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Chapter 15: McArthur Basin

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Chapter 15: McARTHUR BASIN

M Ahmad, JN Dunster and TJ Munson

INTRODUCTION

The Palaeo- to Mesoproterozoic McArthur Basin is exposed over an area of about 180 000 km^2 in the northeastern NT. It unconformably overlies Palaeoproterozoic metamorphosed and deformed rocks of the Pine Creek Orogen (PCO) to the west, the Murphy Province to south and the Arnhem Province to the northeast (**Figure 15.1**). To the southeast, the McArthur Basin succession extends to the Isa Superbasin in Queensland. The Murphy Inlier of the Murphy Province was probably a palaeogeographical high separating the McArthur Basin from the South Nicholson Basin and Lawn Hill Platform (Plumb and Wellman 1987, Wygralak *et al* 1988). Phanerozoic strata of the Georgina, Carpentaria and Arafura basins unconformably overlie the McArthur Basin succession. McArthur Basin strata apparently continue beneath the Georgina and onshore Carpentaria basins and are probably continuous with that of the Tomkinson Province of the Tennant Region.

The basin has been modelled as several north-trending asymmetric rifts or grabens separated by northwest-trending faults and transverse ridges. Previous workers (Plumb and Derrick 1975, Plumb *et al* 1980, 1990, Plumb and Wellman 1987) identified two north-trending troughs (Walker and Batten troughs), separated by the east-trending Urapunga Tectonic Ridge (**Figure 15.1**). Tectonically 'stable' shelves to the east and west flanked these troughs. The Caledon Shelf was located to the east and the Arnhem Shelf to the west of the Walker Trough, whereas the Batten Trough was flanked by the Wearyan Shelf to the east and Bauhinia Shelf to the west. However, more recent studies (Rawlings *et al* 1997, Rawlings 1999, Rawlings *et al* 2004) have presented evidence suggesting that the 'troughs' represent zones of faulting rather than depositional features and accordingly have renamed these the Walker Fault Zone (WFZ) and Batten Fault Zone (BFZ). The Urapunga Tectonic Ridge has similarly been reinterpreted as a major fault zone. Pietsch *et al* (1991) proposed that McArthur

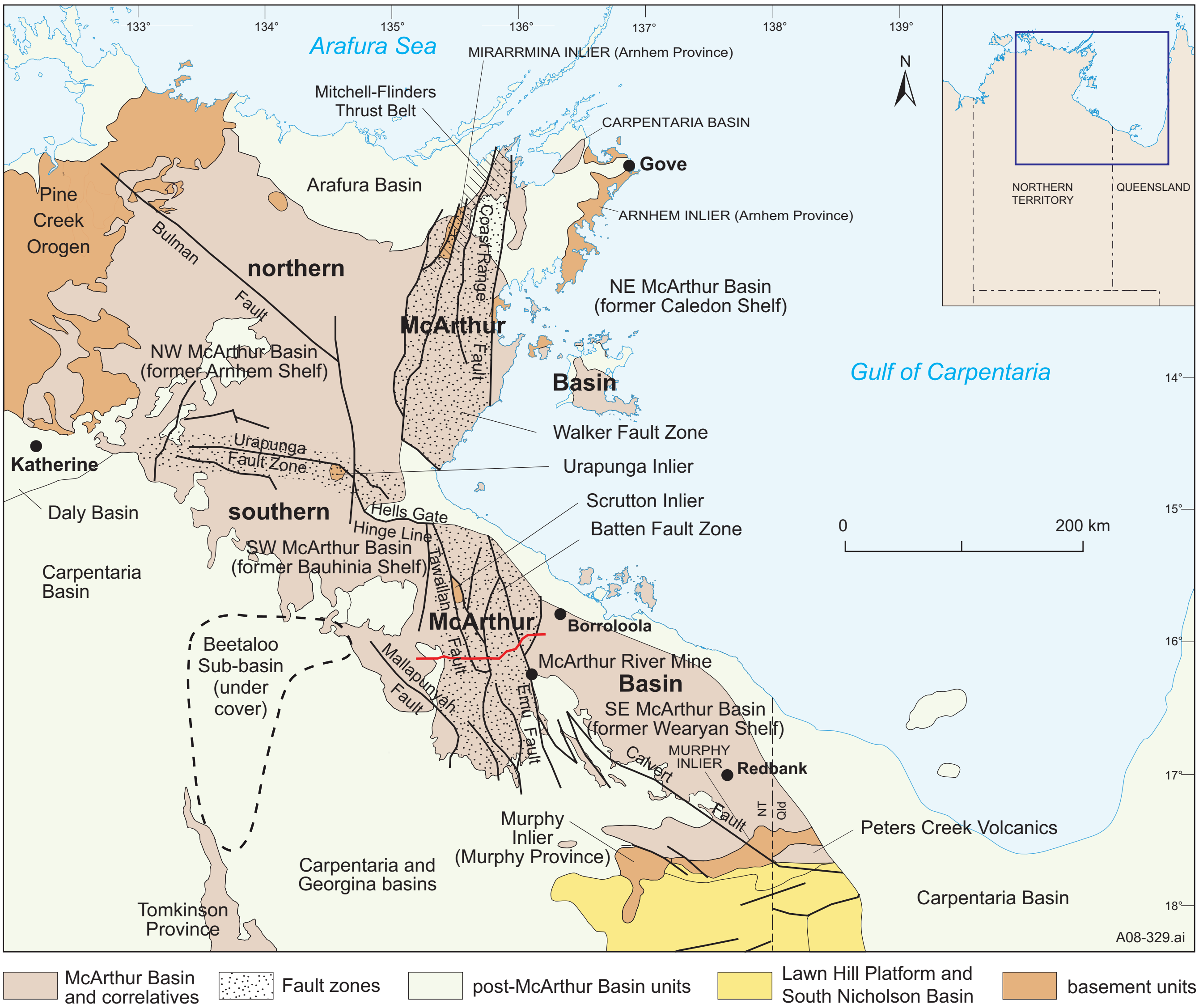

Figure 15.1. Geological setting of McArthur Basin (slightly modified after Rawlings 1999). Position of southern McArthur Basin deep seismic line (Rawlings *et al* 2004) shown by solid red line.

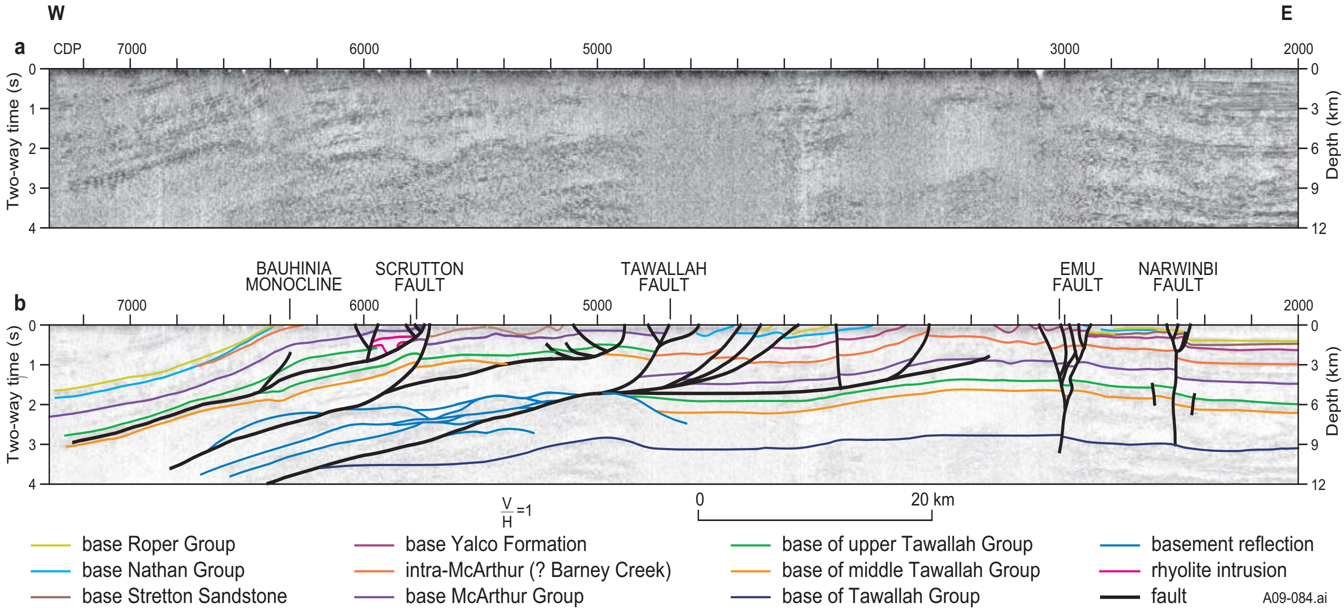

Figure 15.2. Interpreted seismic data for McArthur Basin deep seismic line 02GA-BT1 (after Rawlings *et al* 2004: figure 9). Position of line shown in **Figure 15.1**.

Group succession in the Batten Fault Zone was thicker as the result of differential uplift along the margins of the fault zones, but Rawlings *et al* (2004) presented outcomes of a deep seismic reflection survey that showed that the entire succession is essentially horizontal and about 8 km thick (**Figure 15.2**). There was no evidence in the seismic data for the Batten 'Trough' to be a separate depocentre, with the sedimentary succession appearing to continue in both directions away from the implied boundaries of the 'trough'.

This seismic data argues against dividing the McArthur Basin into depositional 'troughs' and 'shelves' and the traditional 'shelf' names are therefore here abandoned. For descriptive purposes, these terranes are instead referred to according to their geographic position within the basin; thus, the former Arnhem, Caledon, Bauhinia and Wearyan shelves equate to the northwestern, northeastern, southwestern and southeastern McArthur Basin, respectively. Areas north and south of the Urapunga Fault Zone are referred to herein as the northern and southern McArthur Basin (**Figure 15.1**).

PALAEOPROTEROZOIC

The McArthur Basin contains an unmetamorphosed and relatively undeformed succession of sedimentary and minor volcanic rocks with a preserved thickness of up to 10 km (Plumb and Wellman 1987). In the southern McArthur Basin, this succession has been subdivided, in ascending stratigraphic order, into the Tawallah, McArthur, Nathan and Roper groups. In the northern McArthur Basin, the succession comprises, in ascending order, the Groote Eylandt, Katherine River, Donydji, Parsons Range, Habgood, Balma, Mount Rigg, Nathan and Roper groups. In both areas, groups are separated by regional unconformities.

There have been two broad approaches to subdividing the successions of the McArthur Basin and correlative terranes (Isa Superbasin, Lawn Hill Platform, Murphy Province) and a comparison of the previous terminology is given in **Figure 15.3**. Using sequence stratigraphy,

<table>
<tr><th>Rawlings (1999)</th><th>Jackson et al (1999, 2000)</th></tr>
<tr><td>Wilton Package
(Roper Group)</td><td>Roper Superbasin</td></tr>
<tr><td>Favenc Package
(Mount Rigg/Nathan groups)</td><td rowspan="2">Isa Superbasin</td></tr>
<tr><td>Glyde Package
(McArthur, Vizard, Balma and Habgood groups)</td></tr>
<tr><td>Goyder Package
(Parsons Range, upper Spencer Creek groups)</td><td rowspan="2">Calvert Superbasin</td></tr>
<tr><td rowspan="2">Redbank Package
(Katherine River, Tawallah, Donydji, lower Spencer Creek groups)</td></tr>
<tr><td>Leichhardt Superbasin</td></tr>
<tr><td>basement</td><td>basement</td></tr>
</table>

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Figure 15.3. Subdivisions of McArthur Basin succession by Rawlings (1999) and Jackson *et al* (1999, 2000).

Jackson *et al* (1999, 2000) and Southgate *et al* (2000) subdivided the Palaeoproterozoic of the region into four first-order sequences, the Leichhardt, Calvert, Isa and Roper superbasins, most of which have been subdivided into formally defined and named second- and third-order sequences. An alternative scheme subdivided the entire McArthur Basin succession into five basin-wide, non-genetic units, originally referred to as 'supersequences' (Rawlings *et al* 1997), but later renamed 'packages' (Rawlings 1999). These depositional packages are disconformity or unconformity bounded and each is characterised by similarities in age, stratigraphic position, lithofacies composition, style and composition of volcanism, and

