The Petroleum Geology of the Amadeus Basin

By

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INTRODUCTION

The Amadeus Basin (Figure 1) has intermittently been the focus of oil industry activity since the discovery of hydrocarbons in the 1960s culminating in the development of the Ordovician Mereenie and Palm Valley fields in the mid-1980s. These were significant fields and initial reserves at Mereenie were 18 MMSTB of oil reserves and 333 BCF of gas reserves, and at Palm Valley 230 BCF of gas reserves. However, only minor exploration occurred from this time up until 1992 when the last exploration well was drilled. The basin is now a generation behind world standards, not only in terms of exploration activity, but also in terms of applied technology, particularly seismic technology. The current revival of energy prices has seen a resurgence of interest in this 'sleeping giant' which covers 170 000 km^2 with only one well per 5200 km^2. Figure 1 outlines an aeromagnetic image of the basin with major structural trends.

A watershed in terms of exploration activity is approaching and NTGS has delivered a number of new products that will hopefully facilitate exploration successes in coming years.

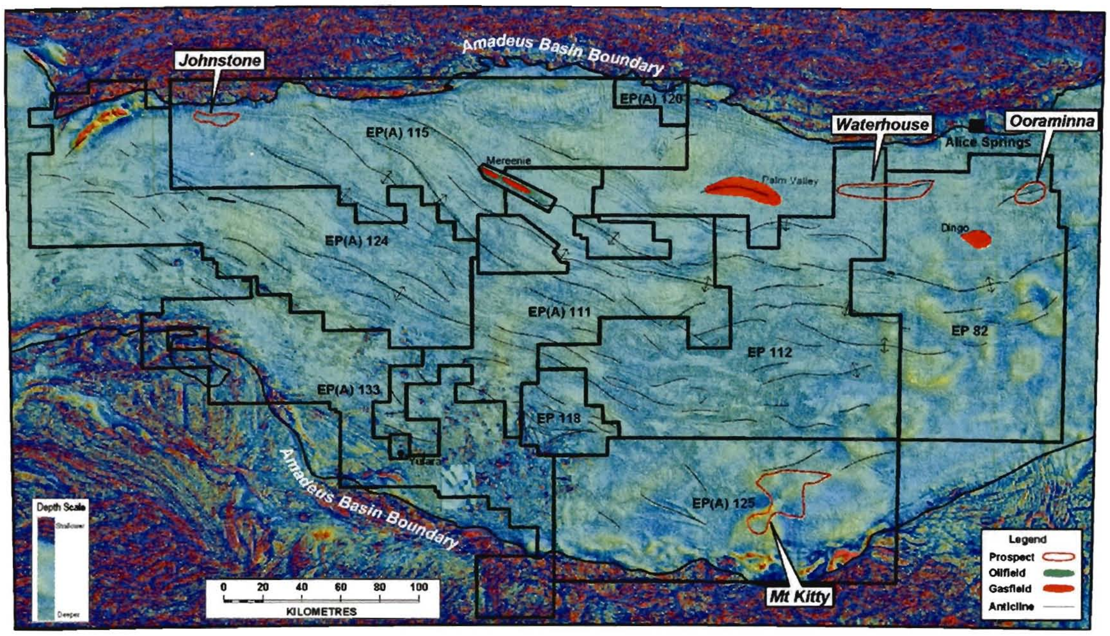


Figure 1 Amadeus Basin – aeromagnetics image with major structural trends

Key geological breakthroughs relevant to the Amadeus Basin and other central Australian Basins were presented at the Central Australian Basins Symposium (CABS) held in 2005. All abstracts have been published and a compilation of final papers should be available by mid-year 2007 in the proceedings volume (*Northern Territory Geological Survey, Special Publication* 2). Six key papers delivered at CABS and relevant to the Amadeus Basin are listed below: Basin, central Australia.

1) Dyson and Marshall. The influence of salt tectonics on Neoproterozoic to early Paleozoic sedimentation, Amadeus Basin.

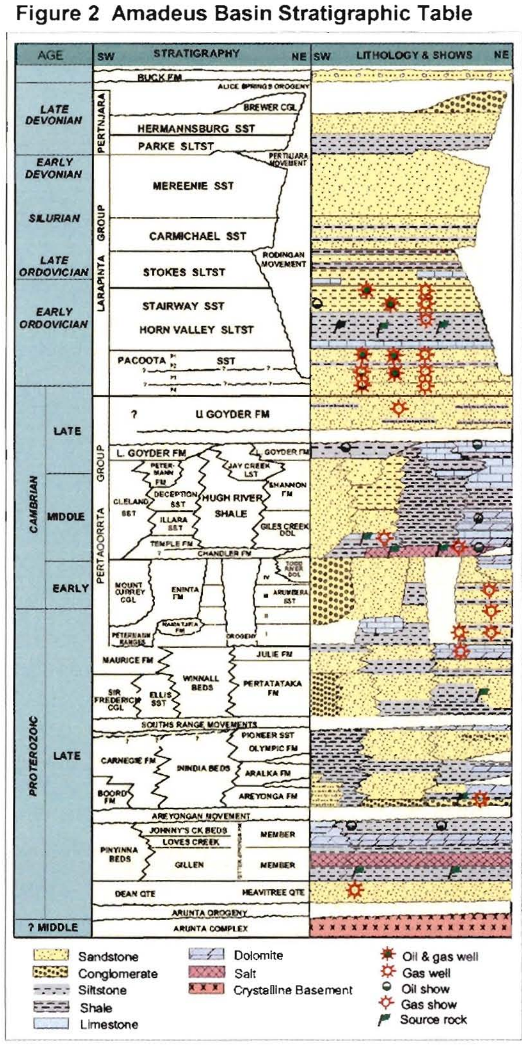
2) Young, Ambrose and Marshall. Petroleum Geology of the southeastern Amadeus Basin: the search for sub-salt hydrocarbons.
3) Marshall and Dyson. Halotectonics – a key feature of Amadeus Basin development.
4) Marshall, Murray, Warburton, Gonzalez, Camac, Christie and Little. The results of an integrated fault seal and petroleum resource assessment of the Amadeus Basin.
5)Gibson, Duddy, Ambrose and Marshall. Regional perspectives on new and reviewed thermal history data from central Australian basins.

Note recent information addressing NTGS stratigraphic drill holes in the western Amadeus Basin occurs in Ambrose 2006a and 2006b, and Ambrose 2007. The most recent basin modeling in the north of the basin occurs in Gibson et al, (2004).Subsequent to the CABS Symposium, the latest version of the stratigraphy and related petroleum systems is shown in Figure 2. Three additional NTGS products, available on CD ROM free of charge, relate to a regional seismic review of leads and prospects (Young Geoconsultants Pty Ltd 2004), a review of the basin's petroleum source rocks (Marshall 2004) and an overview of the basin's untapped petroleum potential (Warburton *et al* 2005).

AMADEUS BASIN –STRATIGRAPHY AND GEOLOGICAL HISTORY

The initiation of the Amadeus Basin probably coincided with the onset of Mesoproterozoic rifting, which was associated with the Giles Event (1080–1040 Ma) and may have centred on the Musgrave Province. A number of the resultant northwest-trending faults were reactivated at this time (SRK 2004). This process defined the shape of the basin and location of

Figure 2 Amadeus Basin Stratigraphic Table



basement highs. Renewed rifting, related to continued northeast-directed extension, occurred at the commencement of the Neoproterozoic (800–840 Ma) and ultimately lead to the breakup of the Rodinian Supercontinent along the Tasman line (Powell *et al* 1994). Faults defining the basement fabric were intermittently rejuvenated during later rifting and orogenesis through to the Palaeozoic.

In the Bloods Range region, located in the southwest Amadeus Basin, a thick package of sediments and volcanics (Tjauwata Group) unconformably overlies basement of the Musgrave Province. Incipient rifting at this time resulted in the deposition of quartz-rich sediments, volcaniclastic sediments and bimodal volcanics, the Tjuninanta Formation (Close *et al* 2005). Conformably overlying this succession is the Mount Harris Basalt, which comprises an estimated 1–2 km-thick accumulation of basaltic flows, interpreted to be approximately 1080 Ma in age. The overlying Bloods Range Formation comprises red beds, volcaniclastic rocks and fine-grained to conglomeratic clastic rocks. A change from this alluvial / fluvial setting to a shallow-marine–tidal depositional environment (Heavitree Quartzite/Dean Quartzite) marks the onset of the Amadeus Basin succession *sensu stricto*.

The relationship between the Mesoproterozoic rift succession and the basal Amadeus Basin clastic rocks is contentious and the evidence for continuous rift-sag basin evolution is equivocal; various interpretations are in Close *et al* 2005. The Neoproterozoic section in the Amadeus Basin averages about 2000 m, increasing to about 3000 m in the northeast. Lindsay (1993) described the stratigraphy of the basin which, together with three basin studies completed for the Northern Territory Geological Survey (Weste 1989) and 6 papers presented at the Central Australian Basins Symposium, form the basis of the following discussion.

NEOPROTEROZOIC

Heavitree Quartzite

Sedimentological and stratigraphical analyses by Lindsay (1993 and 1999) show that basal Amadeus Basin clastic strata resulted from quartz sandstone sedimentation in a shallow, low-gradient ramp setting. Heavily laden braided streams transported quartz clastic material to the basin to be dispersed in a high-energy, shallow-marine environment, forming extensive, sheet-like sand bodies. Clarke (1974) and Dr I Dyson (pers com) have suggested that some of the sandstones resulted from, and were modified by giant storms as shoreface facies prograded across a broad, shallow shelf subjected to tidal amplification. Trough cross-beds show that the main direction of sediment supply was to the north-northwest onto what is now the exposed Arunta Complex. Zircon provenance studies also suggest that the Musgrave Province was emergent at this time (Camacho *et al* 2002).

