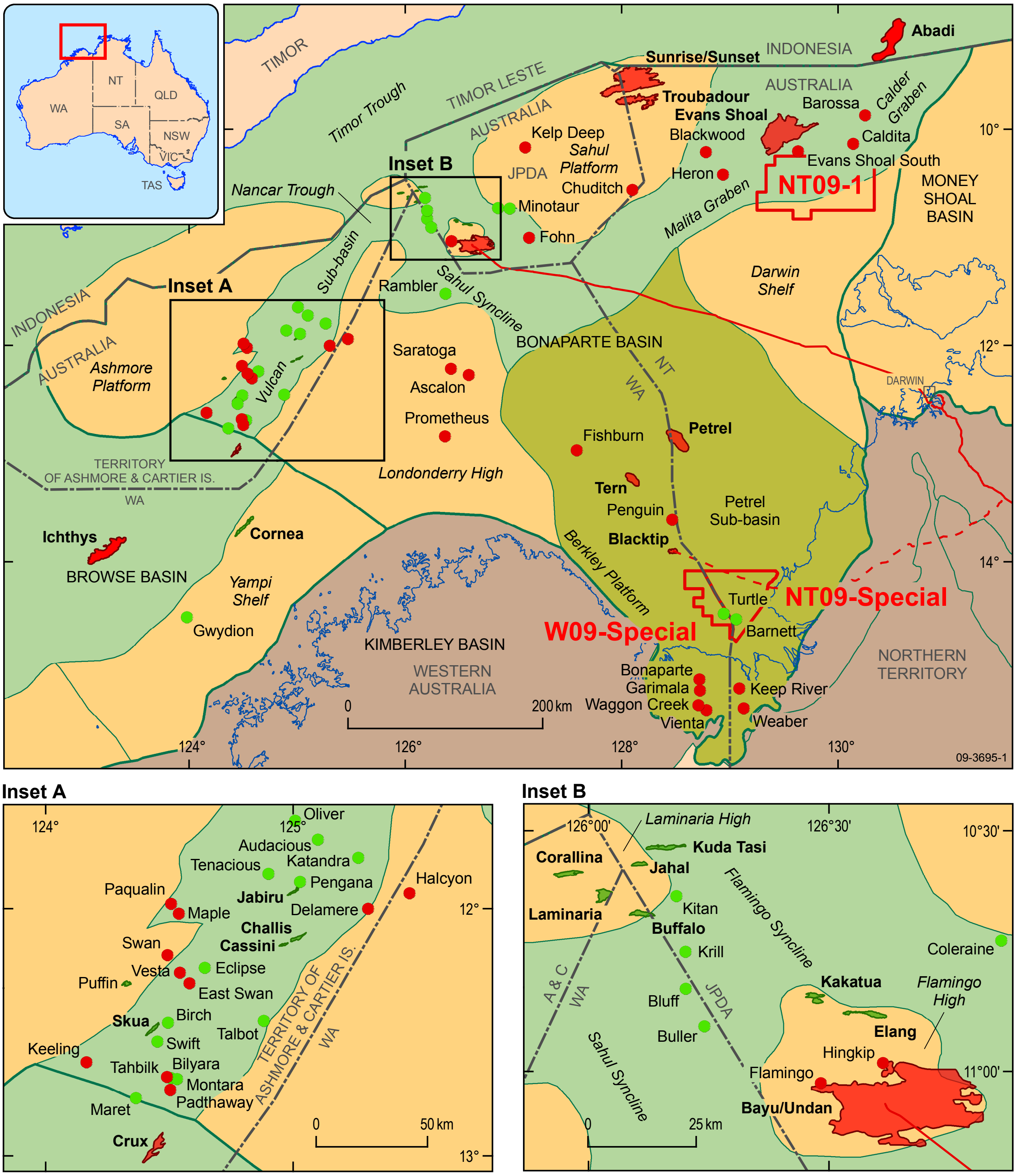


Field outlines are provided by GPinfo, an Encom Petroleum Information Pty Ltd product. Field outlines in GPinfo are sourced, where possible, from the operators of the fields only. Outlines are updated at irregular intervals but with at least one major update per year. Locations of hydrocarbon accumulations are indicative only.