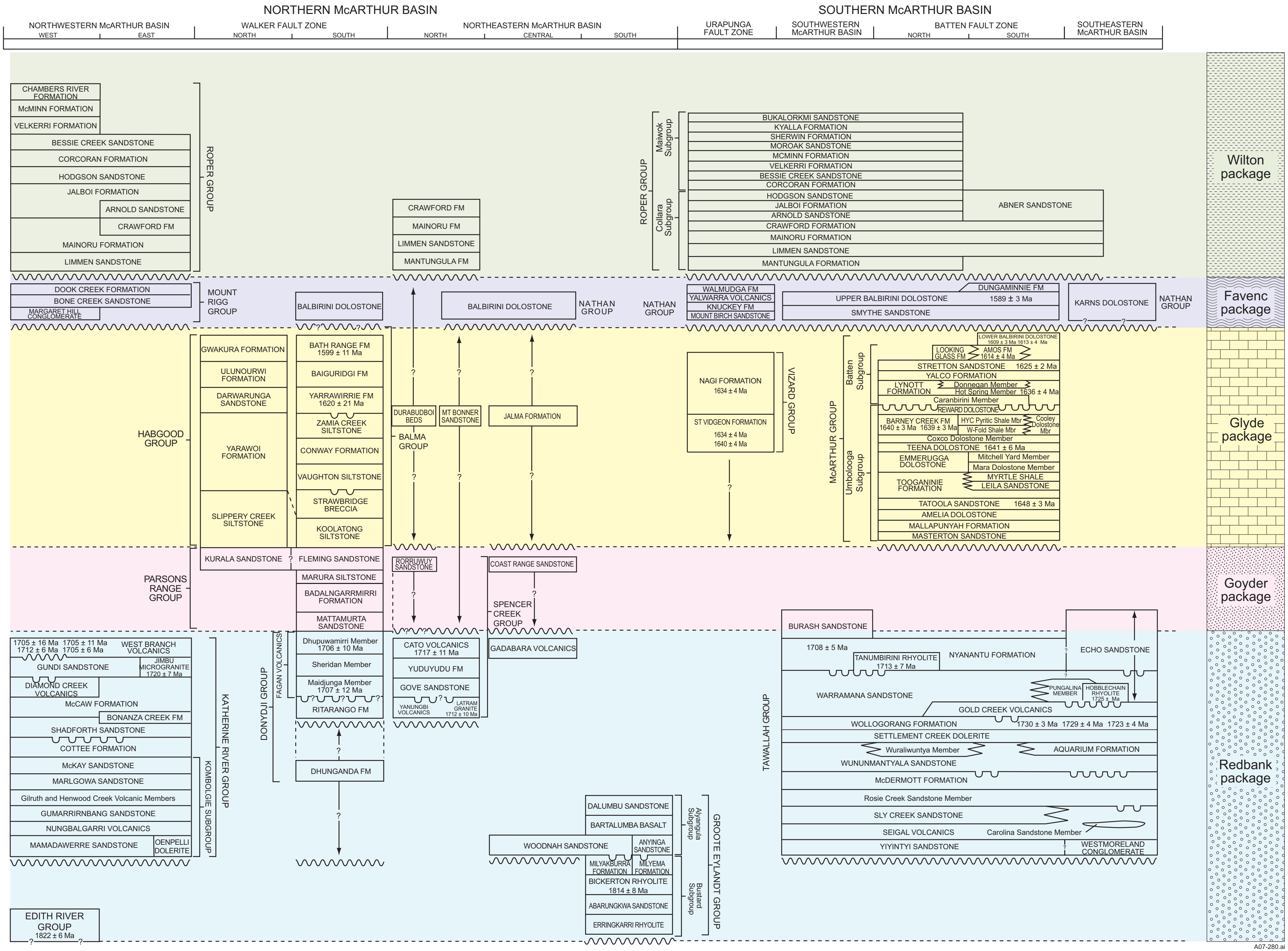


Figure 15.4. Lithostratigraphic correlations of various rock units of McArthur Basin (after Rawlings 1999).

basin-fill geometry, as shown in **Figure 15.4**. **Figure 15.5** shows their spatial distribution across the McArthur Basin.

Both the package and sequence stratigraphic approaches support the superbasin concept in the sense of Walter *et al* (1995). This concept proposes that large-scale stratigraphic packages were once continuous or contiguous with other Proterozoic depocentres. To date, all authors agree that cyclicity in the McArthur succession was driven predominantly by episodic tectonism.

Redbank Package

The Redbank Package (Rawlings 1999, 2007) or Supersequence 1 (Rawlings *et al* 1997) represents the basal succession of the McArthur Basin, and includes the Donydji, lower Spencer Creek and Groote Eylandt groups in the northeast, the Katherine River Group in the northwest, and the Tawallah Group in the southeast. It is correlated with the basal sandstone successions of the Tomkinson Province (Tennant Region) and Birrindudu Basin, and corresponds to the Ᵽ5–Ᵽ6 subdivisions of Ahmad (2000). Together with the overlying Goyder Package, the Redbank Package is equivalent to the Calvert Superbasin succession (Southgate *et al* 2000, Jackson *et al* 2000). It is characterised by shallow-marine to fluvial sandstone, and lesser volcanic rocks and shale, and is up to 6 km thick.

The oldest (1815 Ma) Bustard Subgroup of the Groote Eylandt Group in the southern and central parts of the northeastern McArthur Basin (Pietsch *et al* 1997) is likely to be older than the rest of the Redbank Package, and includes possible correlatives of the Edith River/El Sherana groups in the Pine Creek Orogen.

The lower two-thirds of the Redbank Package is represented by a marginally younger, 2–4 km-thick, monotonous succession of fluvial to intertidal sandstone, with an intervening, regionally extensive, flood basalt unit, and an upper shallow-marine shale-carbonate unit. Its components include the lower to middle Katherine River and Tawallah groups, and the Alyangula Subgroup of the Groote Eylandt Group. It is apparently absent on the southern and central parts of the northeastern McArthur Basin.

The topmost succession represents an assemblage of sandstone, basalt, rhyolite, conglomerate, dolostone and shale. It includes the upper Katherine River and Tawallah groups, the 2 km-thick sandstone-shale-bimodal volcanic Ritarango Formation and Fagan Volcanics (Donydji Group), and igneous units of the Spencer Creek Group. Comagmatic subvolcanic plutons (eg Latram Granite) and numerous thin dykes of microgranite are associated with the volcanics in several parts of the basin (Rawlings *et al* 1997).

The Donydji, Spencer Creek, Katherine River and Tawallah groups all have well defined minimum ages of 1710 Ma, but poorly constrained maximum ages.

Groote Eylandt Group

Outcrops of the Groote Eylandt Group, **Table 15.1**) in the northeastern McArthur Basin comprise flat-lying to gently

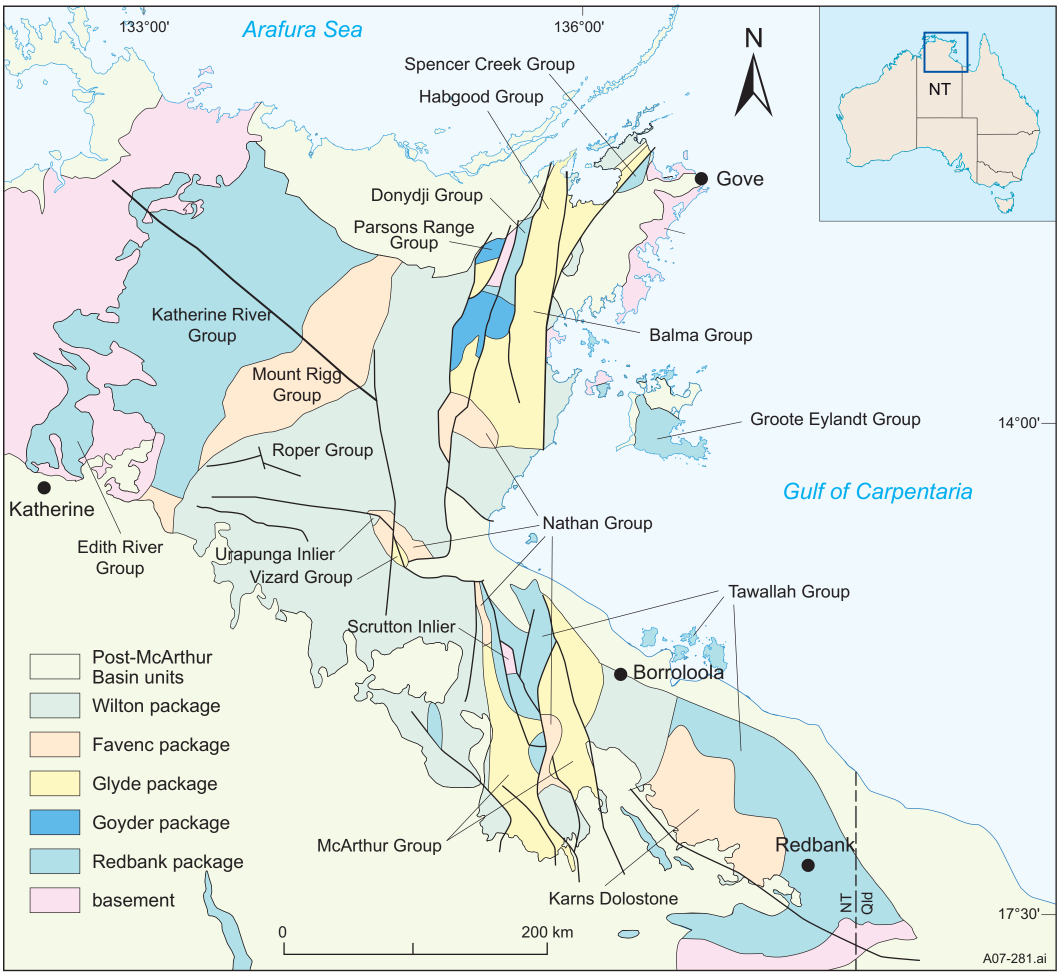


Figure 15.5. Spatial distribution of stratigraphic packages across McArthur Basin (slightly modified after Rawlings 1999).

dipping sandstone and conglomerate interbedded with felsic and mafic volcanic rocks. The preserved thickness is extremely variable, from a few tens of metres on some islands, to in excess of 1 km on southern Groote Eylandt.

The *Bustard Subgroup* is separated from the overlying Alyangula Subgroup by an erosive disconformable contact (Rawlings *et al* 1997). It comprises fluvial sandstone, conglomerates and subaerial felsic volcanic rocks. The basal *Erringkarri Rhyolite* is mainly cryptocrystalline and porphyritic, but in places may be aphanitic. It was emplaced as large domes and coulées in a dry terrestrial environment. A short period of weathering and erosion preceded deposition of the overlying *Abarungkwa Sandstone*, a fluvial sandstone-conglomerate unit estimated to be 100–150 m thick. This is overlain by the *Bickerton Rhyolite* (**Figure 15.6**), which consists of porphyritic rhyolite to rhyodacite, and which has yielded a U-Pb SHRIMP zircon age of 1814 ± 8 Ma (Pietsch *et al* 1997). This unit is likely to be a correlative of the Edith River Group in the Pine Creek Orogen. The overlying *Milyakburra Formation* comprises cobble and boulder conglomerate, locally interbedded with granule conglomerate and coarse-grained lithic sandstone (**Figure 15.7**). This formation is interpreted to be the product of deposition in a high-energy fluvial and alluvial fan environment, with sediments sourced from elevated areas to the west and north (Rawlings *et al* 1997). It is correlated with the *Milyema Formation* in the Groote Eylandt region, which also represents a succession of fluvial conglomerate and coarse-grained pebbly sandstone (Pietsch *et al* 1997).

The *Alyangula Subgroup* comprises fluvial sandstone, conglomerates and basaltic volcanic rocks and forms most of Groote Eylandt, Connexion Island and the southeastern part of Bickerton Island. On Groote Eylandt, the *Alyinga Sandstone* comprises about 300 m of fluvial to marginal-marine cobbly sandstone and conglomerate, containing

Unit, thickness, age	Lithology	Depositional environment	Stratigraphic relationships
ALYANGULA SUBGROUP			
Dalumbu Sandstone 500–1000 m exposed on Groote Eylandt	Sandstone, white, coarse-grained, cross-bedded, pebbly (mainly quartz), granule lenses, quartz-rich; sandstone, white to pink, medium-grained, cross-bedded, quartz-rich; Basalt, very weathered and ferruginised.	Mostly braided fluvial, with minor marine incursion. Subaerial basalt lava flow.	Conformably overlies Bartalumba Basalt. Unconformably overlain by Cretaceous rocks and Cenozoic sediments.
Bartalumba Basalt 200–400 m in northern part of Groote Eylandt	Basalt and microdolerite, massive to amygdaloidal.	Subaerial lava flows.	Lower contact not exposed, but no evidence of disconformity. Upper contact concordant with Dalumbu Sandstone.
Alyinga Sandstone Approximately 300 m in type area	Sandstone, medium- to coarse- grained, very large trough cross-beds in lower part. Basal polymict granule to boulder conglomerate and pebbly and cobbly sandstone.	Mostly high-energy braided fluvial, with minor marginal marine.	Apparently disconformable on Milyema Formation Interpreted lateral equivalent of Woodah Sandstone.
Woodah Sandstone Maximum thickness 50–60 m exposed at type section	Medium to coarse grained sandstone, cobble to boulder conglomerate, mudstone.	Braided fluvial.	Unconformably overlies Grindall Formation and Bukudal Granite. Interpreted lateral equivalent of Alyinga Sandstone.
BUSTARD SUBGROUP			
Milyema Formation 50 m	Basal granular to boulder conglomerate; pebbly lithic sandstone, cross-bedded	High energy, braided, fluviatile, shallow marine in the upper part	Correlated laterally with the Milykaburra Formation to the east.
Milyakburra Formation Maximum of 40 m in incomplete sections	Cobble and boulder conglomerate, matrix- to clast-supported, polymict, coarse sand to granule matrix, massive to cross-bedded; locally interbedded with granule conglomerate and medium- to very coarse-grained lithic sandstone.	High-energy fluvial and alluvial fan.	Erosional contact with Bickerton Volcanics. Unconformable on Abarungkwa Sandstone. Laterally correlated with Milyema Formation.
Bickerton Rhyolite Maximum estimated thickness 150–250 m 1814 ± 8 Ma	Rhyolite, red, porphyritic (K-feldspar).	Large subaerial lava domes and coulées.	Intrudes and lies conformably on Abarungkwa Sandstone. Contact with overlying Milyakburra Formation is erosional.
Abarungkwa Sandstone Most complete section estimated to be 100–150 m	Sandstone, white, coarse- to very coarse-grained, cross-bedded, pebbly, quartz-rich (lithic at base); granule conglomerate, quartz-rich; pebble and cobble conglomerate, polymict; minor medium-grained quartz sandstone.	High-energy braided fluvial.	Overlies Erringkarri Rhyolite with an erosional contact and unconformably overlies Grindall Formation. Overlain conformably by Bickerton Rhyolite or unconformably by Milyakburra Formation.
Erringkarri Rhyolite +20 m	Rhyolite, dark red, variably porphyritic (K-feldspar).	Large subaerial lava domes and coulées.	Inferred to unconformably overlie Grindall Formation and granite. Overlain by Abarungkwa Sandstone with erosional contact.

Table 15.1. Stratigraphic succession of the Groote Eylandt Group modified from Pietsch *et al* (1997) and Haines *et al* (1999).

clasts from the underlying sandstone units. It defines the base of the Alyangula Subgroup. Elsewhere, the *Woodah Sandstone*, comprising a 50–60 m-thick succession of fluvial conglomerate, sandstone and mudstone, represents the base of the succession (**Figure 15.8**). These two units are interpreted to be laterally equivalent (Pietsch *et al* 1997). The *Bartalumba Basalt* overlies the Alyinga Sandstone and consists of up to 400 m of deeply weathered, red and black, subaerial vesicular and amygdaloidal basalt, and microdolerite. The *Dalumbu Sandstone* conformably overlies the Bartalumba Basalt and comprises a 500–1000 m-thick fluvial succession of pebbly sandstone with minor interbeds of finer-grained non-pebbly sandstone. It also includes a thin unit of weathered basalt.