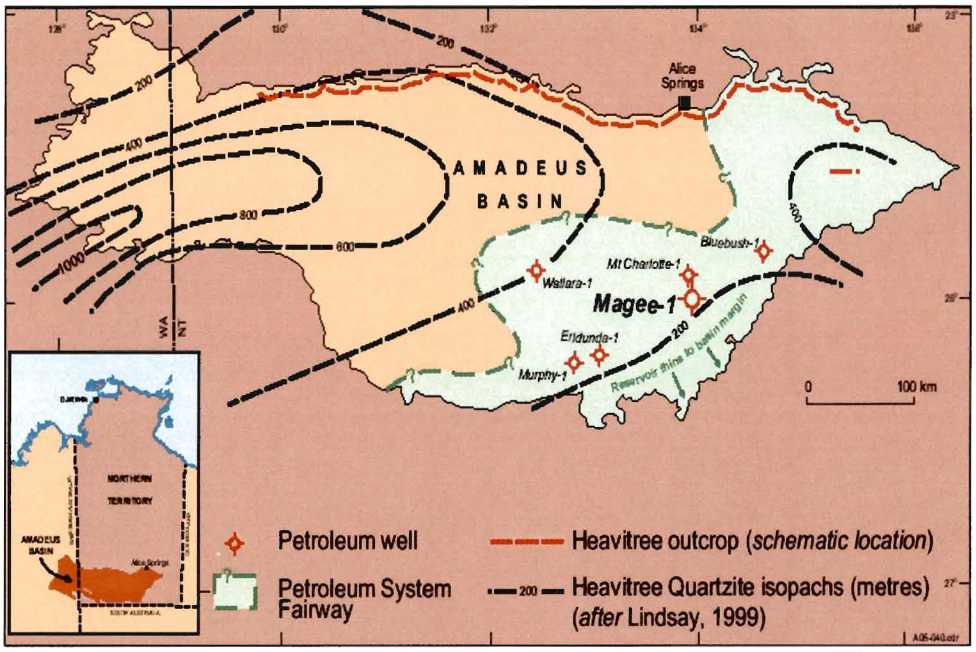


Figure 3 Heavitree Formation Isopach

Lindsay (1999) showed that the Heavitree Quartzite is relatively uniformly distributed over wide areas of the basin and averages 100–300 m in thickness, grading westwards to 800 m. In the eastern portion of the basin, this author described a major ravinement surface, 20–40 m above the basement contact, which may have regional extent, and which is capped by minor fluvial conglomerate. A distinctive feature of the Heavitree Quartzite is the presence of beds up to 10 m thick, consisting of individual sets of low-angle, sigmoidal crossbeds, which formed in a tidally dominated environment as flow-transverse sand waves.

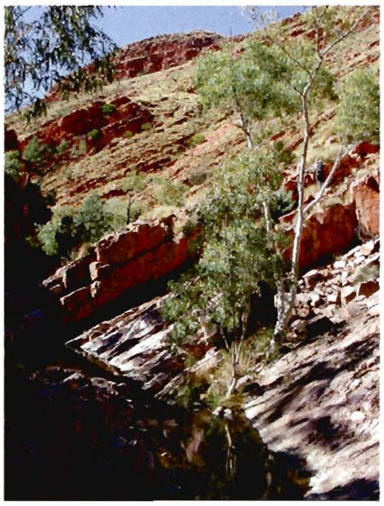


Figure 4 Heavitree Formation outcrop in Ellery Creek.

To the west, data is scarce and there has been only one well intersection, in Magee-1. This well was drilled on a basement high, and the quartzite was only 4.6 m thick and flowed gas to surface at a low rate. From seismic data, Young and Ambrose (2007) interpreted crestal thinning of this potential reservoir over major topographic highs and this could be a major factor controlling large structural / stratigraphic hydrocarbon plays. Silicification inhibits the reservoir potential of the succession, but this may be restricted to the MacDonnell Homocline as a result of fluid movement along deep-seated thrust faults, and more basinal sections may retain better reservoir quality. Generally however, the development of fracture porosity will be fundamental to most exploration plays at this stratigraphic level.

Bitter Springs Formation

The Bitter Springs Formation comprises three members, namely the Gillen Member, the overlying Loves Creek Member and the topmost Johnnys Creek Member. The thickness of the Gillen Member is highly variable and has been largely determined by intraformational salt movements, which greatly distort the original stratigraphic thickness. The Loves Creek (4–500 m thick) and Johnnys Creek (maximum thickness 380 m) members are less affected.

Gillen Member

The contact between the Heavitree Quartzite and the overlying Bitter Springs Formation (Gillen Member) is paraconformable. The following descriptions are based on the work of Lindsay (1993), Young and Ambrose, (2007) and Dyson and Marshall (2007). At the base of the Gillen Member, a major transgressive event resulted in the deposition of thick transgressive black shale, which has oil source rock potential and which may be lacustrine in origin. The overlying section comprises stromatolitic dolostone, occasional grey shale and cross-bedded sandstone.

An upper evaporitic succession was deposited during a sea level low-stand and can be generalized as a lower dolomite/anhydrite unit, overlain by a thick halite unit, and capped by a dolomite/anhydrite unit (Lindsay 1993). Halite units up to 850 m thick are recognized in wells, but much thicker, remobilised salt layers are recognized on seismic (Figure 4, after Young and Ambrose, 2007). For example, the Gosses Bluff structure is underlain by over 2200 m of salt (Lindsay 1987) and in the northeast portion of the basin, salt is generally over 1350 m thick.

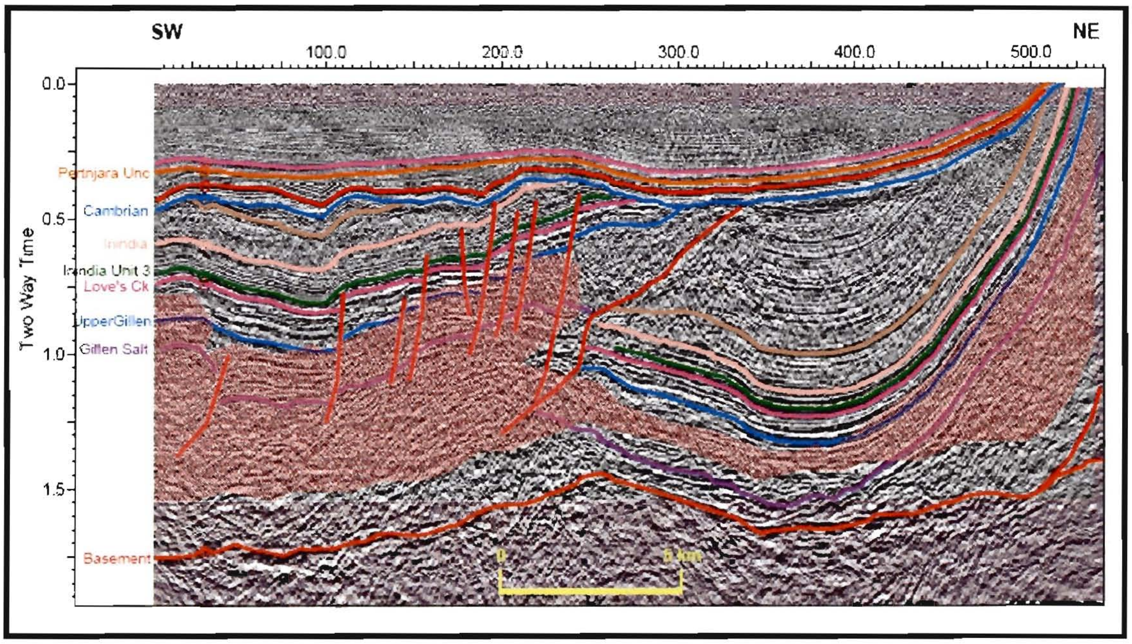


Fig.4 Seismic line from the Murphy-1 area. Note major compression and halotectonics associated with the Petermann Ranges Orogeny. The area was largely unaffected by the Alice Springs Orogeny

The Gillen Member has been an important focus for halotectonics in the Amadeus Basin and in an exposed section at Ellery Creek, the unit displays a diapiric habit defined by tectonic breccia, isoclinal folds and sedimentary breccia (Dyson and Marshall, 2007). The latter can be correlated over 100 km to the Ross River section and the breccia is interpreted to have been extruded as an allochthonous sheet or tongue of diapiric breccia (viz salt glacier), marking the earliest onset of diapirism in the Amadeus Basin. All unconformities within the Neoproterozoic and Palaeozoic, some of which are assigned to orogenies and other movements, are best developed adjacent to diapirs and within interpreted salt-withdrawal mini-basins. Sedimentation occurred at various times during the Neoproterozoic to Palaeozoic, in a series of salt nappe complexes and mini-basins that were formed under the influence of gravity sliding and salt withdrawal (Dyson and Marshall, 2007).

Loves Creek Member

The Loves Creek Member is bounded by erosional surfaces at base and top. This unit was fully cored in Wallara-1 (204 m), and a full intersection also occurs in Murphy-1 (108 m). The Wallara-1 section comprises mainly dolostone in the form of wackestone and packstone, with occasional chert and also rare oolitic beds; stromatolites are common near the top of the unit. Some evaporites are present with anhydrite occurring as beds, nodules and veins. The basal contact with the Gillen Member is deemed unconformable (Lindsay, 1993), but sedimentation is continuous with the overlying Johnnys Creek Member.