Field outlines for Ichthys, Cornea and Abadi are sourced from IHS Energy, 2006

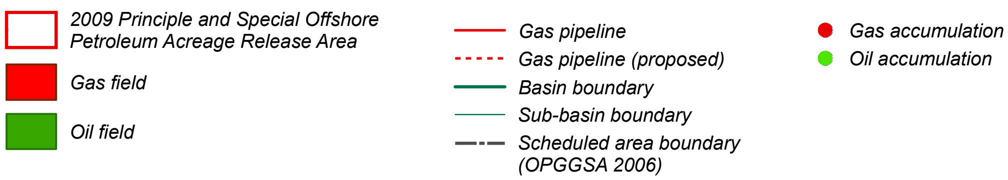


Figure 1. Structural elements map of the Bonaparte Basin showing location of the 2009 Release Areas and petroleum accumulations.

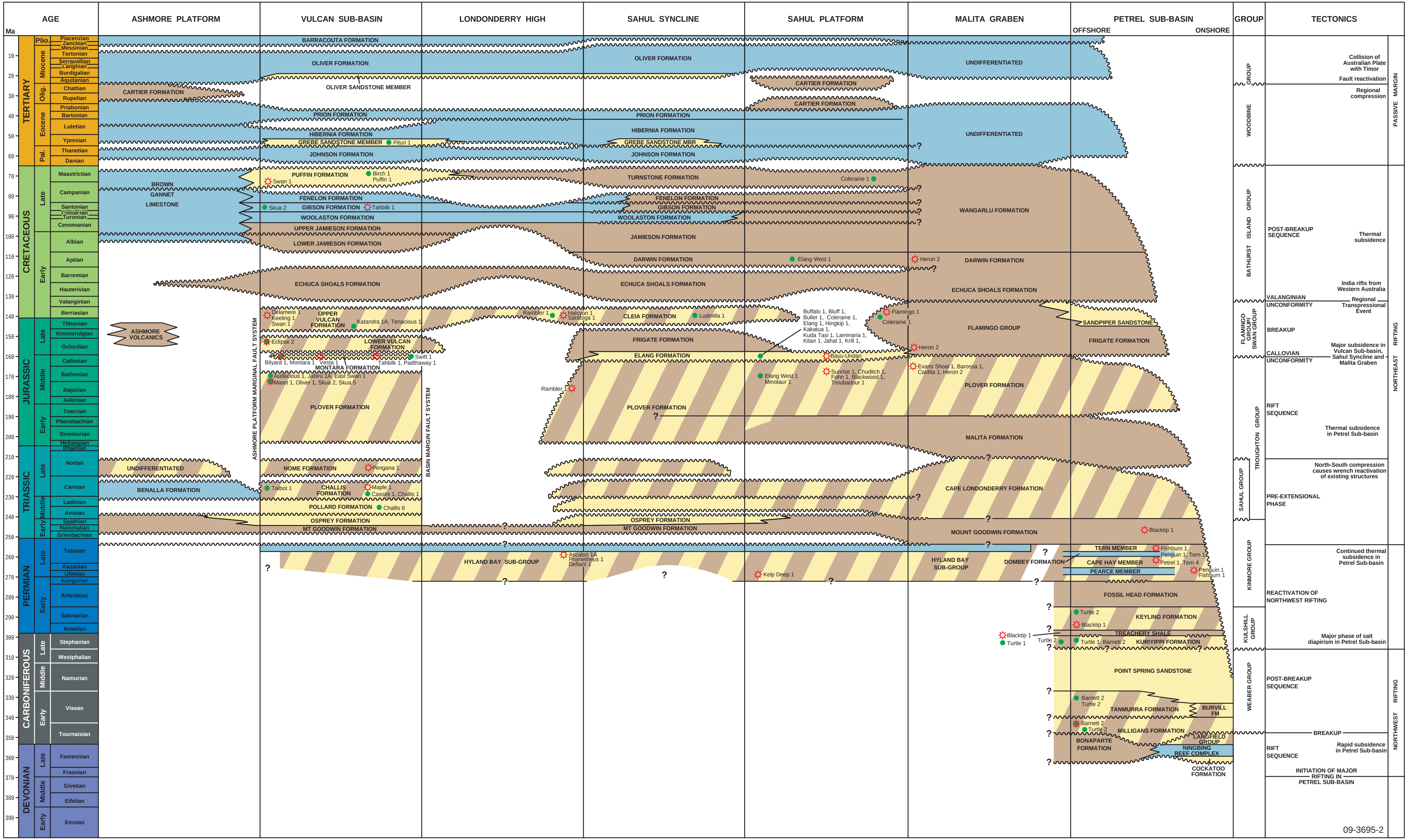


Figure 2. Stratigraphic summary of the Bonaparte Basin (after Cadman and Temple, 2004).