Donydji Group

The Donydji Group is a succession of dominantly fluviatile to shallow-water, coarse-grained, siliciclastic sedimentary rocks and felsic and mafic igneous rocks outcropping in the southern Walker Fault Zone (**Table 15.2**). It is inferred to unconformably overlie the Mirarrmina Complex and is in turn conformably overlain by the Parsons Range Group. Outcrop is restricted to the Mitchell Ranges. Structural repetition of some formations has complicated the calculation of total thickness, which is probably in the order of 2000–3000 m. The age is constrained by concordant igneous units at the top of the group (Maidjunga and Dhupuwamirri members), dated at 1710 Ma. The succession is divided into three formations, the Dhunganda and Ritarango formations and Fagan Volcanics (Rawlings *et al* 1997).

Ductile and brittle deformation has greatly modified the original fabrics of many rocks in the Donydji Group, imposing foliations, fracture cleavages, jointing, silicification and quartz veining on the rocks. This deformation resulted from a localised episode of wrench faulting and thrusting.

The *Dhunganda Formation* is a succession of strongly deformed sandstone, and lesser felsic and mafic igneous rocks, volcaniclastic rocks and mudstone. The lower half of the formation comprises mainly lithic sandstone, deposited in a fluvial or possibly deltaic environment. It is locally pebbly, particularly near the base, and the succession tends to fine upwards. The upper half of the formation comprises white, fine- to medium-grained quartzic and lithic sandstone, felsic (rhyolite) and mafic igneous rocks (dolerite and microdolerite), volcaniclastic rocks, mudstone/fine-grained ferruginous sandstone, and undifferentiated sheared rocks, deposited in moderately deep-water to shallow and emergent environments (Rawlings *et al* 1997). The *Ritarango Formation* is a succession of mildly deformed coarse-grained (partly conglomeratic) fluvial lithic sandstone with minor mudstone and volcaniclastic rocks. It is intruded by a large number of rhyolite and basalt dykes and sills. The *Fagan Volcanics* conformably overlie the Ritarango Formation and comprise a 1000–1200 m-thick succession of felsic and mafic igneous rocks, sandstone, mudstone and minor conglomeratic and volcaniclastic rocks. The bottom and top parts of the Fagan Volcanics have been dated using U-Pb zircon SHRIMP geochronological methods at 1707 ± 12 and 1706 ± 10 Ma, respectively (Page *et al* 2000). Rawlings *et al* (1997) divided this unit into three members; these are, in ascending order, the igneous-dominated Maidjunga Member (mainly rhyolitic), the exclusively sedimentary Sheridan Member (mainly a sandstone-mudstone succession), and the mixed sedimentary-igneous Dhupuwamirri Member (**Figure 15.9**).

Katherine River Group

The Katherine River Group outcrops extensively in the northeastern McArthur Basin (**Figure 15.1**) and

Figure 15.6. Jointed rhyolite outcrops of Bickerton Rhyolite, South Bay, Bickerton Island (53L 529000mE 8473000mN, after Haines *et al* 1999: plate 2).

Figure 15.7. Boulder conglomerate of Milyakburra Formation, southern Bickerton Island (53L 530500mE 8470500mN, after Haines *et al* 1999: plate 4).

Figure 15.8. Outcrops of Woodah Sandstone unconformably overlying Bukudal Granite (bench in foreground) at its type locality on Morgan Island (53L 618300mE 8510000mN, after Haines *et al* 1999: plate 5).

comprises sandstone with volcanic intervals in the lower part. It is lithostratigraphically equivalent to the Tawallah and Donydji groups. Walpole (1958) originally recognised two formations, the Edith River Volcanics and Kombolgie Formation, but the former has since been raised to group status within the underlying Pine Creek Orogen succession. Ruker (1959) and Randal (1963) subdivided the Katherine River Group into several units. Walpole *et al* (1968) revised these units and identified several formations. Carson *et al* (1999) subsequently identified three sandstone formations and volcanic members within the Kombolgie Formation and revised the name to Kombolgie Subgroup. The stratigraphic succession is given in **Table 15.3**.

The *Kombolgie Subgroup* comprises a succession of essentially fluvial sandstone (Mamadawerre Sandstone, Gumarrirnbang Sandstone, Marlgowa Sandstone and McKay Sandstone) and extrusive volcanic units (Nungbalgarri Volcanics and Gilruth Volcanic Member). It forms the spectacular escarpment country of the Arnhem Land Plateau (**Figure 15.10**). The age of the Kombolgie Subgroup is constrained by the underlying 1830–1820 Ma Edith River Group and the younger Oenpelli Dolerite (1729 Ma), which intrudes the subgroup. The lowermost unit, the *Mamadawerre Sandstone*, is essentially a fine- to coarse-grained, medium to thickly bedded, white to grey quartz sandstone. Trough cross-bedding dominates the lower part of the succession, with large-scale trough beds at the base. Palaeocurrent directions indicate a westerly or southwesterly source (Carson *et al* 1999). The *Nungbalgarri Volcanics* is a recessive formation that conformably separates the Mamadawerre and Gumarrirnbang sandstones. It is estimated to be 60 m thick and is dominantly a fine-grained equigranular

Unit, thickness, age	Lithology	Depositional environment	Stratigraphic relationships
Gadabara Volcanics 50 m	Felsic igneous rock; volcanic sandstone and breccia.	Lavas and talus deposited into shallow-water to emergent environment.	Intrude and disconformably overlie Woodah Sandstone. Unconformably overlain by Coast Range Sandstone.
DONYDJI GROUP 2000–3000 m			
Fagan Volcanics 1000–1200 m			
Dhupuwamirri Member 450–550 m 1706 ± 10 Ma	Rhyolite; volcaniclastic mudstone, sandstone and breccia; dolerite, basalt and hybrid igneous rocks.	Sediments are shallow water low-energy. Igneous rocks are extrusive and high-level intrusive.	Conformable over Sheridan Member and is conformably overlain by Mattamurta Sandstone.
Sheridan Member) 250–400 m	Sandstone, interbedded with mudstone; local volcaniclastic breccia, conglomerate and sandstone	Shallow water, low– to moderate-energy setting (lacustrine or fan-delta).	Conformable over Maidjunga Member. Overlain conformably by Dhupuwamirri Member.
Maidjunga Member 150–250 m, locally removed 1707 ± 12 Ma	Rhyolite; minor volcaniclastic sandstone and mudstone; locally foliated and sheared.	Sediments are shallow-water low-energy. Igneous rocks are extrusive and high-level intrusive	Lies with conformity or mild disconformity on the Ritarango Formation. Overlain conformably by Sheridan Member.
Ritarango Formation 500–1500 m	Sandstone; minor volcaniclastic sandstone; minor mudstone; locally foliated and sheared.	Mostly shallow-water high-energy fluvial and lesser low-energy deltaic.	Possibly unconformably overlies Dhunganda Formation and is conformably to disconformably overlain by Fagan Volcanics.
Dhunganda Formation >500 m	Sandstone, mudstone, felsic-mafic-hybrid igneous rocks, volcaniclastic rocks.	Lower part fluvial to shallow-water deltaic. Upper part ranges from alluvial to moderately deep-water lacustrine.	Overlies Mirarrmina Complex with apparent angular unconformity. Possibly unconformably overlain by Ritarango Formation.

Table 15.2. Stratigraphic succession of the Donydji Group and Gadabara Volcanics after Rawlings *et al* (1997).

Figure 15.9. Contorted flow banding in rhyolite of Dhupuwamirri Member of Fagan Volcanics, south of Koolatong River (53L 543000mE 8551000mN, after Haines *et al* 1999, plate 8).

Figure 15.10. Kombolgie Subgroup escarpment in Kakadu National Park, near Mount Brockman (53L 273000mE 8610000mN).

basalt. The basalt is largely subaerial, but some pillow structures suggest localised subaqueous extrusions. The *Gumarrirnbang Sandstone* is predominantly a fine-to medium-grained, medium to thickly bedded, pink-grey to white quartz sandstone, deposited in a fluvial, braided river environment. Palaeocurrent directions indicate a source area to the south, which contrasts with a westerly source for the Mamadawerre Sandstone. The *Gilruth Volcanic Member* is a 5 m-thick band of tuffaceous siltstone, tuff, banded quartz-jasper and amygdaloidal and vesicular basalt, assumed to be a subaerial in origin. It corresponds to a distinct, narrow, high uranium and thorium pattern on the radiometric image. The *Marlgowa Sandstone* conformably overlies the Gumarrirnbang Sandstone and comprises medium-grained to granular, thickly to very thickly bedded white-grey quartz sandstone, with some coarse-grained to pebbly bands and interbeds of ferruginous sandstone. This succession is interpreted to have been deposited under tidal influences.

The upper Katherine River Group is divided into nine formations and mainly comprises sandstone, and minor dolostone and mudstone. The *McKay Sandstone*, at the base of this succession, could be a lateral equivalent of the ferruginous facies of the upper Marlgowa Sandstone. This unit conformably overlies the Marlgowa Sandstone and comprises fine- to medium-grained, white-grey quartz sandstone interbedded with red-brown to purple, recessive ferruginous sandstone with a clay matrix. It is considered to have been deposited in a shallow-marine tidal environment (Carson *et al* 1999). The *Cottee Formation* is

Unit, thickness, age	Lithology	Depositional environment	Stratigraphic relationships
KATHERINE RIVER GROUP			
West Branch Volcanics 1500–2000 m ca 1705 Ma	Vesicular and amygdaloidal basalt, dolerite, peperite; fine-grained sandstone; minor medium-grained and pebbly sandstone	Lacustrine sediments; intrusive and extrusive basalts	Conformable, or locally disconformable on Gundi Sandstone; overlain unconformably by Mount Rigg Group
Jimbu Microgranite ca 1720 Ma	Pink-green, massive porphyritic microgranite; lesser aplite and pegmatite/granophyre veins and dykes	High-level granitic intrusive	Intrudes Katherine River Group formations up to and including the Gundi Sandstone
Gundi Sandstone 300 m	Feldspathic sandstone, local pebble to boulder conglomerate; minor mudstones; ferruginous mafic igneous rocks and porphyritic rhyolite	Shallow-marine, aeolian dune systems, fluvial, and probable subaerial volcanic activity	Both upper and lower contacts are unconformities
Diamond Creek Volcanics 230 m	Vesicular and amygdaloidal mafic lava; minor tuff and volcaniclastic sandstone	Subaerial extrusive, fluviatile	
McCaw Formation 250–300 m	Feldspathic sandstone, medium- to thick-bedded, massive, planar laminated and trough cross-bedded. Minor glauconitic horizons and mudstone	Shallow-marine shelf	Contacts not observed. Lower contact probably conformable
Bonanza Creek Formation 85 m	Very fine- to fine-grained sandstone; glauconite common in some beds	Marine shoreface deposits	Both lower and upper contacts sharp, but apparently conformable
Shadforth Sandstone 40 m	Medium- to coarse-grained quartz arenite, trough and tabular cross-bedded	Fluvial, to probable shallow-marine conditions at the top	Lower contact probably unconformable
Cottee Formation 300 m	Hemispherical stromatolitic bioherms, interbedded mudstone, dolostone, and fine- to medium-grained sandstone.	Shallow-marine, often above wave base; bioherms grew in at least 6 m of water	Contacts are not observed. Lower contact conformable on Marlgowa Sandstone and McKay Sandstone
McKay Sandstone 340 m	Fine- to medium-grained, thin- to medium-bedded, trough cross-bedded, quartz arenite, lithic and ferruginous sandstone	Shallow tidal marine	Lower contact conformable and gradational. Probably laterally equivalent to ferruginous facies in the Marlgowa Sandstone
KOMBOLGIE SUBGROUP			
Marlgowa Sandstone 360 m	Quartz arenite; fine- to medium-grained, thin- to medium-bedded and trough cross-bedded, ferruginous sandstone interbeds	Braided fluvial and shallow tidal marine	Probably conformable lower contact
Gilruth Volcanic Member 5 m	Basalt, tuffaceous siltstone, minor banded quartz-jasperite.	Extrusive volcanism	Probably conformable lower contact
Gumarrirnbang Sandstone 125 m	Fine- to very coarse-grained, medium- to thick-bedded quartz arenite, dominantly planar laminated, trough cross-bedded	Distal braided fluvial system; aeolian environment at the top	Conformable lower contact
Nungbalgarri Volcanics 92 m	Vesicular and amygdaloidal basalt	Extrusive volcanism	Conformable lower contact
Oenpelli Dolerite ca 1730–1720 Ma	Fine- to coarse-grained olivine dolerite, commonly porphyritic; quartz dolerite, granophyre	Intrusive sill	Intrudes Marlgowa Sandstone
Mamadawerre Sandstone >176 m	Fine- to coarse-grained, medium- to thick-bedded quartz arenite, planar cross-bedded, trough cross-bedded and minor planar laminated	Distal braided fluvial system; aeolian environment at the top	Unconformably overlies the Nimbuwah Complex

Table 15.3. Stratigraphic succession of the Katherine River Group modified after Carson *et al* (1999), Abbott *et al* (2001), Sweet *et al* (1999) and Kruse *et al* (1994).

a recessive unit with very poor outcrop. It is characterised by large hemispherical bioherms, and carbonate and siliciclastic sedimentary rocks deposited under shallow-marine conditions. The *Shadforth Sandstone* is a fine- to medium-grained, medium to thickly bedded, grey-white to cream-orange quartz sandstone, with coarse-grained to granular bands. The depositional environment of the medium–coarse-grained quartz sandstone is interpreted as braided fluvial, whereas the fine-grained sandstone is likely to be marine (Carson *et al* 1999). The *Bonanza Creek Formation* is gradational with the underlying Shadforth Sandstone, and its relationship with the overlying McCaw Formation is presumably conformable. It comprises fine- to medium-grained laminated quartz sandstone, cross-bedded and massive in places, and medium to thickly bedded fine-grained sandstone with medium to coarse laminae. The *McCaw Formation* represents shallow-marine sandstone, commonly massive and cross-bedded, with minor glauconite horizons. The *Diamond Creek Volcanics* (Kruse *et al* 1994) are conformable on and interfinger with the McCaw Formation. They represent an up to 230 m-thick succession of subaerial mafic lavas, tuff, volcaniclastic sandstone and coarse-grained lithic sandstone. The *Gundi Sandstone* comprises medium-to coarse-grained, medium to thickly bedded, pink lithic and feldspathic sandstone with a mud matrix and ferruginous, maroon to red-brown finer-grained units near the top. The latter are interpreted to be lava flows. Peperite and volcaniclastic rocks have also been recorded. The *West Branch Volcanics* lie with apparent conformity or slight disconformity on the Gundi Sandstone and comprises over 1000 m of mostly massive to vesicular basalt and fine-grained sandstone and mudstone, with local development of medium-grained to pebbly sandstone, fine- to medium-grained dolerite, and peperite. The volcanic units are interpreted as a series of semi-concordant sills that have intruded sediments at shallow depths prior to lithification and complete dewatering (Rawlings and Page 1999). SHRIMP U-Pb dating of zircons from felsic volcanic rocks in the upper part of the West Branch Volcanics yielded a well-constrained age of 1710 Ma. The maximum constraining age of 1720 Ma for the formation is provided by the Jimbu Microgranite, which was emplaced concurrent with sedimentation in the underlying Gundi Sandstone (Kruse *et al* 1994, Rawlings and Haines 1998, Rawlings and Page 1999.)