Johnnys Creek Member

This unit varies in thickness up to about 400 m, reflecting in part variable erosion during the Areyonga Movement. In the southern/central portion of the basin, the succession has a distinctive E-log signature and the lowermost unit is a distinctive 60 m thick brown/red siltstone. The remainder of the succession comprises alternating intervals of dolostone/lime mudstone and brown-grey siltstone, with occasional chert, algal boundstone and glauconitic sandstone near the top of the succession. The unit is widespread in the central –western portion of the basin and was recently intersected in NTGS stratigraphic drill hole BRD05 DDO1.The unconformity surface with the Areyonga Formation is often marked by development of a rubbly fractured regolith and there is up to 200 m of topographic relief on this surface (Lindsay, 1993).

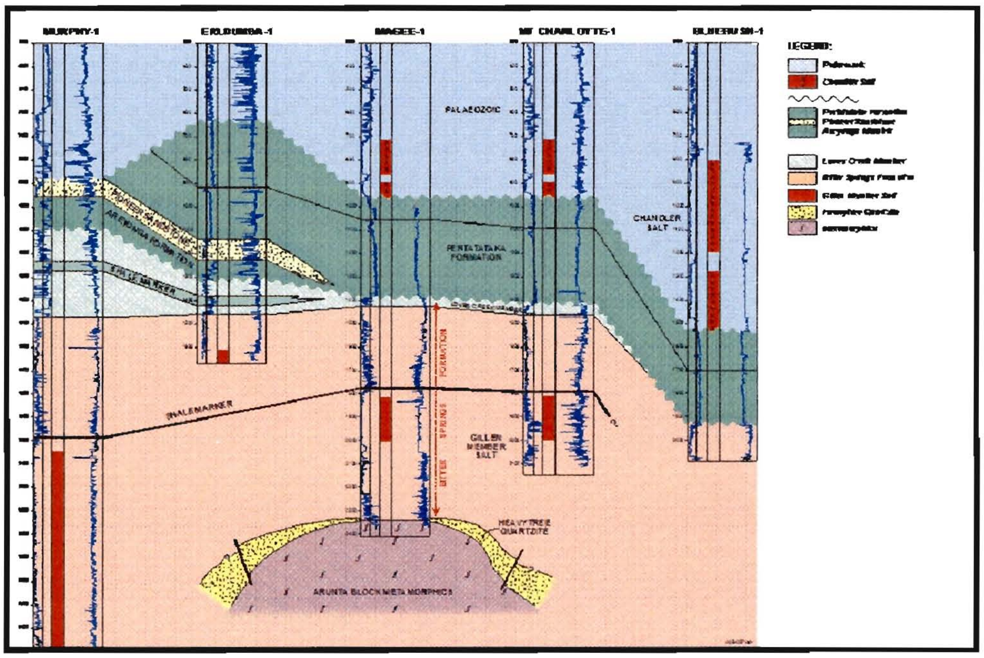


Figure 5. Stratigraphic cross-section: southern Amadeus Basin

Continued northeast-directed extension and dyke emplacement, related to continued breakup of the supercontinent Rodinia, created a widespread erosional break at the top of the Bitter Springs Formation, which can be correlated to the Adelaide Geosyncline. The Areyonga Formation, which was deposited in an extensional rift regime, is a correlative of the Sturtian glacial succession from the Adelaide Geosyncline, where Rb-Sr dates have yielded an age of approximately 730 Ma. The occurrence of thick glacial successions in the northeast Amadeus and southwest Georgina basins may reflect a rift depocentre in the eastern Arunta Province (M Hand pers com – Adelaide University).

Areyonga Formation / Aralka Formation

This glaciogenic succession shows marked lithological variation from massive, indurated diamictite/conglomerate to carbonaceous siltstone/shale, feldspathic sandstone and occasional dolostone. A major depocentre was centred on the northeastern portion of the basin and the Arunta Province was a dominant source area. The diamictites were deposited on an intermittent, but extensive ice sheet, which spread over much of the basin as shown by a recent drilling intersection of "Sturtian" diamictites in the far southwest of the basin in drill hole BRD05 DD01 (Ambrose, 2006a and b, 2007). Black shales of the Aralka Formation occur in the northeastern portion of the basin and are up to 1000 m thick, being unconformable/disconformable on the Areyonga Formation (Kennard and Nicoll 1986). To date, there have only been sporadic, generally thin well intersections of this unit and the distribution of this potentially important source rock remains uncertain.

Olympic Formation/Pioneer Sandstone

The Olympic Formation and its lateral equivalent, the Pioneer Sandstone, disconformably overlie the Aralka Formation and are believed to correlate with Marinoan glacial strata of the Adelaide Geosyncline (Lindsay 1993). In the northeast, the Olympic Formation consists of lenticular units of sandstone, siltstone, conglomerate/diamictite, shale and dolostone, and is up to 190 m thick. To the west, in the Ellery Creek type section, the Pioneer Sandstone consists of intertidal sandstone capped by a "marker" dolostone. It is correlated with the Marinoan Nucaleena Dolomite from the Adelaide Geosyncline.

This unit was not intersected in recent stratigraphic drillholes located in the far southwest of the basin. Equivalent successions may have been eroded during the Souths Range Movement in other areas, where the overlying Pertatataka Formation rests unconformably on the Bitter Springs or Areyonga formations. This was a period of uplift, folding and erosion, intervening between the second glacial succession and thick, extensive marine shale of the overlying Pertatataka Formation. The Souths Range Movement may represent the initial compressive phase of the later, Early Cambrian Petermann Orogeny.

Pertatataka Formation (Winnall Beds) and Julie Formation

In the eastern portion of the basin, the Pertatataka Formation conformably to disconformably overlies the Olympic Formation, or disconformably overlies the Bitter Springs Formation. It is absent over at least part of the Central Ridge, but is widespread south of this high, where it is 400–500 m thick, and in the past has been referred to as the Winnall Beds, a term that is now redundant. An upward-coarsening regressive cycle in the upper part of the unit can be correlated over a wide area. The succession consists mainly of fine-grained clastics, predominantly red and green shale with minor fine-grained sandstone. Recent drilling in the southwestern portion of the basin intersected 450+ m of red/brown to occasionally grey, silty mudstone, becoming evaporitic towards the top. The succession defines a major regressive, upward-shallowing cycle which in its lower part includes thin, sandy, upward-fining cycles, representing input from turbidity currents (Ambrose, 2006a and b, Ambrose, 2007).

North of the Central Ridge, the Pertatataka Formation shallows upward into the Julie Formation, which is a widespread, relatively thin succession of ooid grainstone, dolostone and limestone up to 150 m thick. The Pertatataka and Julie formations form a major regressive,

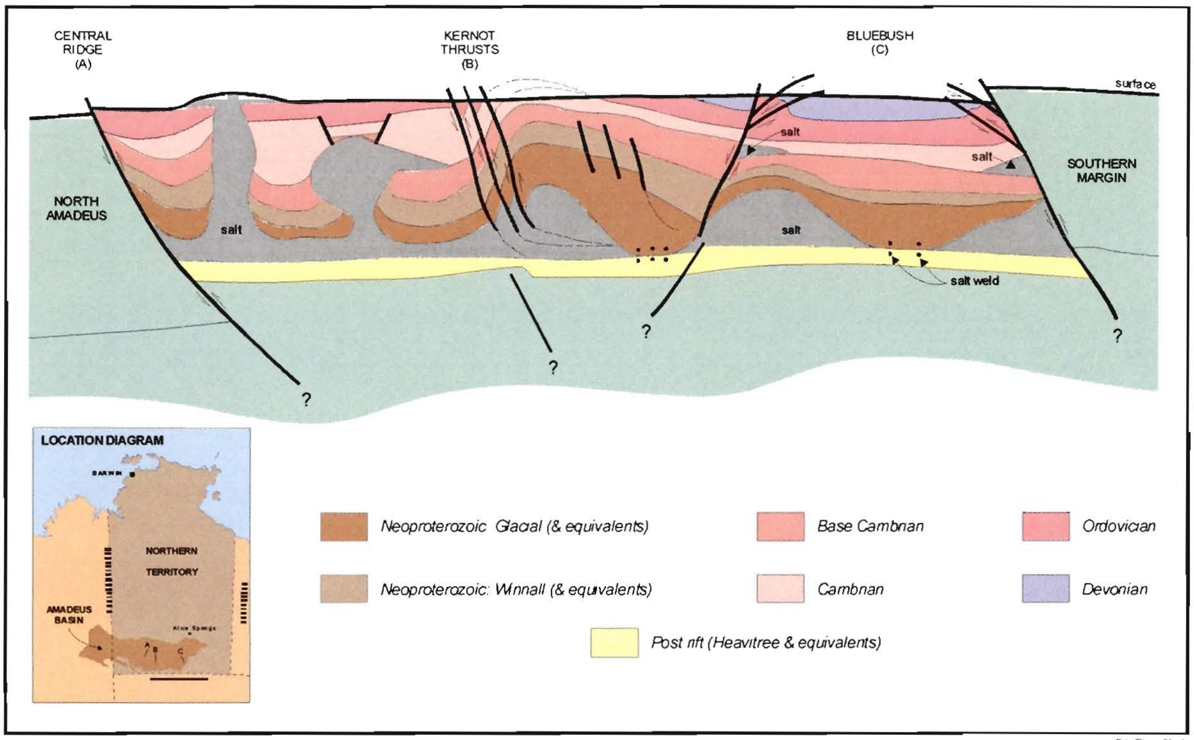


Fig.6 Structural style during the Petermann Ranges Orogeny – southern Amadeus Basin

upward shoaling cycle beginning with deep water pelagic and turbiditic rocks that terminate abruptly in oolittic platform carbonates. Major structuring associated with the Petermann Orogeny followed deposition of the Julie Formation.