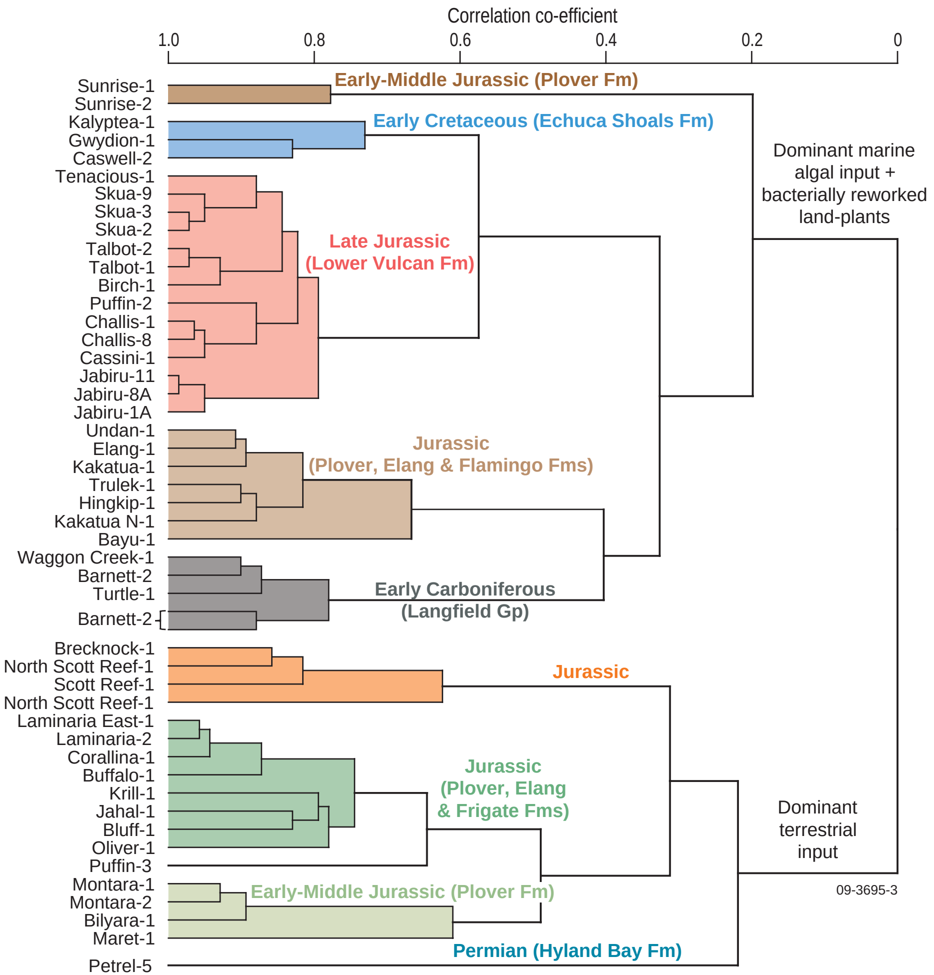
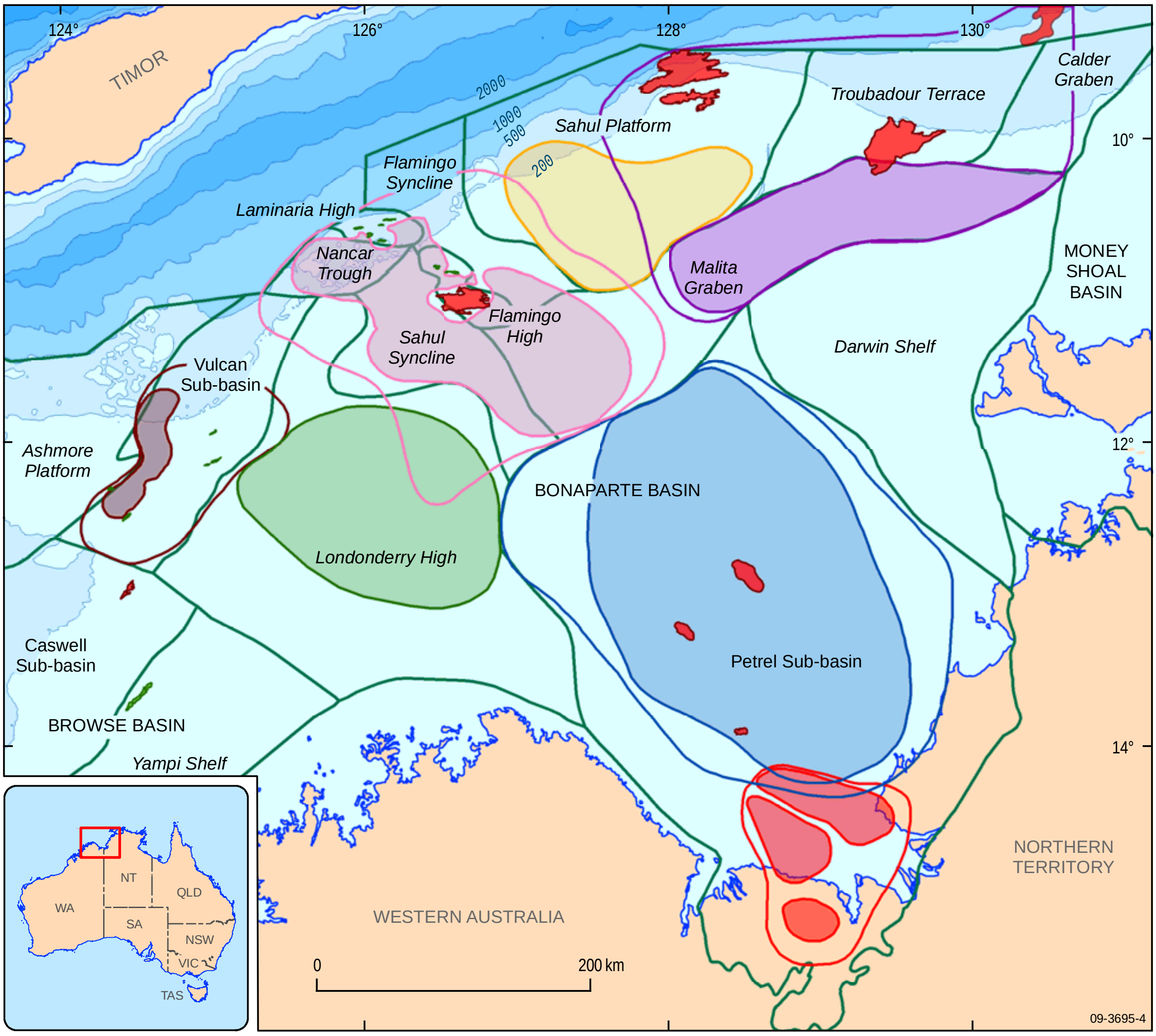