The *Jimbu Microgranite* is a small (10–50 km^2) high-level microgranite pluton intruding the Kombolgie Subgroup. The dominant rock-type is pink-green, massive, porphyritic microgranite, with lesser aplite and pegmatite/granophyre veins and dykes. The Jimbu Microgranite was emplaced during deposition of the upper Gundi Sandstone, therefore predating the West Branch Volcanics (Rawlings and Haines 1998, Rawlings and Page 1999). SHRIMP U-Pb zircon geochronology has yielded an emplacement age of 1720 ± 7 Ma. On the basis of geochemical and petrological characteristics, this unit is interpreted to be an early-stage, but essentially comagmatic, high-level intrusive equivalent of the felsic part of the West Branch Volcanics.

Oenpelli Dolerite

The Oenpelli Dolerite was defined by Needham *et al* (1975), and later formalised and described in detail by Smart *et al* (1974, 1975). Petrographic and geochemical studies were undertaken on the unit by Stuart-Smith and Ferguson (1978). It occurs as sills and lopoliths and was previously considered to be unconformably overlain by the Kombolgie Subgroup (Needham 1988). However, field evidence shows an intrusive relationship with the Nimbuwah Complex and the Kombolgie Subgroup, and this relationship is supported by aeromagnetic data (Carson *et al* 1999). The contact relationship is usually sharp and shows occasional chilled margins (Rippert 1992).

Sills and lopoliths are zoned and are characterised by a central ophitic olivine dolerite grading outwards with a decrease in grain size to a porphyritic olivine dolerite, which sometimes has a microcrystalline olivine dolerite chilled margin. The olivine component decreases with increasing fractionation. Minor quartz and granophyric dolerite differentiates are usually described in the thicker intrusions towards the centres of the sills. The Oenpelli Dolerite represents a continental tholeiite and was probably generated as a result of partial melting of the upper mantle. Slow and/or intermittent rising of this melt fed fractionated bodies at shallow crustal levels (Stuart-Smith and Ferguson 1978).

A Rb-Sr isotopic study of 16 samples in the Alligator River area determined the age of the Oenpelli Dolerite to be 1688 ± 13 Ma (Page *et al* 1980). More recent geochronological data shows that Oenpelli Dolerite intruded at 1725–1720 Ma (OZCHRON, Polito *et al* 2004).

Tawallah Group

The Tawallah Group (**Table 15.4**) is extensively exposed in the southeast and in the Batten Fault Zone. It unconformably overlies basement units of the Murphy Province and Scrutton Inlier (Ahmad and Wygralak 1989, Pietsch *et al* 1991) and is unconformably overlain by the McArthur Group in the Batten Fault Zone and by the Nathan Group in the southeastern McArthur Basin. It comprises shallow-marine and fluvial sandstone, with lesser mudstone, dolostone and mafic and felsic volcanic rocks, and coeval and younger intrusive bodies. The group is correlated with, and is probably contiguous with the Katherine River Group in the subsurface of the northwestern and southwestern McArthur Basin. To the south, it may be contiguous with the Tomkinson Creek Group of the Tomkinson Creek Province and to the southeast, with the Haslingden Group of the Isa Superbasin (Plumb and Wellman 1987, Pietsch *et al* 1994). The succession is generally shallow dipping or flat lying, except in the vicinity of major faults.

A number of SHRIMP U-Pb zircon dates are available for parts of the succession, including the Wollogorang Formation (ranging between 1730–1725 Ma), Hobblechain Rhyolite and Packsaddle Microgranite (both 1725 Ma), Tanumbirini Rhyolite (1715 Ma) and Nyanantu Formation (1708 Ma, maximum deposition age). Geochronological data are documented in Page *et al* (2000), Page and Sweet (1998) and Rawlings (2002).

In the southeastern McArthur Basin, the *Westmoreland Conglomerate* is the lowermost unit of the Tawallah Group and comprises a thick succession of mainly fluvial sandstone and conglomerate (**Figure 15.11**). It unconformably

Unit, thickness. age	Lithology	Depositional environment	Stratigraphic relationships
TAWALLAH GROUP			
Echo Sandstone (Formerly Masterton Sandstone) 265–365 m	Dolomitic-lithic sandstone, lithic sandstone and mudstone, pebbly lithic sandstone, lithic to quartzic sandstone and minor conglomerate	Ephemeral restricted marine, braided fluviatile	Disconformable on Gold Creek Volcanics; unconformably overlain by McArthur Group
Burash Sandstone (Formerly Masterton Sandstone) <370 m	Quartzic sandstone, with minor coarse or granular intervals near top	High-energy shallow-water	Conformably overlies Nyanantu Formation; overlain by Roper Group
Nyanantu Formation 450 m	Lithic conglomeratic sandstone with numerous pebble- and cobble-rich intervals	Fluvial and alluvial fans	Conformably or disconformably overlies Warramana Sandstone. Overlain with probable disconformity by Masterton Sandstone (McArthur Group).
Tanumbirini Rhyolite 1713 ± 7 Ma	Porphyritic rhyolite lava with phenocrysts of quartz and feldspar set in spherulitic groundmass	Subaerial lava flows and domes	Overlies Warramana Sandstone. Overlain by and interbedded with Nyanantu Formation.
Warramana Sandstone >250 m	Litharenite, ferruginous sandstone, mudstone, pisolitic ironstone and conglomerate, sublitharenite and quartzarenite	Mainly shallow-marine high-energy	Conformably overlies Wollogorang Formation or Gold Creek Volcanics. Overlain conformably by Tanumbirini Rhyolite or disconformably by Nyanantu Formation.
Pungalina Member Undifferentiated <200 m	Cobble-boulder conglomerate, pebbly sandstone, minor siltstone, ferruginous-lithic mudstone	Alluvial and debris flows, restricted marine or lacustrine	Conformable to disconformable on Gold Creek Volcanics; conformably overlain by Echo Sandstone
Packsaddle Microgranite	Red or pink, porphyritic (K-feldspar-quartz), microgranophyric to spherulitic rhyolite and microgranite	High-level laccolith	Intrusive contacts with Wollogorang Formation and Gold Creek Volcanics; contiguous and comagmatic with Hobblechain Rhyolite
Hobblechain Rhyolite 70–100 m 1752 ± 2 Ma	Rhyolite, pink, porphyritic (K-feldspar-quartz), massive to flow-banded, spherulitic to microgranophyric	Lava flow with talus-lined margin	Disconformable on Gold Creek Volcanics conformably overlain by Pungalina Member
Gold Creek Volcanics 15–230 m	Porphyritic basalt; dolomitic to quartzic sandstone, mudstone, peperite breccia, local autobreccia, local stratiform polymict breccia and massive sandstone bodies, local chlorite-bitumen alteration and sulfides	Intertidal to supratidal hypersaline lake or restricted marine	Conformable on Wollogorang Formation conformably to disconformably overlain by Pungalina Member
Wollogorang Formation >350 m 1730 ± 3 Ma 1729 ± 4 Ma 1723 ± 4 Ma	Mudstone, dolostone, carbonaceous shale, dolomitic siltstone, dolomitic sandstone, dolarenite and stromatolitic dolostone and chert, lithic sandstone, evaporitic carbonaceous shale	Lower part is shallow marine. Upper part is locally reworked fluvial deposits in shoreface and intertidal channels.	Paraconformity between lower and upper parts; intrusive contact with Settlement Creek Dolerite below, which locally intrudes higher into formation; conformably overlain by Gold Creek Volcanics
Settlement Creek Dolerite 20–200 m	Dolerite and lesser basalt; brecciated or ropy upper surface; local hornfelsed mudstone enclaves	High-level sill or laccolith intruded into evaporitic mudstone	Intrusive contacts with Aquarium Formation below and Wollogorang Formation above
Wununmantyala Sandstone <800 m	Quartzarenite and sublitharenite, red-brown to purple, haematitic, mainly medium grained	Storm-dominated subtidal marine to very shallow-marine, occasionally exposed	Gradational contact with Aquarium Formation
Aquarium Formation >200 m	Siltstone, shale and fine sandstone: dolomitic, glauconitic and ferruginous, local evaporites	Shallow-marine storm-dominated shelf, shallowing upward into marginal-marine or lacustrine saline	Conformable on Sly Creek Sandstone
Sly Creek Sandstone 320 m	White, pink or grey massive medium-grained quartzic sandstone, pebbly sandstone, conglomerate	Nearshore shallow-marine	Conformably overlies McDermott Formation and gradually changes into glauconitic sandstone of Aquarium Formation
McDermott Formation 200 m	Dolostone, sandstone and siltstone	Shallow-water marginal marine, subtidal to supratidal carbonate bank shoreline facies	Conformably overlies Seigal Volcanics and overlain by Sly Creek Sandstone
Seigal Volcanics 225–1100 m	Amygdaloidal basalt flows 5–30 m thick; thin siltstone and tuffaceous interbeds in upper part. Includes Carolina Sandstone Member, a prominent sandstone bed.	Mostly subaerial lava	Conformable on Westmoreland Conglomerate; overlain conformably by McDermott Formation
Yiyintyi Sandstone <4000 m	Quartzarenite, sublitharenite and litharenite	Fluvial to alluvial fans near base; shallow-marine above	Unconformable over Scrutton Volcanics. Sharp unconformable contact with Seigal Volcanics
Westmoreland Conglomerate <1900 m	Conglomerate, coarse argillaceous sandstone with scattered pebbles	Fluvial to alluvial fans	Unconformable on Cliffdale Volcanics; conformably overlain by Seigal Volcanics

Table 15.4. Stratigraphic succession of the Tawallah Group after Rawlings (2002, 2006), Haines *et al* (1993).

overlies the Murphy Metamorphics, Nicholson Granite Complex and Cliffdale Volcanics (Robert *et al* 1963, Sweet *et al* 1981, Ahmad and Wygralak 1989). The sediments were derived from a northeastern source (Ahmad *et al* 1984, Wygralak *et al* 1988). This formation is probably equivalent to the lower part of the Kombolgie Subgroup. The Westmoreland Conglomerate is conformably overlain by the *Seigal Volcanics*, comprising basaltic lavas of intra-plate tholeiitic affinities, minor tuff, and sandstone and siltstone beds (Darby 1986). Several feeder dykes to the Seigal Volcanics are known and a plug of volcanic breccia intrudes the volcanics about 1.5 km northwest of Cobar 2 uranium mine (**Figure 15.12**). The conformably overlying *McDermott Formation* (Jackson *et al* 1987) consists of alternating bands of shallow-marine dolostone and siltstone with sandstone at the base. The stratigraphic term *Wununmantyala Sandstone* as defined by Pietsch *et al* (1991) replaces the previously defined *Sly Creek Sandstone*. The latter term is now used for the succession overlying the Seigal Volcanics in the Batten Fault Zone and southwestern McArthur Basin (Rawlings 1999, Pietsch *et al* 1991). The Wununmantyala Sandstone conformably overlies the Aquarium Formation and comprises medium-grained laminated sandstone deposited in a nearshore environment, with the shoreline probably following the Murphy Inlier (Ahmad and Wygralak 1989). Its contact with the overlying *Aquarium Formation* is gradual and conformable. The latter formation mainly comprises glauconitic sandstone. Halite and anhydrite pseudomorphs are present in the upper part and are generally associated with disrupted fine lamination. The overlying unit was previously considered to be mainly volcanic flows, but it is now established that it represents composite dolerite sills. Therefore, Rawlings (2006) has redefined the unit and renamed it the *Settlement Creek Dolerite* (previously Settlement Creek Volcanics). The unit represents a composite set of dolerite sheets, 20–200 m thick, that are recognised throughout the southern McArthur Basin. It generally occurs between the Aquarium Formation and Wollogorang Formation, but some dolerite sheets and protrusions are also present higher up in the middle Wollogorang Formation. It has been suggested that the Settlement Creek Dolerite is a deeper-level intrusive equivalent of the uppermost Gold Creek Volcanics (Rawlings 2006). The overlying *Wollogorang Formation* is a mixed dolostone, mudstone and sandstone succession that is exposed throughout the southern McArthur Basin. This lower part of the formation is characterised by isolated large, domical-digitate stromatolite bioherms linked by stratiform or tabular-digitate microbial mats (**Figure 15.13**). It usually contains nodules of crystalline dolomite or chert that are commonly bituminous (**Figure 15.14**). The lower

Figure 15.11. Cliff exposures of gritty sandstone facies of Westmoreland Conglomerate, near the El Hussen Au/U mine in southern McArthur Basin (53K 803000mE 8058000mN, see **Figure 15.40**, photo Andrew Wygralak, NTGS).

Figure 15.12. Plug of volcanic breccia within Seigal Volcanics, 1.5 km northwest of the Cobar 2 mine (53K 806000mE 8061200mN). Plug is composed mainly of brecciated amygdaloidal lava.