PERTAOORRTA GROUP

The depositional architecture of the Centralian Superbasin suffered major disruption during the Petermann Orogeny (650–530 Ma), when the superbasin suffered major fragmentation. Further rejuvenation of the basement structural fabric affected sedimentation within the Amadeus Basin. Major crustal shortening on the northeastern margin of the Musgrave Province resulted in the deposition of a thick Early Cambrian clastic wedge adjacent to the southwest basin margin.

During the Cambrian, depositional loci moved northwards and sedimentation was concentrated in major sub-basins and troughs north of the Central Ridge. A total of 2800 m of clastics were shed into the Carmichael Sub-basin and 1500 m into the Missionary Plains Trough (Lindsay 1993).These sub-basins may have been bounded by high-angle reverse faults, or by extensional faults, which were later rejuvenated during the Alice Springs Orogeny, thereby masking the structural mechanism. Recently SRK (2004) have defined extensional northwest-trending faults based on regional trends, and the widespread development of Early Cambrian flood basalts north of the basin is indicative of significant underplating. The focus of rifting may have been in the eastern Arunta Province where 20 km of syn-orogenic early Cambrian sediments may have been deposited in the Harts Range area (M Hand pers com).

Arumbera Sandstone

The basal unit of the Pertaoorrta Group, the Arumbera Sandstone is divided into two depositional successions with maximum thicknesses of 800 m and 500 m, respectively, in the Carmichael sub-basin, although the thickest section is 2000 m in the northeast of this sub-basin (Weste, 1989). A disconformity separates the lower and upper Arumbera sandstones, which are late Neoproterozoic and Early Cambrian in age, respectively, both being mainly fluvio-deltaic in origin. The sediments accumulated in three sub-basins, namely the Carmichael in the centre, the Idirriki in the west and the Ooraminna to the east. These depocentres and their connecting troughs lose definition southward towards the Central Ridge, which was an effective buttress to major southward progradation of deltaic successions (Lindsay 1993). However, thin transgressive successions occur in Wallara-1 (90 m) and also Mount Winter-1 (73 m) and East Johnnys Creek-1 (73 m).

The Lower Arumbera Sandstone is conformable with the Julie Formation on the northern basin margin, but an intervening unconformity occurs elsewhere. This unit onlaps the Central Ridge, whereas the southern platform was largely an area of sediment bypass (Lindsay 1993). To the southwest, coarse clastic rocks (Mount Currie Conglomerate) were shed northward into the basin from the Musgrave Province, as a result of major thrusting associated with the Petermann Orogeny and these probably interfinger with the Arumbera Sandstone. To the north, major progradation into the Carmichael Sub-basin resulted and a major coarsening-upward cycle developed, capped by fluvial and distributary mouth-bar deposits. A mounded facies at the base of the succession may be a lowstand fan (Lindsay 1993).

The Upper Arumbera Sandstone is also a regressive, shallowing-upward deltaic succession capped by shallow-marine carbonate rocks of the Todd River Dolostone. The succession records extensive progradational seismic signatures (clinoforms) and has a maximum thickness of about 500 m near the centre of the Ooraminna and Carmichael sub-basins (Lindsay 1993).

The Arumbera Sandstone is the key reservoir in the Dingo and Orange gas fields and is an important gas target in the northern and southern Amadeus Basin.

Chandler Formation

The Chandler Formation is a Lower Cambrian carbonate and evaporite succession, and includes organic-rich, foetid, carbonate mudstone, which is a potential petroleum source rock. These sediments were probably deposited during post-Petermann relaxation / extension prior to more regional Cambrian rifting (SRK 2004). In some areas the Chandler Formation disconformably overlies the Arumbera Sandstone and a regional depositional model for the unit occurs in Bradshaw (1991). The succession was probably deposited in a shallow-water, deep desiccated basin in three depositional phases: 1) desiccation and evaporite precipitation; 2) basin flooding and carbonate deposition; and 3) karstification and evaporite precipitation. The western end of the basin is envisaged as the distal end of a salt lake.

Recent drilling suggests the succession is probably absent or very thin west of Magee-1 and Mount Winter-1. Deposition was concentrated in the central-eastern portion of the basin in three north–south-trending facies belts. In the westernmost belt, the Chandler carbonate facies is dominant, comprising relatively thin (10–50 m), areally extensive, black, foetid carbonate mudstone with siltstone, shale and abundant chert. An anoxic, shallow-water, restricted marine environment of deposition has been interpreted (Bradshaw 1991). The section thickens eastward to a mixed carbonate/salt facies up to 500 m thick and the salt ranges in thickness from less than 50 m to over 1000 m. In the easternmost facies belt, evaporites dominate and the thickest well intersection is over 700 m in Bluebush-1. Intraformational salt movements have probably distorted sedimentary isopachs, and extensive salt flowage and dissolution have produced tectonic contacts with numerous older and younger units.

Tempe Formation / Giles Creek Dolostone

The Tempe Formation disconformably overlies the Chandler Formation and is a shallow-water shelf succession, averaging about 150 m in thickness. It is dominated by a persistent basal sandstone sheet overlain by siltstone and shale, and capped by a dolomite in the Gardiner Range (Kennard and Nicoll 1986). Glauconite and phosphatic skeletal material are abundant. The section also occurs in Wallara-1 (184 m) and Mount Winter-1 (163 m). Conformably overlying the Tempe Formation is the 'Illara Sandstone' and it is suggested herein that this term be made redundant and, in future, the 'Illara Sandstone' should be included in the Tempe Formation. The latter interfingers to the north and east with the Hugh River Shale and westward with the lower portion of the Cleland Sandstone.

The Giles Creek Dolostone interfingers with the Tempe Formation and disconformably overlies the Chandler Formation. It is conformably and gradationally overlain by the Shannon Formation and to the west, the succession interfingers with the basal part of the Jay Creek Limestone. The Giles Creek Dolostone is only known to the north of the Central Ridge and has a maximum known thickness of 383 m in Wallaby-1. The succession comprises mainly terrigenous-rich carbonate rocks and mudstone/siltstone, often variegated red-brown to green, and minor sandstone. Depositional environments include shallow-marine, tidal flat, intracoastal lagoon, shallow open-shelf and shoal settings. A detailed description of sedimentary environments is in Kennard and Nicoll (1986).

Petermann Sandstone / Deception Siltstone / Cleland Sandstone / Shannon Formation

These stratigraphic units are sometimes lateral equivalents, but the temporal and lithostratigraphic relationships between them are uncertain and hence they are discussed as a whole. The Shannon Formation conformably overlies the Giles Creek Dolostone and reaches a thickness of over 700 m in the northeastern portion of the basin, while progressively thinning to the north and west. The lower Shannon Formation comprises up to 270 m of silty shale with interbeds of thin siltstone and dolostone, deposited in an oxygenated, low-energy marine environment. The upper Shannon Formation is carbonate rich, representing the progradation of peritidal carbonate flats. The main lithofacies are shallow subtidal (ribboned carbonate-mudstone, grainstone and thrombolites), intertidal (stromatolites) and supratidal evaporitic facies (Kennard and Nicoll 1986). Palaeontological data indicates a Middle Cambrian age for this section.

Across the Central Ridge and on the southern platform, the equivalent Middle Cambrian succession is dominated by fluvial and overbank facies of the Deception Siltstone and Petermann Sandstone. These are genetically related red-bed alluvial clastics up to 1250 m thick (East Johnnys Creek-1). An equivalent succession in the Idirriki Sub-basin consists of gravelly braided stream deposits of the Cleland Sandstone which reach a maximum measured thickness of over 1000 m. Recent drilling in the southwestern portion of the basin recorded 115 m of red beds (Petermann Sandstone in NTGS LA05 DDO1- Ambrose 2006a and b, Ambrose, 2007), comprising a prograding alluvial fan at the base capped by channelised braid-plain deposits with some marine influence.

The Cleland Sandstone outcrops in the western Amadeus Basin and reaches a maximum thickness of 1060 m in the Glen Edith Hills area, where the unit is a medium- to coarse-grained sandstone, which is believed to change facies eastward into the Tempe Formation, Deception Siltstone and Petermann Sandstone (Kennard and Nicholl, 1986).

Goyder Formation

The Goyder Formation, which is late Cambrian in age, has a gradational lower contact with aforementioned clastic successions and reaches a maximum thickness of 600 m in the northeastern Amadeus Basin. The unit transgresses the Central Ridge, but generally thins to the south and west, and is only 95 m thick in Mount Winter-1. It is subdivided into lower and upper units, both deposited in shallow subtidal to intertidal environments (Kennard and Nicoll 1986). The lower Goyder Formation is up to 300 m thick and consists of a basal carbonate-clastic unit and overlying sandstone; the top of this unit is marked by an important unconformity. The upper Goyder Formation consists of up to 300 m of sandstone and siltstone and marks the base of the Larapinta Group (Lindsay, 1993).

An unconformity, denoted by a weathering surface and faunal break (Oaks *et al* 1991, Shaw *et al* 1991), separates the two 'members'. This break in sedimentation also occurs in the Officer and Ngalia basins and SRK (2004) showed a correlation with the Delamerian Orogeny (510–490 Ma), known locally as the Bloods Range Movement which marks the base of the Larapinta Group (Lindsay, 1993). However, the Delamerian Orogeny is only weakly expressed in the Amadeus Basin and no significant folds or fault movements are interpreted in central Australia (SRK 2004).