Figure 3. Oil family dendrogram from hierarchical cluster analysis showing origin of major petroleum accumulations in the Bonaparte and Browse basins (after Edwards et al, 2004).



Where well symbol information is sourced from publicly available "open file" data, it has been provided by Geoscience Australia from Well Completion Reports. These symbols were generated from open file data as at 31 March 2009. Where well symbol information is not publicly available from titleholders' data, the information has been extracted from other public sources. Field outlines are provided by GPinfo, an Encom Petroleum Information Pty Ltd product. Field outlines in GPinfo are sourced, where possible, from the operators of the fields only. Outlines are updated at irregular intervals but with at least one major update per year.

Field outlines for Cornea and Abadi are sourced from IHS Energy, 2006.

	Source Pods	Petroleum System limit
Vulcan-Plover(!)		
Elang-Elang(!)		
Permian-Hyland Bay(?)		
Hyland Bay-Hyland Bay(?)		
Plover-Plover(.)		
Hyland Bay/Keyling-Hyland Bay(.)		
Milligans-Kuriyippi/Milligans(!)		

Gas field

Oil field

200 *Bathymetry contour (depth in metres)*

Figure 4. Distribution of the petroleum systems of the offshore Bonaparte Basin (after Barrett et al, 2004; Earl, 2004).