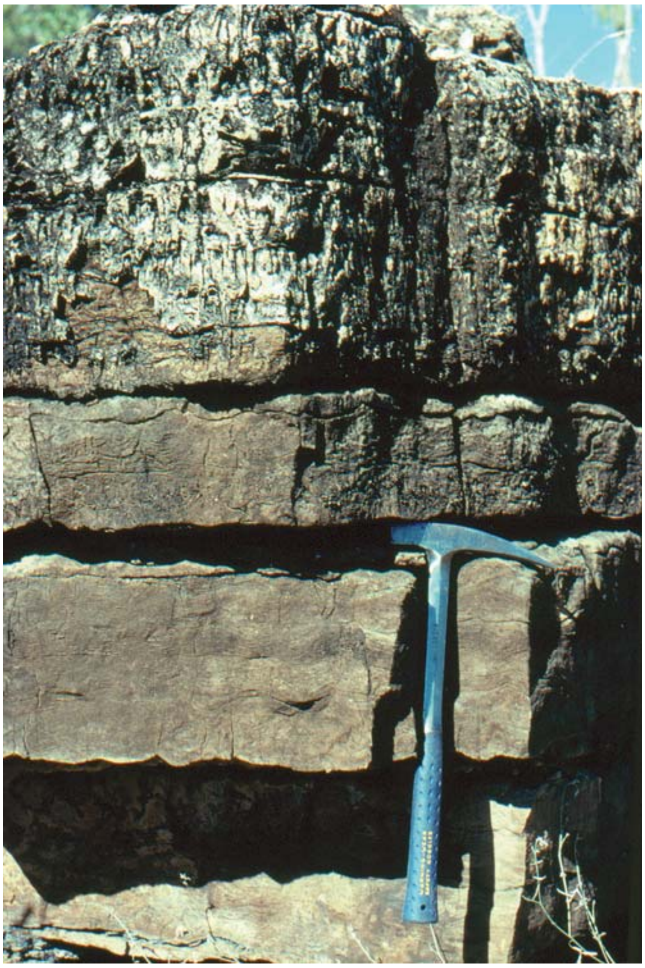


Figure 15.13. Lower Wollogorang Formation showing stacked, microbially bound ripples (lower) and tabular digitate stromatolites (upper). Hammer is 40 cm long (53K 713800mE 8147620mN).

part is interpreted to have been deposited in shallow-marine conditions (Rawlings 2002). The upper part is considered to have been formed via the reworking of local fluvial deposits and intraclastic dolomite by tide- and wave-generated currents in the shoreface and intertidal flats and channels (Rawlings 2002). U-Pb SHRIMP dating of zircons from the lower and upper parts of the formation have yielded 1730 ± 3 Ma and 1723 ± 4 Ma, respectively (Jackson *et al* 1997). The conformably overlying *Gold Creek Volcanics* comprise a mixed basalt-sedimentary succession of massive and vesicular basalt, fine-grained dolerite, sandstone and mudstone, conformably to disconformably overlain by the *Pungalina Member* of the *Echo Sandstone*, and locally disconformably, by the *Hobblechain Rhyolite*. The Gold Creek Volcanics have been interpreted as a product of the emplacement of shallow basaltic intrusions into bodies of unconsolidated water-saturated sediment (Rawlings 1993, 2002). The *Hobblechain Rhyolite* is a semi-contiguous sheet of porphyritic rhyolite (**Figure 15.15**) that outcrops about 15 km north of Wollogorang Station. A SHRIMP U-Pb zircon age of 1725 ± 2 Ma has been determined by Page and Sweet (1998). The *Packsaddle Microgranite* is a small (70 km^2 in outcrop area), elongate, northwest-striking, high-level rhyolite intrusion located about 10 km north of Wollogorang Station. It intrudes the Wollogorang Formation and Gold Creek Volcanics, which dip radially outward from the outcrop belt at a shallow angle (Roberts *et al* 1963). This unit has yielded has a SHRIMP U-Pb zircon age of 1724 ± 4 Ma (Page *et al* 2000), suggesting that it is probably coeval with the Hobblechain Rhyolite.

The *Echo Sandstone* (formerly part of the Masterton Sandstone) comprises a succession of pink lithic to quartzic sandstone, pebbly sandstone, mudstone and conglomerate in the southeastern McArthur Basin and is partly equivalent to the lithologically-similar *Warramana Sandstone* in the Batten Fault Zone. The succession in the southeastern McArthur Basin was formerly assigned to the Masterton Sandstone of the lower McArthur Group by previous workers (Jackson *et al* 1987, Ahmad and Wygralak 1989). However, the Masterton Sandstone is now only recognised in the Batten Fault Zone, where it unconformably overlies the Warramana Sandstone and other Tawallah Group units (Rawlings 1999, 2002). The *Pungalina Member* of the Echo Sandstone represents a basal 0–120 m-thick mudstone, conglomerate and sandstone succession, resting conformably to disconformably on the Gold Creek Volcanics and, locally conformably, on the Hobblechain Rhyolite. It was interpreted by Rawlings (2002) as an evolving volcanic apron, recording the emplacement, denudation and final burial of a relatively high-relief volcanic landscape. The upper Echo Sandstone comprises pink, lithic to quartzic sandstone, pebbly sandstone and minor conglomerate. Rawlings (2002) suggested that whole succession is essentially fluvial, except the very base, which may represent an intertidal environment.

In the Batten Fault Zone and southwestern McArthur Basin, the lithological subdivision of the Tawallah Group is essentially similar to that in the southeastern McArthur Basin. The *Yiyintyi Sandstone* unconformably overlies the Scrutton Volcanics and is predominantly a medium to thickly bedded quartz sandstone, with coarse-grained sandstone and conglomerate beds. It is conformably overlain by the Seigal Volcanics, which are relatively thin (300–400 m), compared to 1500 m in the southeastern McArthur Basin. The *Sly Creek Sandstone* and *Rosi Creek Sandstone Member* are correlated with the upper part of the Seigal Volcanics and represent a succession, up to 900 m-thick, of shallow-marine sandstone (Rawlings 1999, Pietsch *et al* 1991). Outcrops previously mapped as the *Aquarium Formation* in this area are now included in the *McDermott Formation* (Rawlings 1999), which comprises a succession of dolostone, with minor shale and siltstone. This is overlain by the *Wunumantyala Sandstone*, representing a thick succession of shallow-marine sandstone. The *Settlement Creek Dolerite* separates this unit from the overlying *Wollogorang Formation*, which is lithologically identical to that in the southeastern McArthur Basin. The *Gold Creek Volcanics* thins out in the Batten Fault Zone and is absent in the southwestern McArthur Basin. The conformably overlying *Warramana Sandstone* comprises medium- to coarse-grained feldspathic and lithic sandstone with minor conglomerate, deposited under fluvial conditions. This interval is correlated with the Pungalina-Hobblechain Rhyolite succession in the southeastern McArthur Basin (Rawlings 1999). The *Tanumbirini Rhyolite* represents a 100 m-thick succession of massive, pink-brown weathered porphyritic rhyolite (Pietsch *et al* (1991), which

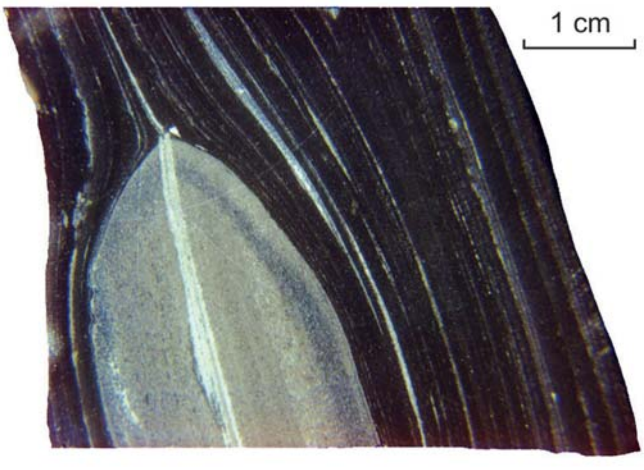


Figure 15.14. Lower Wollogorang Formation: bituminous ovoid nodule in finely parallel laminated black shale (drillhole DD95RC128, approximately 4 km east-southeast of Stanton Co/Ni/Cu prospect, after Rawlings 2006: figure 19).

Figure 15.15. Hobblechain Rhyolite: polished slab of flow-banded rhyolite from base of formation (53K 802350mE 8131240mN, Camel Creek, after Rawlings 2006: figure 36).

has yielded a U-Pb zircon age of 1713 ± 6 Ma (Page *et al* 2000). The overlying *Nyanantu Formation* comprises fluvial conglomerate and sandstone, and is correlated with the Echo Sandstone (formerly Masterton Sandstone) in the Redbank area. U-Pb SHRIMP dating of detrital zircon from the Nyanantu Formation has yielded an age of 1708 ± 4 Ma (Page *et al* 2000). Rawlings (1999) named a succession of fine- to medium-grained sandstone in eastern TANUMBIRINI[1] as the *Burash Sandstone*. This conformably overlies the Tanumbirini Rhyolite.

Goyder Package

A regional unconformity separates the Redbank and Glyde packages throughout the McArthur Basin, except in the Walker Fault Zone, where the succession between the Donydji Group and Balma Group is continuous and conformable. This interval, which is represented by the Parsons Range Group, ranges in age from 1710 to 1670 Ma (Rawlings 1999) and is designated the Goyder Package. Possible equivalents in the northeastern McArthur Basin are the Rorruwuy Sandstone and Coast Range Sandstone. The Burash Sandstone and top of the Echo Sandstone in the southeastern McArthur Basin might also be possible correlatives. The Goyder Package corresponds to the Ᵽ6–Ᵽ7 divisions of Ahmad (2000).

Parsons Range Group

The Parsons Range Group comprises a 5 to 6 km-thick succession of mainly quartz sandstone and siltstone in the southern Walker Fault Zone (**Table 15.5**). The succession is divided into four formations (Plumb and Roberts 1965, 1992, Dunnet 1965). Its maximum age is well constrained by the age of the uppermost formation of the Donydji Group,

[1] Names of 1:250 000 mapsheets are in large capital letters eg TANUMBIRINI.

Unit, thickness	Lithology	Depositional environment	Stratigraphic relationships
Jalma Formation 70–130 m	Sandstone, brown to purple, medium-grained, thinly- to medium-bedded, ferruginous; fine-grained, thinly-bedded sandstone near base; local basal conglomerate; upper recessive laminated claystone unit	Shallow-marine	Unconformable on Coast Range Sandstone and Grindall Formation. Overlain with probable unconformity by Balbirini Dolomite
Coast Range Sandstone 20–40 m	Quartz sandstone, white, medium- to coarse-grained, thickly bedded, commonly pebbly; lenticular basal pebble or cobble conglomerate	High-energy transgressive coastal deposit, with some fluvial facies	Unconformably overlies Grindall Formation, Bradshaw Complex, undifferentiated volcanics and felsic dykes. Apparently unconformably overlies Gadabara Volcanics and Woodah Sandstone. Unconformably overlain by Jalma Formation
PARSONS RANGE GROUP 5000–6000 m			
Kurala Sandstone >300 m	Medium-grained and minor fine-grained quartz arenite	Shallow-marine	Lower contact not exposed; upper contact with Slippery Creek Siltstone is conformable
Fleming Sandstone 50–200 m	Quartz sandstone, white to pink, fine- to medium-grained, thinly- to thickly bedded; local intraclast conglomerate and cauliflower chert	Shallow-marine: shoreline and tidal flat	Conformable on Marura Siltstone; conformable and gradational contact with overlying Koolatong Siltstone
Marura Siltstone 100–250 m	Mudstone and siltstone, laminated to massive, grey, green and purple; dololutite and sandstone interbeds; stromatolitic chert near base	Supratidal mudflats; sabkha	Lower and upper contacts presumed conformable
Badalngarrmirri Formation 1900–2800 m	Quartz sandstone, medium- to thickly bedded, fine- to coarse-grained; laminated mudstone, siltstone and fine sandstone; pyrit ic and ferruginous mudstone and sandstone; minor dolostone and chert	Storm-dominated shelf, from deep basinal to shoreline	Lower and upper contacts presumed conformable
Fairy Glen Sandstone Member 0–100 m	Sandstone, thickly bedded, fine- to medium-grained, ferruginous (glauconitic?)	Offshore transition zone within a storm-dominated shelf	Lower and upper contacts presumed conformable
Gali Member 0–360 m	Siltstone, laminated and wavy bedded; sandstone, thinly to medium-bedded, fine-grained, clayey	Storm-dominated shelf to upper shoreface	Lower and upper contacts presumed conformable
Mount Fawcett Member 0–240 m	Siltstone, olive-green and grey, laminated to thinly bedded; sandstone, thickly bedded, glauconitic, coarse-grained; stromatolitic dolostone at base	Shelf to marginal marine	Lower contact locally disconformable; upper contact presumed conformable
Mattamurta Sandstone 2700–3000 m	Quartz sandstone, fine- to coarse-grained; scattered granule and pebble layers; shallow sills of porphyritic rhyolite near base	Shallow-marine and possibly braided fluvial	Conformable on Dhupuwamirri Member of Fagan Volcanics; overlain conformably (or locally erosionally) by Mount Fawcett Member

Table 15.5. Stratigraphic succession of the Parsons Range Group, Coast Range Sandstone and Jalma Formation after Rawlings *et al* (1997) and Haines *et al* (1999).

the Fagan Volcanics, at 1710 Ma (Pietsch *et al* 1994). Its minimum age is poorly constrained, but must be greater than the 1621 Ma Yarrawirrie Formation in the overlying Balma Group, and the 1640 Ma Barney Creek Formation in the southern McArthur Basin (Pietsch *et al* 1994).