LARAPINTA GROUP

The Larapinta Group is herein informally divided into upper and lower successions bounded by major unconformities, comprising in total seven formations that range in age from latest Cambrian to Silurian. The group is marked at the base by a significant unconformity within the Goyder Formation, which is associated with the Bloods Range Movement and is clearly denoted by seismic data and biostratigraphy (Lindsay 1993). This orogenic phase is probably equivalent to the Delamerian Orogeny noted in the Adelaide Geosyncline and elsewhere. The Larapinta Group marks the first time the Central Ridge failed to partition a depositional phase into sedimentary regimes (Lindsay 1993).

The top unconformity bounding the lower Larapinta Group probably relates to the Rodingan Movement (Shaw *et al* 1991, Walley *et al* 1991). This deformation denotes initial compression associated with the Alice Springs Orogeny, which in places, has formed an erosion surface at the base of the Carmichael Sandstone. However, this erosion surface, while representing a major time break, is paraconformable over large areas of the missionary Plains Trough and Carmichael Sub-basin, and the relationship to basin orogenesis remains uncertain (Lindsay 1993). The upper Larapinta Group, comprising the Carmichael and Mereenie sandstones, is bounded at the top by a major unconformity related to the Pertnjara Movement of the Alice Springs Orogeny.

During the Ordovician, shallow-marine conditions prevailed, mostly in the tidal range, and clastic sedimentation came into dominance (Lindsay 1993). During the mid–late Ordovician, northeast–southwest intracratonic extension opened a broad rift basin connecting the Canning, Amadeus and Warburton basins to the proto-Pacific Ocean, forming the Larapintine Seaway (Walley *et al* 1991). The basin was asymmetrical at this time and most formations thicken to the present north-central margin of the basin, while onlapping the southern margin. The group's average thickness is 1030 m and reaches a maximum of 2100 m at the northern boundary of the central portion of the basin; southwards there is a progressive depositional overstep up through the stratigraphic section. An important oil reservoir, the Pacoota Sandstone, is gradational with the underlying upper Goyder Formation and is progressively overlain by the Horn Valley Siltstone, Stairway Sandstone and Stokes Siltstone. The final phase of clastic sedimentation is defined by the Carmichael and Mereenie sandstones.

The group is of economic importance in that the succession includes the basin's only commercial petroleum system, viz the Horn Valley Siltstone source rock, which is responsible for attendant petroleum production from the Pacoota and Stairway sandstones.

"LOWER" LARAPINTA GROUP

Goyder Formation / Pacoota Sandstone

The basal Larapinta Group includes the upper Goyder Formation which comprises up to 300 m of sandstone and siltstone. The conformably overlying Pacoota Sandstone, which is Late Cambrian to Early Ordovician, is described in detail by Deckelman *et al* (1992), and the following discussion draws heavily on this study. The succession accumulated in response to thermally induced, regional basin subsidence which was in part affected by halokinesis in the Neoproterozoic Bitter Springs Formation. It appears that from this time on, the Central Ridge ceased to be a pivotal barrier to clastic sedimentation. The sandstone is up to 800 m thick in the central-north of the basin and thins progressively southward to its depositional limit. The depositional setting was largely shallow marine, with subordinate non-marine deposition occurring in response to sea level fluctuations.

Initial deposition formed upper shoreface quartz sandstone, succeeded by a tidally influenced clastic succession in the north-central and northeastern parts of the basin. Major upward-coarsening cycles overstep one another southwestward. Subsequent westward transgression formed transitional fluvial to shallow-marine deposits. Braided streams eroded a northwestern hinterland and deposited sheets of mudstone, conglomerate and arkose which in turn, grade upward into estuarine mudstone and shoreface quartz arenite. Rising sea levels instigated a west-southwestward transgression, which resulted in an overlying section of lower shoreface clastic rocks, offshore marine clastic rocks and minor limestone. The final phase of Pacoota deposition responded to further slow, southwest-directed, marine transgression. Additional quartz arenite and subarkose accumulated at the shoreface, whereas dark grey/black shale/siltstone was deposited offshore.

The Pacoota Sandstone constitutes the main reservoir in the Mereenie and Palm Valley fields (Do Rozario, 1991) and is an important oil and gas target in the northern Amadeus Basin.

Horn Valley Siltstone

The Horn Valley Siltstone contains the most important source rocks in the Amadeus Basin (Gorter 1984). The succession is of Arenigian age and was deposited on a relatively deep-marine shelf, where the black shale component of the succession was presumably deposited under euxinic bottom conditions. The unit has gradational contacts with both the underlying Pacoota Sandstone and the overlying Stairway Sandstone. A maximum thickness of 120 m is recorded in the western McDonnell Ranges, from where the succession thins to the south, west and east, which follows the depositional configuration for the Larapinta Group as a whole.

The base of the succession is defined by the first dolomitic limestone above the Pacoota Sandstone; this unit is rich in conodonts and nautiloids. An overlying black shale with minor limestone is up to 40 m thick. There follows up to 35 m of interbedded marl and shelly limestone with occasional black shale. In Temp Vale-1, this section includes thin storm beds made up of coquina at the base, grading to calcilutite, with dark grey mudstone capping the cycle (Kennard and Nicoll 1986). The uppermost Horn Valley Siltstone marks a transition from black shale and siltstone to fine sandstone. The contact with the Stairway Sandstone is arbitrarily placed where the sand component becomes dominant.

Stairway Sandstone

This sandstone succession lies conformably on the Horn Valley Siltstone, except in the south where the upper unit progressively overlaps older rocks. The Stairway Sandstone is Lower Ordovician (Llanvirnian) and is gradationally overlain by the Stokes Siltstone. The formation isopach largely mimics those of the underlying Horn Valley and Pacoota successions; a maximum isopach of 550 m is recorded in the north-central part of the basin, gradually decreasing to the east, west and south. A tripartite subdivision (Kennard and Nichol 1986) is applied in this area comprising: 1) a lower massive/crossbedded sandstone with pyrite ooids, capped by a quartz pebble horizon (60 m); 2) A middle unit containing black shale, siltstone, fine-grained sandstone and phosphorite (200 m); and 3) an upper unit containing thinly bedded, fine-grained sandstone with interbeds of siltstone and mudstone (300 m).

Stokes Siltstone

The Stokes Siltstone is of Middle Llanvirnian age and defines a succession of fine clastics reaching a thickness of 650 m in the north-central part of the basin, thinning southward and westward. The depositional environment had become more saline by this time and intertidal, supratidal and hypersaline conditions prevailed (Kennard and Nicoll 1986). The dominant lithologies are shale and siltstone with occasional evaporites. The lack of organic matter indicates a restricted, rather than open marine environment, suggesting that the eastern Larapintine seaway closed at this time (Walley *et al* 1991).

"UPPER" LARAPINTA GROUP

Carmichael Sandstone

An erosion surface at the base of the Carmichael Sandstone marks a major change in the evolution of the Amadeus Basin from an extensional to a compressional setting, despite some doubts about the regional continuity of this surface (Lindsay, 1993). This erosion surface corresponds to the Rodingan Movement of the Alice Springs Orogeny (450-430), which was coincident with the onset of convergent subduction at the eastern margin of the Australian continent (SRK 2004). This marked the demise of the Larapintine Seaway, as deltaic sedimentation prevailed, with progradation from source areas in the northwest and southeast (Lindsay and Korsch 1991). The Carmichael Sandstone is believed to be Late Ordovician in age and comprises a reasonably continuous red/brown sandstone, siltstone and mudstone succession up to 150 m thick in the southern part of the basin.

Mereenie Sandstone

The Mereenie Sandstone is largely gradational with the underlying Carmichael Sandstone, but marked onlap of older Palaeozoic units occurs in the northeast portion of the basin, where there was uplift during the Rodingan Orogeny. The succession spans the Late Ordovician to Early Devonian and reaches a thickness of about 900 m in the axis of an extensive east–west-trending depocentre. Three major units occur in the Mereenie Sandstone; a lower aeolian succession with evidence of ephemeral lakes is overlain by a locally developed fluvial unit, in turn capped by an upper aeolian sandstone displaying large dune crossbedding (Lindsay 1993).

PERTNJARA GROUP

The mid-Devonian marked a period of convergent subduction on the eastern margin of the continent, and coincident structuring in central Australia occurred during the Alice Springs Orogeny. Earliest orogenesis occurred during the Rodingan Movement, but the later Pertnjara Movement (395–375 Ma, Haines *et al* 2001) is denoted by synorogenic deposition of the Pertnjara Group and its equivalents in the Amadeus, Georgina and Wiso basins. In the Amadeus Basin, this group comprises an upward-coarsening, foreland basin succession which unconformably overlies the Mereenie Sandstone and spans the Middle to Late Devonian.

During the Pertnjara Movement, major exhumation of the Arunta Province was accommodated in a series of south-directed thrusts, resulting in the formation of an extensive, thick clastic wedge in the northern Amadeus Basin (Pertnjara Group). The basal part of the succession (Parke Siltstone) has a maximum thickness of 1000 m and consists of mainly fluvial/alluvial, lithologically immature siltstone and sandstone with occasional lacustrine influence (Kennard and Nicoll 1986). This unit gradually coarsens upward to a succession of litho-feldspathic quartz sandstone deposited in upward-fining fluvial/alluvial cycles, as sediment was swept off the Arunta Province (Hermannsberg Sandstone). This unit is up to 1000 m thick in the northern portion of the basin and the sandstone become more mature in composition to the south and east.

Syn-orogenic, coarse alluvial conglomerate of the Brewer Conglomerate rest unconformably to conformably on the Hermannsberg Sandstone, reaching a thickness of 3000 m in the north of the basin. The succession formed as a syn-orogenic molasse formed by deposition on coalescing piedmont alluvial fans, coincident with south-directed deformation on the rising northern margin of the basin.

The final phase of the Alice Springs Orogeny, convergent deformation during the Carboniferous, is known as the Mount Eclipse Movement (340–310 Ma, Haines *et al* 2001). This corresponds to the Kanimblan Orogeny beneath the Cooper-Eromanga Basin and convergent subduction at Australia's eastern margin (SRK 2004). The direction of compression was probably northeast–southwest, but there was no coincident syn-orogenic sedimentation in the Amadeus Basin. Synorogenic deposition occurred to the north in the Ngalia Basin (Mount Eclipse Sandstone), and associated folding and thrusting of Amadeus Basin successions occurred to the south.

During the later phases of the Alice Springs Orogeny, uplift of the Musgrave Province resulted in deposition of Devonian continental clastics (Finke Group) described in detail by Jones (1973) and Edgoose *et al* (2002). Inboard of the southeastern basin margin, coarse alluvial facies of the Finke Group (Polly Conglomerate) are up to 400 m thick. The overlying Horsebend Shale forms a variably thick, discontinuous sheet over a much wider area of the southeastern basin. Both this unit and the Langra Formation were sourced from the south and interfinger northward with the Pertnjara Group. Distal facies of the Brewer Conglomerate (Idacowra Sandstone) occur in this area, where there is also minor deformation of the Finke Group; this indicates structural overprint during the latter phases of the Alice Springs Orogeny, which effectively marked the close of sedimentation in the basin.

PETROLEUM GEOLOGY

Exploration History

Exploration began in the Amadeus Basin in the 1950s with a period of reconnaissance work by the then BMR. The Mereenie Oil and Gas Field was discovered in early 1964 and the Palm Valley Gas Field in 1965. Both of these are in the Ordovician Pacoota-Horn Valley-Stairway succession. Since then, exploration and scientific study in the basin has largely focused on the Ordovician petroleum system in the northern and eastern part of the basin. (Korsch and Kennard 1991). However, with only 5 wells located away from the central ridge to the south and west, and most recent data in these areas dating back to the 1960s, the greater Amadeus Basin can be considered a 'greenfields' area. It is therefore a frontier basin for petroleum exploration.

Encouraging results have been observed that indicate a number of active, but poorly defined older petroleum systems in the Amadeus Basin. The stratigraphy and prospective petroleum systems are outlined in Figure 2. The curently uneconomic Dingo gas field is a good example. It is located 80 km south of Alice Springs, and has proven and probable reserves of 25 BCF. Other prospects in the basin, which have recorded small but significant gas flows, but which have been the subject of little (if any) further work, include West Walker, Orange, Magee and Ooraminna.

Petroleum Systems / Source Rocks

1) *Early Neoproterozoic - The lower Gillen Member- Heavitree Quartzite Petroleum System*

A summary of prospective petroleum systems and their related stratigraphy occur in Figure 2. The Heavitree-Gillen petroleum system and related reservoir/seal couplet is most recently described by Ambrose (2006a and b) and Young et al (2007). The source rock facies occurs at the base of this unit and comprises oil prone, transgressive, black marine shales; details are published in Marshall (2004). The lower Gillen Mbr is preserved in outcrop in the Ormiston Gorge type section on the northern margin of the basin. In the southern part of the basin in Magee-1, the only well penetration, a 20 m interval of dolomite and siltstone directly overlies the Heavitree Quartzite and includes thin bitumen stained, carbonaceous laminae. This interval is relatively lean with depleted TOC's ranging from 0.5 to 0.8%. An MPI- derived reflectance of 1.02 (VRe) indicates this zone is still within the oil window, although this trap has undergone gas flushing attributed to migration from the deeper parts of the basin. The upper member contains relatively little organic shale and is not considered a significant source rock.

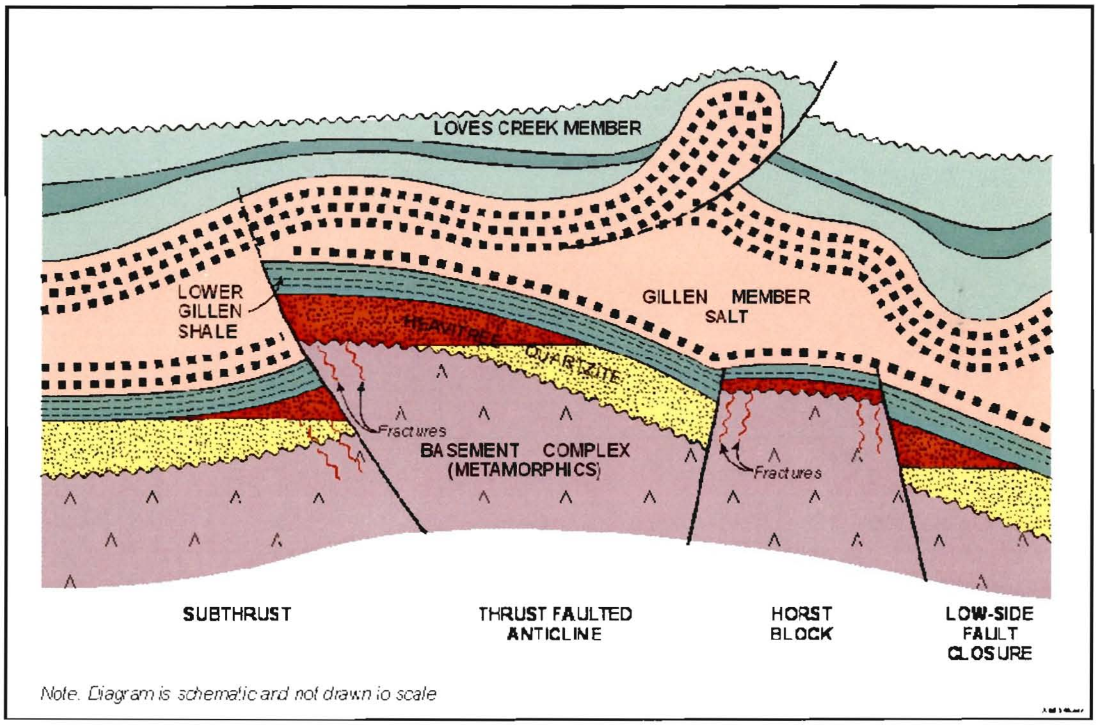


Figure 7 Exploration plays at the level of the Heavitree Formation

The Heavitree Quartzite is sealed by the lower Gillen Member shale-evaporite sequence. The unit recorded a small gas flow in the Magee-1 well which contained 6% Helium. However, because target depths to the Heavitree Quartzite exceed 5000 m over the northern part of the basin, the associated play fairway is generally restricted to the area south of the Central Ridge (Fig.10) and this petroleum system and reservoir/seal couplet are described in detail by Young et al, 2007. These authors suggest initial hydrocarbon charge from Gillen Member source rocks occurred in late Bitter Springs time (ca 700 Ma), following deposition and loading by at least 1-2 km of early Neoproterozoic sediments. Traps are associated with the initial Mesoproterozoic/Neoproterozoic rifting event or halotectonics in mid-late Bitter Springs time. Potential plays include drape closures over faulted basement or palaeotopographic highs, three-way dip closures/pinchouts on plunging basement highs, thrust- faulted anticlines and low side fault traps (Fig.6).

The remainder of the Bitter Springs Formation contains sparse organic shales up to the level of the Loves Creek Member but there is little evidence of an effective petroleum system. The topmost unit, the Johnny's Creek Beds can be mapped on a regional scale but contains mainly red-beds and carbonates and has no source potential.

Significant basin unroofing has masked the fact that hydrocarbon generation from Neoproterozoic source rocks was more pervasive than previously recognised. For instance, in Murphy-1, shale in the Bitter Springs Formation reveals maturities through the gas window at current depths of less than 3000 m, suggesting considerable erosion at this location.

2) Middle Neoproterozoic - Areyonga-Aralka Petroleum System

Black shales of the Aralka Formation occur in the northeastern portion of the basin and are up to 1000 m thick, being unconformable to disconformable on the Areyonga Formation glacials. There is little source rock data available from this sequence but stratigraphically analogous shales (ie in vertical juxtaposition with the Sturtian glacials) have generated prolific oil accumulations at this level in Oman and Siberia, where a key factor controlling entrapment is the presence of thick evaporite seals. Very little is known of this play in the Amadeus Basin and a review of the Aralka source rock potential and possible reservoirs within glacial-outwash facies of the Olympic Sandstone and Areyonga Formation occurs in Figure 7. Thick shales within the overlying Pertatataka Formation have both source and seal potential. In addition substantial evaporites within the early Cambrian Chandler Formation have excellent seal potential. Note that residual oil stains below thick Chandler salt in Finke-1 hint at the possibility of oil charge in this part of the basin.

Significant basin unroofing in Wallara-1 is indicated by MPI-generated Vro values from the Aralka and Bitter Springs Formations which lie in the oil window (Vro= 1.1) at depths of less than 1300 m. This implies considerable erosion and negates earlier notions of increasing maturation from south to north across the basin.

3) *Late Neoproterozoic - Pertatataka Petroleum System*

The Pertatataka Formation is a ubiquitous thick shale package which is usually disconformable on the Areyonga Formation or Pioneer Sandstone. Despite a relatively low organic content (probably due to maturation loss), the shales represent a viable gas prone source rock in the northern part of the basin (eg Dingo field) which is supported by recent isotope studies of source rock extracts and gas samples (C. Boreham, pers.com. – Geoscience Australia) . The producing reservoir/seal couplet (Chandler salt-Giles Creek Dolomite) is prospective over a wide area.