The *Mattamurta Sandstone* is an up to 3 km-thick succession of mainly coarse-grained to pebbly quartz sandstone, deposited under fluvial to nearshore conditions. Palaeocurrents are predominantly to the northeast. The contact with the underlying Fagan Volcanics was interpreted as an unconformity by Plumb and Roberts (1992), but Haines *et al* (1999) considered that the formations are concordant. Bodies of crystal-rich felsic porphyry, similar to the porphyritic rhyolite of the Fagan Volcanics, occur in the lowermost 200 m of Mattamurta Sandstone. The contact with the overlying Badalngarrmirri Formation is concordant and is presumed to be conformable, or to indicate minor lithification and erosion before deposition of the basal Badalngarrmirri Formation (Haines *et al* 1999). The *Badalngarrmirri Formation* represents an up to 3 km-thick succession of quartz sandstone, mudstone, ferruginous (glauconitic-pyritic) sandstone, and minor chert and dolostone. The formation was deposited in a storm-dominated, marine shelf environment and comprises alternating coarse- and fine-grained siliciclastic rocks, which have been used to divide it into thirteen members, three of which have been formally named (**Table 15.5**, Haines *et al* 1999). The *Marura Siltstone* is a 100–2500 m-thick unit, ranging in composition from siltstone to claystone, with minor sandstone, dolostone and chert (**Figure 15.16**). The chert occurs as a single unit near the base, but sandstone is present throughout. The overlying *Fleming Sandstone* is an up to 200 m-thick succession of quartz sandstone.

Other possible stratigraphic equivalents

The *Coast Range Sandstone* comprises fluvial to shallow-marine sandstone and minor conglomerate, exposed in the central part of the northeastern McArthur Basin. Plumb and Roberts (1965) originally mapped most of these outcrops as part of the Groote Eylandt beds (now Groote Eylandt Group). More recent studies indicate that the Coast Range Sandstone is significantly younger than the Groote Eylandt Group and has been separated as an ungrouped formation (Haines *et al* 1999).

Figure 15.16. Silicified dolostone bed near base of Marura Siltstone showing selective silicification of small columnar stromatolites (53L 550000mE 8552430mN, after Haines *et al* 1999: plate 18).

The *Kurala Sandstone* is a prominent ridge-forming unit of white quartz sandstone and quartzite that outcrops in a south- southwest-trending belt along the northeastern flank of the Walker Fault Zone. It was originally included in the Habgood Group (Dunnet 1965, Plumb and Roberts 1992), but was latter placed in the Parsons Range Group by Haines (1994). The Kurala Sandstone was deposited in a high-energy very shallow-water environment.

The *Rorruwuy Sandstone* (Rawlings *et al* 1997) was previously mapped as part of the Mount Bonner Sandstone. The formation comprises white to pink, mature, silicified, fine- to medium-grained quartzic sandstone. The depositional environment is envisaged to have been shallow water, possibly fan-delta or intertidal.

Glyde Package

The Glyde Package mainly comprises an up to 5 km-thick succession of evaporitic carbonate, mudstone and sandstone, and is confined to the Batten and Walker fault zones and nearby areas. The depositional environment is interpreted as shallow- to moderately deep water and locally emergent. This package includes the Balma and Habgood groups in the northern and the McArthur and Vizard groups in the southern McArthur Basin. Evidence of syndepositional fault movement is common and may be responsible for the generation of local and regional hiatuses within the package. Tuffaceous rocks are commonly present and ages of 1640 to 1600 Ma have been obtained from the medial and upper parts of the Glyde Package (Haines *et al* 1999, Rawlings *et al* 1997, Rawlings 1999). Possible stratigraphic equivalents in the northeastern McArthur Basin are the Jalma Formation, Mount Bonner Sandstone and Durabudboi beds, whereas in the Urapunga Fault Zone, the Vizard Group is a possible equivalent of the upper McArthur Group. The Glyde package corresponds to the P7 subdivision of Ahmad (2000).

Previous interpretations of deposition in a rift setting (eg Plumb *et al* 1990) are not supported by subsequent interpretation of seismic data (Rawlings *et al* 2004, see **Introduction**).

The age of the Glyde Package is constrained by U-Pb SHRIMP zircon ages ranging from 1640 Ma to 1600 Ma. The maximum age is constrained only by the 1710 Ma minimum age of the volcanics at the top of the Redbank Package (Rawlings 1999).

McArthur Group

In contrast to the predominantly arenaceous Tawallah Group, the late Palaeoproterozoic (Statherian) McArthur Group is an up to 5 km-thick succession (**Figure 15.17**) of platformal stromatolitic dolostone and clastic sedimentary rocks with local pyritic carbonaceous siltstone units (Winefield 1999). Exposures of the McArthur Group (**Table 15.6**) are confined to the Batten Fault Zone, where it unconformably overlies the Tawallah Group, although seismic data indicates that it continues at depth beyond the inferred extents of the fault zone (Rawlings *et al* 2004).

The McArthur Group is subdivided into the Umbolooga and Batten subgroups, separated by a possible unconformity between the Reward Dolostone and Lynott Formation.

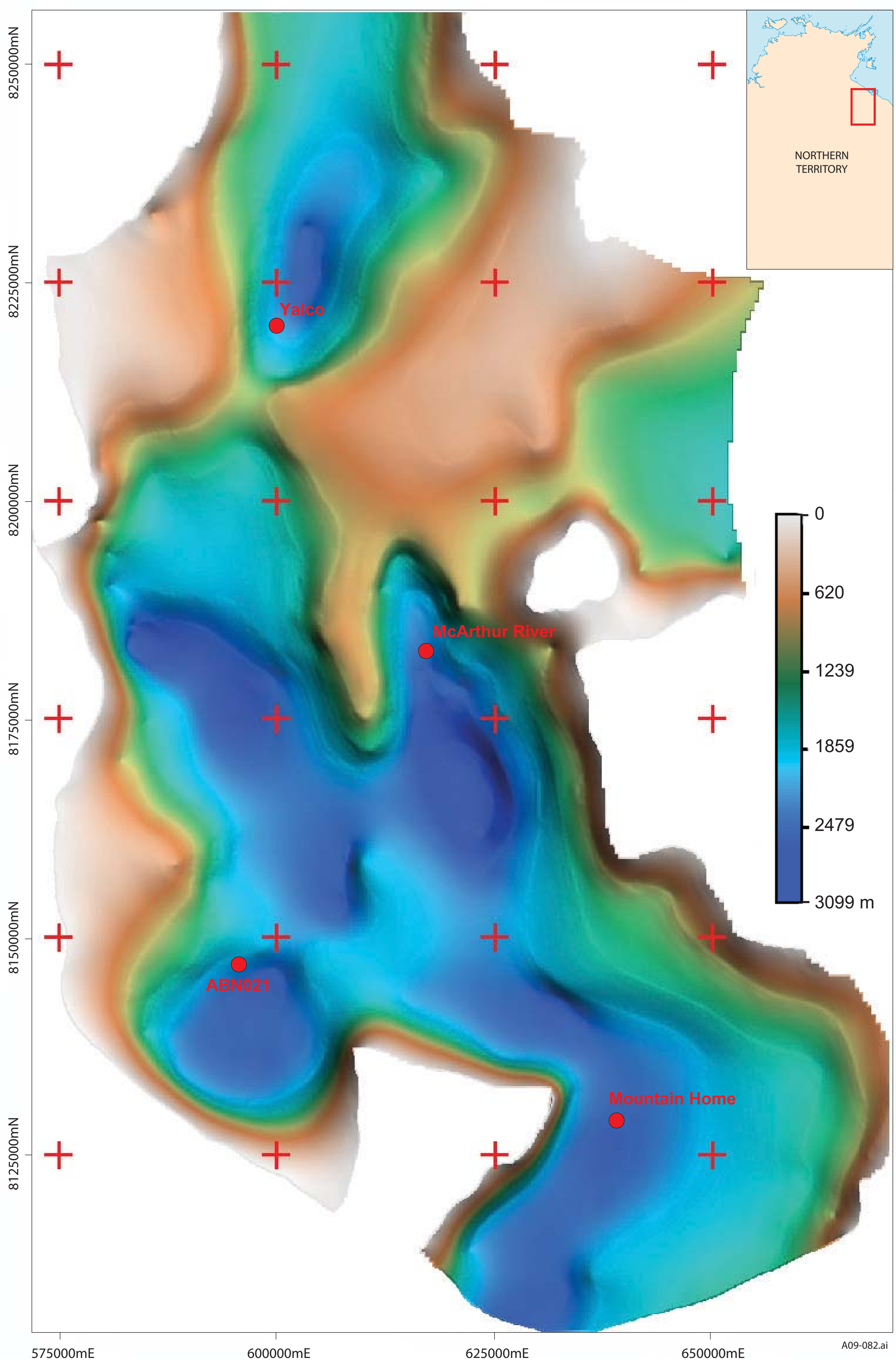


Figure 15.17. Presently preserved thickness of carbonate-dominated McArthur Group, interpreted from geophysical data (after Duffett *et al* 2007).

Unit, thickness, age	Lithology	Depositional environment	Stratigraphic relationships
BATTEN SUBGROUP			
Amos Formation <70 m 1614 ± 4 Ma	*Upper*- Massive karstic-weathering dark-grey to yellow-grey recrystallised dolostone *Lower*- Red siltstone, fine sandstone, sandy dolarenite and dolostone	Upper 30 m probably represent calcrete and the lower part of the formation represents a classic redbed environment. The middle part may be deposited under shallow-marine conditions	Disconformable lower contact. Unconformable upper contact with Nathan Group.
Looking Glass Formation 30–70 m	Silicified, commonly stromatolitic dolostone; dolarenite and sandy dolarenite	Peritidal–shallow-marine	Conformable lower contact. Upper contact with Amos Formation may be erosional
Stretton Sandstone <5–270 m 1625 ± 2 Ma	Fine- to medium-grained, thinly bedded quartzarenite; distinctive wavy bedding, small ripples, toolmarks, mudclast casts, desiccation cracks and convolute bedding	Shallow-marine to sub-wave base	Conformable upper and lower contacts
Yalco Formation <50–250 m	Ridge-forming; thinly interbedded stromatolitic dololutite, silty dololutite, dolarenite and minor sandstone with abundant chert nodules and laminae; abundant small domal stromatolites and common desiccation cracks, tepee structures and gypsum pseudomorphs	Shallow-marine to emergent	Conformable upper and lower contacts
Lynott Formation 50–600 m			
Donnegan Member 0–134 m 1636 ± 4 Ma	Dolomitic siltstone, fine- to coarse-grained dolomitic sandstone and dolarenite; thinly to medium bedded, commonly rippled and cross-bedded; small botryoidal quartz nodules (cauliflower chert and enterolithic chert)	Peritidal, supratidal to sabkha on stable platform	Conformable upper and lower contacts
Hot Spring Member 50–350 m	Thinly bedded dolomitic siltstone and silty dololutite with interbeds of fine-grained sandstone, chertified stromatolitic dolostone, dolarenite, sandy dolarenite and dolomitic sandstone; siltstone and dololutite commonly contain chert pods; sandstone, rippled and cross-bedded, stromatolite mainly stratiform and domical; common desiccation cracks, tepee structures and pseudomorphs after sulfate evaporites and halite	Intertidal to supratidal flats, sporadic brine logging	Gradational upper and lower contacts
Caranbirini Member 0–400 m	Thinly bedded laminated dolomitic siltstone and shale, in part carbonaceous and pyritic; silty dololutite, dololutite; minor fine-grained dolarenite and lenses of slump breccia; uncommon ripples and evaporite mineral casts; small vertical fractures and fenestrae commonly filled with calcite and/or chert	Submarine grading upward to intertidal deposited in actively subsiding sub-basins	Disconformable or unconformable over Reward Dolostone.
UMBOLOOGA SUBGROUP			
Reward Dolostone 30–350 m	Dololutite, stromatolitic dololutite, silty dololutite and dolarenite with lesser sandy dolarenite, dolorudite and sandstone; laminated, thinly to massive bedded, cross-bedded, brecciated and slumped; pseudomorphs after sulfate evaporites; onkoids, ooids, small silica spheroids; pseudomorphs after pyrite (pyritohedron)	Shallow-marine upward-shallowing cycles, local high-energy to peritidal	Generally conformable but locally disconfromable upper and lower contacts
Barney Creek Formation 10–900 m+ 1640 ± 4 Ma	Thinly bedded to laminated, dolomitic, carbonaceous and pyritic shale and siltstone, dololutite, rare breccia and sandstone; occasional gypsum casts; talus slope breccia adjacent to Emu Fault	Basinal shale deposited in actively subsiding sub-basins	Conformably overlies Teena Dolostone and is conformably overlain by Reward Dolostone
Teena Dolostone			
Coxco Dolostone Member 15–70 m	Grey crystalline dololutite with radiating, needle-like gypsum crystal pseudomorphs normal to bedding; rare conical stromatolites; uncommon thin intervals of dolomitic shale and siltstone	Seafloor cement associated with transgression and upwelling	Conformably and gradationally overlain by Barney Creek Formation
lower Teena Dolostone <60 m	Thinly bedded to laminated dololutite, silicified in places; dolomitic shale and sandstone, intraclast breccia and conglomerate, and dolarenite	Marine, partly below wave base. Upward-shallowing cycles	Conformably overlies Emmerugga Dolostone
Emmerugga Dolostone 620 m			
Mitchell Yard Dolostone Member	Massive, dark grey, karstic-weathering, crystalline dololutite; lacks obvious internal sedimentary structures	Possible deep marine	Conformably overlain by Teena Dolostone
Mara Dolostone Member	Dololutite, stromatolitic dololutite, dolomitic siltstone, dolarenite and dolomitic breccia; columnar, domal and conical stromatolites, often forming bioherm series; common halite casts and quartz nodules after evaporites	Shallow-marine, peritidal and flanking carbonate sabkha	Conformably overlies Myrtle Shale and in turn conformably overlain by Mitchell Yard Dolostone or Teena Dolostone.

Table 15.6. Stratigraphic succession of the McArthur Group modified from Pietsch *et al* (1991) and Winefield (1999) (**continued on next page**).