Source rocks in the Cryogenian of the Amadeus Basin

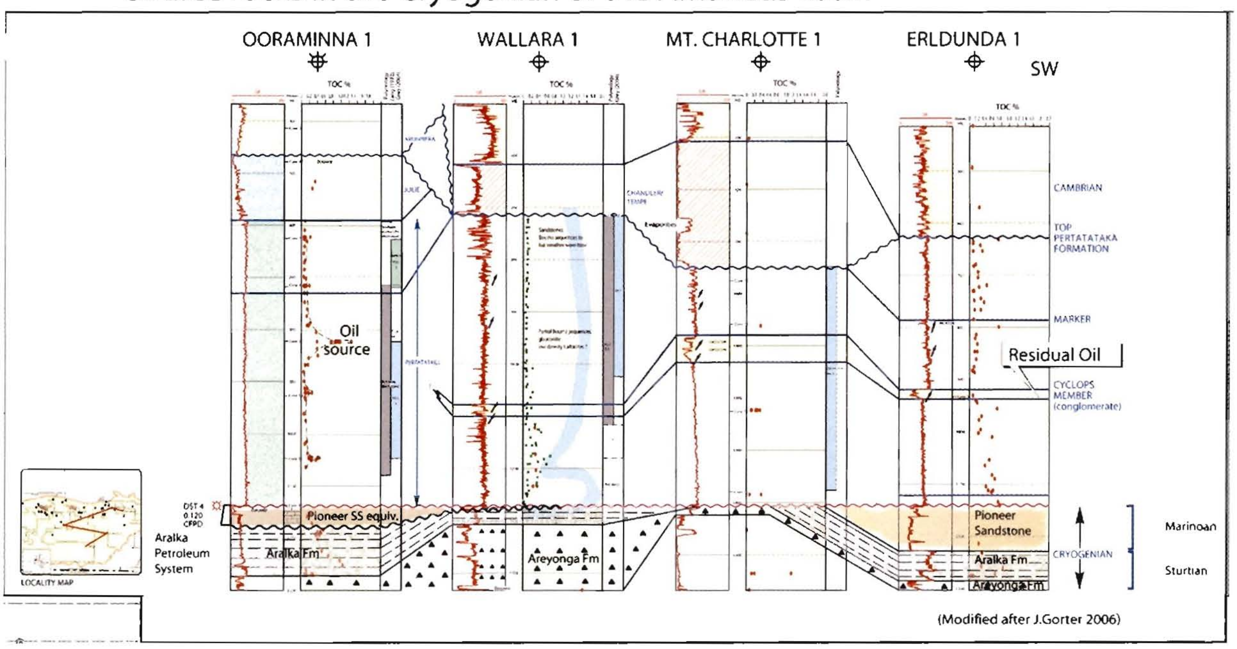


Figure 7. The Aralka and Pertatataka Petroleum Systems- after Gorter et al 2007

New data from stratigraphic drill hole NTGS BRD05-DD01 located in the southwestern portion of the basin has upgraded the hydrocarbon potential of this area (Ambrose, 2006 a and b, Ambrose, 2007). The Pertatataka Formation, although organically lean, is shown to be in the oil window at a depth of 480 m as supported by Tmax data, suggesting basin unroofing in this area. An oil stain was recorded in a small fracture at this depth and this sample, together with a source rock extract from the same zone were submitted for geochemical analysis. New geochemical analytical techniques developed by Dr Jochen Brock, have resulted in the matching of very unusual hydrocarbon signatures from both the source rock extract and the oil stain. The petroleum sample and the sedimentary bitumen share several very unusual characteristics including acyclic isoprenoids >C20 which were unusually abundant and included C40 carotenoids (Dr. J. Brock, pers.com., Ambrose, 2006b). Also present in both samples wre unusual diahopanes and farrihopanes. Furthermore, the hydrocarbon signature compounds, whilst being very unusual, closely match similar Neoproterozoic oils from Oman and Siberia believed to have been derived from a similar stratigraphic interval.

The extent of basin unroofing in the southern Amadeus Basin is uncertain but it is likely Late Neoproterozoic source rocks were generative over a far wider area than previously interpreted (Ambrose, 2006a and b). The Early Cambrian section (Chandler Formation, Giles Creek Dolostone) includes carbonates and shales formed in anoxic environments but there is little geochemical data available and further studies are required.

4) *Ordovician – the Horn Valley Siltstone Petroleum System*

The Horn Valley Siltstone is by far the most important petroleum system in the Amadeus Basin having provided the source for the only commercial oil/gas fields in the basin (Mereenie and Palm Valley). A general description occurs earlier in this volume and previous studies occur in Gorter (1984), Weste (1989), Do Rosario (1991) and Lindsay (1993); a summation of source rock geochemistry occurs in Marshall (2004).

The Horn Valley siltstone comprises mainly anoxic marine shale and lesser carbonate, and has excellent source and seal characteristics, providing top seal to the Pacoota Sandstone reservoir. The sequence lies between two marine sandstones, the Pacoota Sandstone and the Stairway Sandstone, both of which are commercial hydrocarbon reservoirs. The Stokes Siltstone provides top seal to the underlying Stairway Sandstone. A full discussion of these units occurs in Weste (1989).

In a broad sense, maturity trends for the Horn Valley Siltstone are controlled by sedimentary loading contingent on foreland development on the northern basin margin related to the 300-400 Ma Alice Springs Orogeny; the southern limit for hydrocarbon generation is probably adjacent to the central Central Ridge but well control is very sparse.

Maturation Trends / Tectonic Controls

Recent papers by Gibson *et al* (2004, 2007) have reviewed the thermal history of the Amadeus Basin, utilizing new and existing maturity data and Apatite Fission Track Analysis (AFTA). The results indicate that up to four synchronous post–Early Carboniferous cooling episodes occurred in the Amadeus, Georgina and Pedirka basins, and these events were probably even more widespread, but have not been evaluated in other areas. In the northern Amadeus Basin, peak palaeotemperatures associated with each of these events decreased with each progressively more recent episode. In the northern Amadeus Basin, cessation of hydrocarbon generation from the Horn Valley Siltstone (Ordovician), the only known commercial petroleum system, occurred in the Late Carboniferous to Early Permian.

The Amadeus Basin includes four petroleum systems in total, ranging in age from early Neoproterozoic to Ordovician. Maturation distribution for Neoproterozoic petroleum systems, excepting the early Neoproterozoic Gillen Member, were largely controlled by the distribution of foreland sedimentary loading sequences at various times during the basin's history. Severe erosion, ie basin unroofing, has in many instances removed evidence of the loading section, thereby masking maturity trends in source rocks currently at shallow depths (Ambrose 2006a and b, and Young et al, 2007). In the southern Amadeus Basin, maturity data from Wallara-1 and Murphy-1 indicate regional unroofing of the basin, suggesting that hydrocarbon generation from Neoproterozoic successions was more pervasive than previously recognized. For instance, MPI-generated VRo values from Wallara-1 indicate that the Aralka and Bitter Springs formations (Loves Creek Member) lie in the oil window (VRo= 1.1) at current depths of 1300 m. This suggests that a significant portion of the sediment load has been eroded, probably at the end of the Alice Springs Orogeny and later during the Tertiary; this negates earlier notions of increasing maturation from south to north across the basin. In the southwest portion of the basin, oil mature shales near the base of the Pertatataka Formation occur at a depth of 480 m in NTGS stratigraphic drillhole BRD05-DD01, indicating major basin erosion at this location. Similarly, 250 km to the east in Murphy-1, shale in the Bitter Springs Formation shows maturities through the gas window at current depths of less than 3000 m (C Boreham pers com), suggesting unroofing in the southern portion of the basin has regional extent.

On the south-southwestern margin of the basin, intense compression in the Musgrave Block during the Petermann Ranges Orogeny (640-530 Ma) initiated major uplift and erosion at the Proterozoic/Cambrian boundary as north-vergent structures were propagated into the foreland (Hand and Sandiford, 1999). As a result, a very thick section (up to 6000 m) of alluvial sheets and piedmont fanglomerate (Mount Currie Conglomerate; Scrimgeour et al, 1999) prograded northwards into the basin providing the sedimentary load which initiated hydrocarbon maturation in underlying Neoproterozoic source rocks. On the southeast basin margin, orogenesis at this time was relatively subdued and thick clastic wedges are largely missing, being replaced by a slightly younger, early Cambrian evaporite/shale sequence (Chandler Fm). None the less, Neoproterozoic source rocks have reached oil/gas maturity in local topographic/fault defined depressions (Young and Ambrose, 2007) as demonstrated by a small gas flow from the Heavitree Quartzite in Magee-1.

Foreland development along the northern margin of the Amadeus Basin was controlled by major compression during the latter phases of the Alice Springs Orogeny (400-300 Ma), and thick, southward prograding clastic deposits were shed into the basin. Burial under this thick clastic wedge (Pertnjarra Group) pushed the Horn Valley Siltstone through the dry gas window and charged the Palm Valley and Mereenie structures. Basinward (south) of this foreland wedge, the influence of Devonian-Carboniferous loading decreased, enabling oil expulsion from the Horn Valley Siltstone which charged the Mereenie structure and was later partially displaced by gas (Gibson et al, 2004).

Regional tectonic elements have also played a major role in controlling sedimentary patterns and hence maturation trends. The Central Ridge, which has clear basement aeromagnetics expression, effectively divides the basin into northern and southern components. The Erldunda Fault Zone which also dislocates basement, controls the northwest deviation of this ridge (Young and Ambrose, 2007). The ridge effectively partitioned depositional phases into separate sedimentary regimes, and was influential from the early Proterozoic through to the end of the Late Cambrian when the Bloodwood Movement (Delamerian Orogeny) terminated sedimentation (Lindsay, 1993). The Ordovician Horn Valley Siltstone appears to be mature for hydrocarbons north of the Central Ridge while Neoproterozoic peroleum systems were generative both to the north and south of this feature. Also south of the Central Ridge, folding associated with the Peterman Ranges Orogeny and the later Alice Springs Orogeny are largely controlled by regional decollement zones in the Bitter Springs and Chandler Formations, resulting in a dominant east-west structural grain. In contrast, north of the Central Ridge, the current basement topography parallels the Alice Springs Orogeny structural trend, which is variably northeast to northwest (Young and Ambrose, 2007).

Play Types

The most successful play types in the Amadeus Basin are 4-way dip closed overthrust anticlines (Mereenie field, West Walker prospect) and 4-way dip closed anticlines (Palm Valley, Dingo fields). Late Neoproterozoic and Ordovician sections are productive in these structures. Most of the Ordovician structural plays occur north of the Central Ridge and there is considerable remaining oil potential in this area. Neoproterozoic structural closures are valid targets over most of the basin and the relatively shallow depths of some prospects reflects basin unroofing over wide areas.

A sub-thrust play has been tested, and live oil and gas shows were encountered but the existence of a valid trap is doubtful. Additional thrust related traps occur as both hanging- wall and foot-wall plays and Mereenie field is an example of a successful test. The Johnston prospect is an example of a sub-thrust play targeting the Pacoota Sandstone and recent seismic detailing has been undertaken by Central Petroleum. Figure 14 is a composite schematic cross-section halotectonic features and major structuring in the southern Amadeus Basin. (Young al, 2007).

Over 60 new anticlinal structures have been mapped on recently acquired aeromagnetics thereby forgoing the need for regional seismic control in many instances (Figs.15 and 16). Sedimentary horizons with anomously high magnetic susceptibilities occur in the Winnall Beds (G. Wakelin-King, pers.com) and also in oolitic and pisolitic ironstones in the Ordovician section (Gorter, 1991). These present outstanding aeromagnetic signatures of the folded geological terrain over much of the Amadeus Basin and render aeromagnetics a very powerful exploration tool, in some cases dispensing with the need for regional seismic.

At this stage of exploration, a plethora of structural plays remain undrilled relegating most stratigraphic and combination plays to secondary status. However Weste (1994) and Young et al, (2007) describe the subsalt potential of the Heavitree Quartzite/ Gillen Member petroleum system in the southern portion of the basin, including a large stratigraphic play immediately south of Murphy-1 (Mt. Kitty Prospect) . The Heavitree Quartzite will probably rely on fracture porosity in this area, but this hurdle may be offset by the size of the play and its possible duplication nearby; potential unrisked gas-in-place exceeds 3 TCF (Young et al, 2007).

Halotectonics

There are numerous examples of salt related hydrocarbon plays, and salt halotectonics in the basin is discussed in detail by Dyson and Marshall (2007) . They predict a halotectonic basin where sedimentation occurred dominantly in a series of salt nappe complexes formed under the influence of gravity gliding, gravity spreading and salt withdrawal. Both the Gillen and Chandler salt successions have undergone halokinesis forming a myriad of potential petroleum traps (Fig.6).

Seismic Studies

The seismic interpretation report undertaken by Young Geoconsultants Pty Ltd (2004) brought all data held in the NTGS data repository together, and as a result, NTGS can now provide all seismic data available, interpreted at key stratigraphic horizons, which has now been incorporated into a Kingdom Suite project, and a substantial report to the public. This study was also presented at the CABS Symposium in 2005. These data and interpretations provide an extremely comprehensive base for explorers operating in the Amadeus Basin. A detailed paper will be published in the CABS proceedings volume later in 2007. The study also made available a regional seismic shot point base map for the entire basin. The highlight of the study was the elucidation of the highly prospective Heavitree Quartzite sub-salt play and the definition of multi-TCF structural /stratigraphic plays at this level in the southern Amadeus Basin.

In late 2006-early 2007, Central Petroleum acquired 473 km of new seismic over the Mt Kitty, Magee, Waterhouse and Ooraminna leads. At time of publication the results of these surveys remained confidential.

Consultants Overview and Resource Assessment

A major overview of the basin, sponsored by NTGS and several operators, reviewed international analogies, salient aspects of the exploration history, and also both risked and unrisked petroleum reserve potential. The study was carried out by consultancy group, Fault Seal and was published as NTGS Record 2005-004 (Warburton *et al* 2005). The main conclusions are summarized below:

1) The Amadeus Basin is a producing basin, which by world standards is vastly underexplored.
2) Exploration statistics are favourable: 33 exploration wells have yielded 2 oil/gas discoveries, 5 technical gas discoveries which flowed gas to surface, and 13 exploration wells which were drilled off-structure.
3) **The commercial success rate is 11%**
4) **The technical success rate is 40%**
5) Reservoir quality and trap definition are major exploration hurdles.
6) Approximately 300 mmbl BOE have been discovered by 33 exploration wells.
7) Exploration technology dates back to the 1980s and the basin is a generation behind modern exploration methodologies. Tight 2D seismic grids are generally absent and there are no 3D grids in the basin.
8) Exploration finding costs are low at between US$0.5–1.3 per BOE.
9) Assuming a success rate of 11% for existing leads and prospects, then the risked "yet-to-find" reserves stand at 634 mmbl BOE or 3.9 TCF of gas. This also assumes all leads and prospects contain deterministic potential hydrocarbon volumes.
10) Five petroleum systems are recognized in the basin. The Ordovician Horn Valley Siltstone is most prospective, yielding 42% of the potential YTF reserves. The Gillen Member Petroleum System may contain 25% of future reserves and commercial viability would be enhanced by high Helium contents (eg Magee-1 gas flow comprised 6% Helium).
11) High-density 3D seismic is needed to optimize pre-drill locations.
12) An analogous petroleum province in Pakistan suggests the application of 3D seismic may provide the breakthrough to define and deliver remaining reserves.

CONCLUSIONS

The Amadeus Basin is highly prospective for both oil and gas and has three proven petroleum systems. These are the Gillen Member (gas/Helium- Magee-1), Pertatataka Formation (gas- Dingo-1, Ooraminna-1. Orange-1) and the Horn Valley Siltstone (gas/oil- Mereenie, Palm Valley respectively). Regional salt seals are locally very thick and occur at the level of the upper Gillen Member and Chandler Formation. Additional seals relate to thick shales at the level of the Aralka Formation, Pertatataka Formation, ? Giles Creek Dolomite, Horn Valley Siltstone and Stokes Siltstone. For most of the Neoproterozoic section, reservoir quality hinges on fracture porosity and this provides the main risk in the basin at this stratigraphic level. This is especially true for the Heavytree Quartzite which is to be targeted as a gas/Helium play in large structural-stratigraphic traps located in the southern half of the basin. New technology, particularly 3D seismic will probably be fundamental to exploration success.

The Ordovician petroleum system (Horn Valley Siltstone) is responsible for the charge of the only two commercial fields in the basin, ie Mereenie (oil/gas) and Palm Valley (gas) fields. It defies geological and statistical theory to assume that this system has only charged one significant oil field (Mereenie - 18 mmbl oil reserves, 333 BCF gas reserves) and one gas field (Palm Valley – 177 BCF gas reserves). The fact that the fields are filled to spill and occur in a highly structured terrain (north of the Central Ridge) which predates hydrocarbon migration suggests additional focused exploration should identify new oil/gas pools.

Of the three viable petroleum systems operating in the Amadeus Basin, the Horn Valley Siltstone (Ordovician) and Gillen Member (Neoproterozoic) are most important. The Sturtian Aralka petroleum system has been underestimated in the past and is far more wide spread than previously thought.

The Horn Valley Siltstone is probably only generative north of the Central Ridge and complacency regarding its remaining potential there is misplaced. This petroleum system is still only sparsely explored considering: 1) only one play type (ie 4 way dip closures) has been addressed; 2) existing seismic grids are very primitive and drilling has been sparse; and 3) only two large commercial oil and gas fields have been discovered and there have been few attendant small- to moderate-sized oil discoveries, as one would predict. The northern part of the basin is areally extensive and structurally complex and it is believed the incumbent Ordovician petroleum (oil) system has been vastly undersold and retains considerable potential for moderate-size oil and wet gas fields.

The Gillen Member of the Bitter Springs Formation provides the second best target petroleum system in the basin and although gas charge was probably widespread there may be potential for oil near the basin's margins. Helium deposits in the target reservoir, the Heavitree Quartzite, would probably be dependant on deliverability from fracture porosity, but will provide commercial options in the case of a discovery. Regional blanket seal, provided by Gillen Member salt, together with the fact that multi-TCF-sized leads have already been defined, but await seismic detailing, both point to a bright future for this play.

Two upper Neoproterozoic petroleum systems, the Pertatataka Formation and Aralka Formation appear to be largely gas prone, but data is very limited. Residual oil stains below the Chandler Formation salt seal in Finke-1 hint at the possibility of oil charge from this part of the section.

New aeromagnetics data over the basin defines almost all the antiformal structures in the region, as well as being definitive of basement topography, thus largely negating the need for expensive regional seismic grids. Future exploration will require tight 2D/3D grids to confirm closure and a crestal location. Structural/stratigraphic plays will emerge as more data is acquired, hopefully verifying some of the very large leads already defined near the basin's southern margin.

There is considerable existing infrastructure and burgeoning resource projects in the Northern Territory will provide future gas markets. In the case of large gas discoveries, there will be: 1) potential to tie into the national gas grid via Moomba; 2) potential to provide feedstock for gas-to-liquids production; and 3) the possibility of contributing to future LNG exports from Darwin.The Palm Valley to Darwin gas pipeline and the new transcontinental railway line provide key infrastructure, which will improve the viability of upcoming resource projects throughout the Northern Territory.

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