Unit, thickness	Lithology	Depositional environment	Stratigraphic relationships
Myrtle Shale 40–60 m	Thinly bedded to laminated, commonly dolomitic siltstone, shale and fine-grained sandstone (halite casts common); dololutite (in places stromatolitic)	Lagoonal and/or low-gradient alluvial plain	Conformable and gradational upper and lower contacts
Leila Sandstone <10–30 m	Dark grey-weathering dolomitic sandstone; fine- to coarse-grained, poorly sorted, thinly to medium bedded, commonly cross-bedded and rippled; thin interbeds of sandy dolostone	Shallow marine	Conformable and gradational upper and lower contacts
Tooganinie Formation ca 200 m	Dololutite, stromatolitic dololutite (stratiform, domal, columnar and conical forms), dolomitic shale and siltstone, ripple-marked and cross-bedded dolarenite and sandstone; common desiccation cracks and pseudomorphs after gypsum and halite; breccia beds and ooids in dolarenite	Peritidal marine to emergent shoreline, possibly deepening to the south	Conformable and gradational upper and lower contacts
Tatoola Sandstone 80–350 m	*Upper*: ridge-forming, mainly medium-grained, thinly to medium bedded and rippled sandstone with shale clasts and evaporite mineral casts and moulds. *Lower*: flaggy, thinly bedded, usually fine-grained sandstone; thinly bedded shale and siltstone (dolomitic in places) and very fine-grained sandstone at base; abundant small-scale cross-beds, pinch and swell, tool marks, ripples and mud clast impressions. Several recessive dolomitic units consisting of dololutite, dolomitic siltstone, stromatolitic dololutite and dolarenite	Changing up-sequence from clastice peritidal to mixed carbonate/siliciclastic subtidal beach to peritidal	Conformable and gradational upper and lower contacts
Amelia Dolostone 50–180 m	Recessive; stromatolitic dololutite (stratiform, domal, conical and columnar forms) and silty dololutite with interbeds of dolarenite and infrequent shale and rare fine-grained sandstone; ooid, brecciated and conglomeratic intervals common; localised development of diagenetic sideritic dololutite	Broad marginal marine, remobilised evaporites and brine flushing	Conformable upper and lower contacts
Mallapunyah Formation 100–ca 450 m	Mainly recessive; red to purple dolomitic, cross-bedded sandstone interbeds; stromatolitic dolostone, more prevalent in the upper part of the formation; common botryoidal quartz nodules (cauliflower chert), ripples, desiccation cracks and gypsum and halite casts and moulds	Continental and coastal sabkha	Lower contact conformable and gradational. Conformably overlain by Amelia Dolostone
Masterton Sandstone 40–650 m	Ridge-forming; pink, brown and buff, fine- to medium-grained, moderately sorted quartzarenite; thinly to thickly bedded, cross-beddded (planar and trough) and extensively rippled; very fine-grained sandstone and siltstone form generally recessive minor units; distinctly ferruginous mottled sandstone with halite and gypsum casts and pseudomorphs mainly in uppermost beds; basal sandstone conglomerate	Alluvial fan and braided river base, the remainder very shallow-marine and intertidal to supratidal	Unconformable on various units of the Tawallah Group. Lower contact marked by basal conglomerate

Table 15.6. Stratigraphic succession of the McArthur Group modified from Pietsch *et al* (1991) and Winefield (1999; **continued from previous page**).

The basal unit of the *Umbolooga Subgroup*, the *Masterton Sandstone* (redefined by Rawlings 1999) comprises a variably thick (40–650 m) succession of fluvial to shallow-marine, white, pink and red sandstone, minor mudstone and conglomerate. This unconformably overlies various formations of the Tawallah Group. The conformably overlying *Mallapunyah Formation* was deposited in a shallow-marine/sabkha environment and comprises mudstone, siltstone, dolostone and sandstone with pseudomorphs after halite and gypsum, and well developed diagnostic botryoidal quartz nodules (cauliflower chert) after anhydrite (Muir 1979, Jackson *et al* 1987). The shallow-marine *Amelia Dolostone* comprises interbedded partly stromatolitic dolostone with local beds of dololutite containing diagenetic siderite. The *Tatoola Sandstone* comprises a lower, fine-grained, thinly bedded sandstone facies and an upper, medium to coarse-grained, more thickly bedded sandstone and dolostone facies. The lower part is interpreted to have been deposited in a subtidal, deeper-marine, storm-affected environment, followed by an agitated shallow-water to intermittently emergent environment for deposition of the upper coarse-grained sediments (Jackson *et al* 1987). The *Tooganinie Formation* is a thick succession of dolostone and interbedded dolomitic sandstone, siltstone and shale. Plumb and Brown (1973) distinguished two members at the top of the formation, the *Leila Sandstone* and *Myrtle Shale*, which Jackson *et al* (1987) elevated to formation status. The Tooganinie Formation is considered to have been deposited in shallow-water to emergent shoreline environments with local evaporitic overprints. The *Emmerugga Dolostone* comprises stromatolitic and brecciated dolostone with minor siltstone. Two members are identified within this unit. The *Mara Dolostone Member* comprises silicified stromatolitic units alternating with silty or non-stromatolitic units. The *Mitchell Yard Dolostone Member* represents a non-stromatolitic, massive, grey featureless dolostone unit mapped in the southern Batten Fault Zone. The Emmerugga Dolostone is considered to have been deposited in a peritidal to deep marine environment on an extensive, relatively flat, intracratonic carbonate platform. It consists of a series of upward-shallowing cycles that deepen and thicken up-section (Winefield 1999).

The package from Myrtle Shale to Emmerugga Dolostone is a partly-laterally equivalent depositional succession. It represents a phase of increasing accommodation, during which carbonate platform lithofacies accumulated in a series of upward-shallowing cycles that thicken and deepen upsection (Winefield 1999). The deeper-water shale facies are partly laterally equivalent to the shallow-water carbonates.

The lowermost *Teena Dolostone* was deposited during basin subsidence. This shallowed up to oolitic and oncolitic grainstone, imbricated flat-plate breccias, ripple-marked mixed carbonate-siliciclastic rocks, finely laminated dololutite with thin interbeds of dolomitic shale, siltstone, dolarenite and rare thin beds of K-metasomatised mudstone. The upper Teena Dolostone is interpreted to have been in very shallow-water to emergent conditions. The *Coxco Dolostone Member* in the upper Teena Dolostone is mapped based on the presence of 'Coxco Needles' (**Figure 15.18**) within grey dololutite. These needles are radiating fans or layers of bottom-nucleated, acicular, near-vertical dolomite crystals, typically 6–10 cm long, that pseudomorph an earlier mineral. Such needles are apparently coeval with similar examples from the Saint Vidgeon Formation of the Vizard Group and from other Palaeoproterozoic north Australian basins. More extensive and thicker layers of radiating needles also characterise much younger Marinoan post-glacial cap carbonates worldwide (http://www.snowballearth.org/week4.html; accessed January 2009). The Coxco Needles in the Teena Dolostone have been interpreted as pseudomorphs of seafloor gypsum (Walker *et al* 1977), seafloor aragonite (Brown *et al* 1978), lacustrine trona (Jackson *et al* 1987), and an abiogenic aragonite seafloor cement (Winefield 1999). Winefield (1999) postulated that these seafloor cements formed as a result of the upwelling of HCO_3^-, Fe^{2+} and Mn^{2+} -rich anoxic bottom water coeval with rapid changes to the basin's bathymetry. Riding (2008) has debated a possible biogenic influence in their formation and concluded that Coxco Needles were an example of botryoidal abiogenic sparry crusts. They are an end member of a spectrum that includes microbial stromatolites. Given their presence in at least one other formation elsewhere in the McArthur Basin, it is debatable whether the Coxco Dolostone Member is a valid lithostratigraphic unit.

The Teena Dolostone is overlain by the Barney Creek Formation. In some places, the transition is sharp and concordant. Elsewhere, Winefield (1999) documented brecciation, fracturing and fissuring of the Coxco Dolostone Member just below the contact. The fissures were commonly infilled by internal sediments, multiple generations of marine cements and contained brecciated clasts of Coxco Needles rimmed with fibrous cements. These features were interpreted as neptunian dykes, formed as a result of localised extension or dilation within the carbonate platform during the onset of rapid differential subsidence.

Figure 15.18. Coxco Needles in Coxco Dolostone Member of Teena Dolostone (precise location unknown, J Dunster collection).

The Barney Creek Formation is a largely recessive unit that comprises finely laminated to thinly bedded dolomitic, carbonaceous and pyritic siltstone, shale and dololutite, with locally abundant tuff beds and breccias (**Figure 15.19a**). Jackson *et al* (1987) defined three members: the Cooley Dolostone Member, W–Fold Shale Member and HYC Pyritic Shale Member. The *W-Fold Shale Member* consists of green and red dolomitic siltstone and shale, and green vitric tuff. Much of the siltstone appears to have undergone potassium metasomatism. The overlying *HYC Pyritic Shale Member* hosts the World-class McArthur River (formerly HYC) Zn-Pb-Ag deposit and is a recessive, thinly bedded, laminated, carbonaceous, dolomitic pyritic siltstone (**Figure 15.19b**). The member also contains thin beds of tuffaceous mudstone

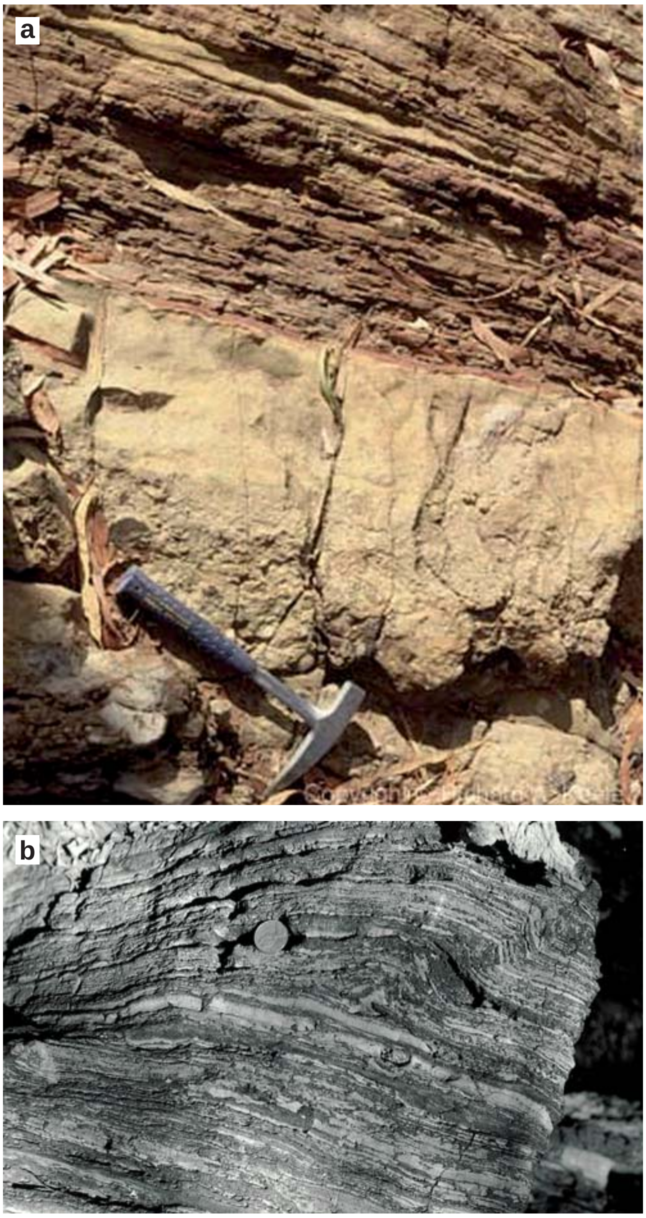


Figure 15.19. (**a**) Cyclic unit in Barney Creek Formation, McArthur River Zn-Pb-Ag deposit. Coarse breccia unit (bottom) grades up into sandy bed and shale (top). Figure courtesy Richard Keele [formerly ARC Centre of Excellence in Ore Deposits (CODES)]. (**b**) Thinly laminated, mineralised, HYC Pyritic Shale Member of Barney Creek Formation, 2 km north of McArthur River mine (53K 618000mE 8183000mN, after Pietsch *et al* 1999: plate 13).

and zircons from three samples of these tuffaceous sediments have yielded SHRIMP dates of 1640 ± 4, 1639 ± 3 and 1638 ± 7 Ma (Page and Sweet 1998, Page *et al* 2000). These dates are comparable to those from tuffaceous units in the Limbunya Group in the Birrindudu Basin (Cutovinos *et al* 2002). In contrast to some shallow-water or lacustrine models proposed previously (eg Jackson *et al* 1987), Bull (1998) and Winefield (1999) interpreted the overall Barney Creek Formation as deeper-water shaly carbonates that were deposited during maximum flooding of a sea-level transgression. The carbonaceous pyritic shales were taken to be indicative of a quiet, anoxic, sub-wave base environment.

An abrupt basinward shift at the top of the Emmerugga Dolostone marks the onset of tectonically-induced basin subsidence accompanied by the Barney Creek Depositional Cycle of Winefield (1999). This cycle comprises the partly laterally equivalent Teena Dolstone, Barney Creek Formation and Reward Dolostone and is characterised by rapid lateral lithofacies variation and development of numerous small sub-basins adjacent to reactivated north–south-trending faults (eg Emu fault). The thickest shale-dominated facies were deposited and preserved adjacent to growth faults. These successions grade laterally into condensed sections developed adjacent to north-northeast–northeast-trending fault segments. Slope facies and abundant slope-related deformation include neptunian dykes, liquification breccias, megabreccias and soft-sediment slump folds (Winefield 1999).

The *Cooley Dolostone Member* is one or more intraformational, locally-derived, fault-related chaotic breccias that interfinger with other units of the Barney Creek Formation in the Cooley area. The clasts, ranging from millimetres to several tens of metres, were largely derived from the Emmerugga and Teena dolostones (Pietsch et al 1991). Such breccias and megabreccias are also locally present at the upper contact of the Coxco Dolostone Member. These and other examples documented by Winefield (1999) are not obviously related to faults. Although the Cooley Dolostone Member has been differentiated and mapped as a separate unit, it may have disparate origins and its status as a member is debatable.

The *Reward Dolostone* comprises dololutite, silty dololutite, minor dolarenite, shale and local dolostone breccia. The lower contact with the Barney Creek Formation is generally conformable and gradational, but a possible palaeo-regolith occurs locally (Haines *et al* 1993). The upper contact may be transitional from dolostone to siltstone and shale of the Caranbirini Member of the Lynott Formation, or disconformable where possible palaeo-regolith is developed at the top of the Reward Dolostone (Haines *et al* 1993, Pietsch *et al* 1991). The depositional environment ranged from peritidal, shallow subtidal to shallow open sea.

The *Batten Subgroup* (Plumb and Brown 1973, Jackson *et al* 1987) overlies the Reward Dolostone. A palaeo-regolith is locally observed on top of the Reward Dolostone, implying a disconformity (Haines *et al* 1993). The succession comprises dolostone, dololutite, quartz sandstone, dolomitic siltstone and shale, deposited in variety of depositional settings, ranging from supratidal sabkha to shallow marine.

The *Lynott Formation* is an evaporite-rich unit of mainly dolomitic siltstone, dolarenite, stromatolitic dolostone and lesser dolomitic sandstone. Three conformable members have been identified: the Caranbirini, Hot Spring and Donnegan members (Jackson *et al* 1987). The *Caranbirini Member* consists of thinly bedded, laminated fine-grained mudstone, dolomitic mudstone, which is locally carbonaceous and/or pyritic, dololutite, intraclast breccia and pink tuffaceous mudstone. The overlying *Hot Spring Member* is typically stromatolitic and mostly comprises dolomitic siltstone, silty dololutite and sandstone, with ubiquitous evaporite pseudomorphs indicating deposition in intratidal to supratidal flats (Pietsch *et al* 1991). The *Donnegan Member* comprises red-brown to buff dolomitic siltstone and sandstone, with lesser dolarenite and thin to medium beds of chertified stromatolitic dolostone. This unit is characterised by abundant cauliflower and enterolithic chert, consistent with deposition in a supratidal to sabkha setting. A sample from near the top of the member returned a date of 1636 ± 4 Ma, which is within error of the Barney Creek Formation (Page *et al* 2000).

The *Yalco Formation* conformably overlies the Donnegan Member and includes silicified, thinly bedded, stromatolitic dololutite, silty dololutite, dolarenite and dolomitic sandstone. These are usually thinly interbedded and stromatolitic, and contain abundant intraclast chert breccias, laminae and nodules. Other sedimentary features include ripple marks, desiccation cracks, tepee structures, and casts and moulds after evaporite minerals. The unit was deposited in a shallow-marine environment that was subjected to periodic emergence.

The *Stretton Sandstone* conformably overlies the Yalco Formation and comprises very fine- to medium-grained, green to grey-brown quartz sandstone and minor micaceous siltstone. The rocks are unusually flaggy and have a distinctly wavy to parallel bedding. Sedimentary structures include small ripples, toolmarks, desiccation cracks and hummocky cross-stratification. The presence of hummocky cross-stratification indicates a sub-wave base depositional environment for part of the formation (Haines *et al* 1993).

The *Looking Glass Formation* comprises intensely silicified stromatolitic dolostone, sandy dololutite and dolarenite, with thin intervals of intraclast conglomerate. This formation is considered to have been deposited in a shallow-marine or peritidal environment (Pietsch *et al* 1991). The *Amos Formation* comprises karstic-weathering dolostone, siltstone, sandstone and sandy dolarenite. The lower part of this formation is a clastic red-bed succession, deposited under terrestrial conditions. The remainder was probably deposited in a shallow-marine setting (Pietsch *et al* 1991) The unit rests disconformably on the Stretton Sandstone or Looking Glass Formation, and is unconformably overlain by the Balbirini Dolostone.

On the basis of a statistical overlap between SHRIMP zircon ages of the lower part of the Balbirini Dolostone (1613 ± 4 Ma and 1609 ± 3 Ma) and the Amos Formation (1614 ± 4 Ma), Rawlings (1999) included the lower Balbirini Dolostone as a part of the Batten Subgroup. However, there is a distinct regional unconformity between the Nathan and McArthur groups. The Balbirini Dolostone is therefore described under the Nathan Group in the succeeding sections.

Habgood Group

The Habgood Group (**Table 15.7**) conformably overlies the Kurala Sandstone of the Parsons Range Group and essentially consists of fine-grained siliciclastic rocks and minor dolostone outcropping in the northern Walker Fault Zone. It was originally defined by Dunnet (1965) and later redefined by Plumb and Roberts (1992) and Haines (1994). The sediments were deposited in shallow- to marginal-marine settings, with evaporitic conditions and periodic exposure. Compared to the McArthur Group, it contains more siliciclastic than carbonate rocks. There is no geochronological data for the Habgood Group and a correlation with the McArthur Group (Haines *et al* 1999, Rawlings *et al* 1997, Rawlings 1999) should at best be considered as tentative.

The *Slippery Creek Siltstone* is the basal unit of the Habgood Group and rests with a sharp conformable contact on the Kurala Sandstone of the Parsons Range Group. It comprises predominantly laminated micaceous mudstone and minor fine-grained sandstone and muddy dololutite. Some beds are pyritic, most notably near the base. The Slippery Creek Siltstone appears to be largely of subtidal origin and was mostly deposited below wave base. The overlying *Yarawoi Formation* consists of mudstone, sandstone and dolostone, deposited under shallow-water to subtidal environments. Neither the upper nor lower contact is exposed. The overlying *Darwarunga Sandstone* has been informally divided into two units: a lower very resistant sandstone-dominated succession with chert and relict stromatolitic layers, and an upper more recessive unit of interbedded sandstone, dolomitic mudstone and minor dolostone. It is interpreted to have been deposited in shallow water with periodic evaporitic conditions and exposure (Rawlings *et al* 1997). The *Ulunourwi Formation* possibly conformably overlies the Darwarunga Sandstone and is disconformably overlain by the Gwakura Formation. It comprises a thick succession of mudstone with lesser sandstone and carbonate rocks. Halite pseudomorphs have been observed in fine-grained sandstone interbeds. Ovoid nodules, 2–10 cm in size, are common and are composed of quartz, carbonate (dolomite and ankerite), chlorite and sometimes barite. Cauliflower chert nodules, after sulfate evaporites (anhydrite or gypsum), are locally common. The Ulunourwi Formation is considered to have been deposited under very shallow, periodically emergent conditions, with evidence of deepening to a subtidal, storm-dominated setting near the top of the succession (Rawlings *et al* 1997, Haines 1994). The *Gwakura Formation* comprises a basal conglomerate succeeded by interbedded sandstone, mudstone, dolomitic mudstone, dolarenite, tuffaceous mudstone and stromatolitic chert after dolostone. This formation was probably deposited in a storm-dominated, marine shelf setting.

Balma Group

Haines (1994) used the term Balma Group (**Table 15.8**) for formations originally mapped in the southern Walker Fault Zone as the McArthur Group (Plumb and Roberts 1965). Haines *et al* (1999) defined the group and

Unit, thickness	Lithology	Depositional environment	Stratigraphic relationships
HABGOOD GROUP			
Gwakura Formation ca 600 m exposed	Sandstone, grey to red, mostly fine-grained, often dolomitic; siltstone, dolomitic; chert (silicified carbonate), microbial-laminated; tuffaceous mudstone; basal conglomerate or pebbly lithic sandstone, polymict. ?disconformity.	Marine? shelf; mostly storm-dominated subtidal	Lower contact with Ulunourwi Formation is erosional and possible disconformable; top not exposed
Ulunourwi Formation Thickness unknown	Mudstone, red, purple and green, dolomitic in part, laminated, desiccation cracks, evaporite nodules; sandstone, fine- to medium-grained; silty dololutite and dolostone, rarely stromatolitic	Very shallow-water low-energy with periodic exposure and evaporitic conditions; subtidal storm-dominated near top	Lower contact sharp though conformable; upper contact with Gwakura Formation is erosional and possibly disconformable
Darwarunga Sandstone ca 350 m	Lower part: sandstone, white to pale grey and pink, fine- to medium-grained, mostly medium bedded, blocky; minor stromatolitic chert (silicified carbonate) and cauliflower chert nodules. Upper part: interbedded fine- to medium-grained sandstone, dolomitic siltstone and silty dolostone, sparse stromatolites.	Shallow-water with periodic exposure and evaporitic conditions; some high-energy facies	Lower contact not exposed; upper contact sharp but conformable
Yarawoi Formation 650–700 m	Mudstone, red, grey and green, variably dolomitic; dololutite and silty dololutite; sandstone, fine- to medium-grained; chert (silicified carbonate), stromatolitic	Very shallow-water subtidal	Contacts not exposed
Slippery Creek Siltstone Thickness unknown	Mudstone, red, purple and dark green, distinctive graded silt laminae, weathered outcrop is ferruginised; minor fine-grained sandstone and silty dololutite; large concretions common in places	Largely subtidal and below wave-base	Sharp though conformable contact with underlying Kurala Sandstone (Parsons Range Group). Upper contact not exposed.

Table 15.7. Stratigraphic succession of the Habgood Group (after Rawlings 1997).

preferred a correlation with the nearby Habgood Group of the northern Walker Fault Zone, rather than with the McArthur Group.

The Balma Group conformably overlies the Fleming Sandstone of the Parsons Range Group and is in turn overlain by the Balbirini Dolostone of the Nathan Group with a possible unconformity. In the central northeastern McArthur Basin, the Balbirini Dolostone unconformably overlies the Jalma Formation.

The Balma Group is composed of a thick (up to about 4.5 km) succession of mainly mudstone, carbonate and sandstone, of shallow-water and locally evaporitic origin, with minor tuffaceous components in some formations. In comparison to the McArthur Group, the Balma Group contains a greater proportion of siliciclastic components and lesser carbonate sediments.

Haines (1994) identified two hiatuses within the Balma Group, and proposed tentative correlations with the McArthur and Habgood groups, based on a sequence stratigraphic approach. The first hiatus is associated with extensive silicification and lies between the Strawbridge Breccia and Vaughton Siltstone. The second lies at the base of the Yarrawirrie Formation, where erosion has locally cut down to the level of the upper Vaughton Siltstone.

Unit, thickness, age	Lithology	Depositional environment	Stratigraphic relationships
BALMA GROUP			
Bath Range Formation ca 600 m 1599 ± 11 Ma	Sandstone, fine- to coarse-grained, lithic (chert clasts), commonly dolomitic; chert (silicified carbonate), relict peloidal and stromatolitic textures; tuffaceous mudstone, white, rarely greenish or pink, thinly to thickly bedded	Shallow-water (marine?), varying from subtidal storm-dominated to very shallow-water high-energy	Conformable; overlain by Nathan Group but contact not exposed
Baiguridji Formation ca 400 m	Sandstone, commonly dolomitic, fine-grained, thinly bedded, more thickly bedded in west, flaggy; mudstone, grey to black, dolomitic in part; tuffaceous mudstone, white, thinly bedded; rock types are interbedded	Subtidal, storm-influenced in part; shallowing at top	Sharp conformable lower contact with Yarrawirrie Formation; upper contact ?conformable
Yarrawirrie Formation ca 600 m 1621 ± 21 Ma	Dololutite and dolarenite, commonly microbially laminated, stromatolitic, nodular, intraclastic; silty dololutite; dolomitic sandstone, mudstone, commonly dolomitic	Very shallow-water (marine?) or lacustrine; periodic exposure and evaporitic conditions	Base conformable or disconformable in the west, top sharp but conformable
Ngilipitji Conglomerate Member 0–100 m	Conglomerate; polymict with dominantly sandstone clasts, pebble- to cobble-size, friable lithic sandstone matrix	High-energy transgressive marginal ?marine/fluviatile	Base unconformable gradational contact with upper Yarrawirrie Formation
Zamia Creek Siltstone Max ca 300 m	Mudstone, grey, laminated commonly dolomitic; dolostone, brown to grey, microbial laminations, often leached and silicified; minor sandstone; cauliflower chert nodules	Subtidal to very shallow evaporitic conditions	Base is probably conformable; overlain by Yarrawirrie Formation
Conway Formation ca 50–100 m	*Upper:* chert bands (silicified carbonate), grey to white, massive to weakly stromatolitic, interbedded lithology very recessive *Lower*: cherty to dolomitic siltstone, laminated, thinly to medium bedded, black to grey when fresh; sandstone, fine-grained, dolomitic; interbedded khaki green mudstone	Upward-shallowing from subtidal to intertidal	Gradational lower contact with Vaughton Siltstone , locally unconformably overlain by Ngilipitji Conglomerate Member
Vaughton Siltstone ca 600–1000 m	Mudstone, khaki green to black, partly carbonaceous, generally massive; minor sandstone and dolostone interbeds; common siderite nodules; basal conglomerate with friable sandstone matrix; very recessive	Mostly deep subtidal below wave base; marginal ?marine transgressive/fluvial unit at base	Basal contact with Strawbridge Breccia is disconformable; upper contact with Conway Formation gradational; locally unconformably overlain by Yarrawirrie Formation
Strawbridge Breccia <100 m	Chert breccia, relict microbial laminations, stromatolites, intraclastic conglomerate, ooids; locally ferruginous and manganiferous	Shallow intertidal	Base not seen, but probably conformable; upper contact with Vaughton Siltstone disconformable
Koolatong Siltstone >500 m	Mudstone, khaki green to red, sometimes dolomitic, evaporite pseudomorphs and desiccation cracks locally; sandstone, fine- grained, thinly bedded, interbedded with mudstone; dolostone and limestone cycles, grey to buff, microbial-laminated, stromatolitic, intraclastic, ooids	Shallow-water low-energy, locally emergent or evaporitic, some high-energy storm-influenced facies	Conformably and gradationally overlies Parsons Range Group (Fleming Sandstone); upper contact with Strawbridge Breccia not exposed

Table 15.8. Stratigraphic succession of the Balma Group (after Rawlings *et al* 1997 and Haines *et al* 1999).

The age of the Balma Group is constrained by SHRIMP zircon ages of tuffaceous sediments at 1620 ± 21 Ma and 1599 ± 11 Ma (Haines *et al* 1999). Constraints on maximum and minimum ages are provided by the underlying Donydji Group at 1710 Ma (Rawlings *et al* 1997) and the overlying Balbirini Dolostone, which yielded SHRIMP zircon ages of 1613 ± 4 Ma and 1609 ± 3 Ma on a tuff bed near the base (Page *et al* 2000, Jackson and Southgate 2000).

The *Koolatong Siltstone* is the lowermost formation of the Balma Group and comprises a thick succession of mudstone, sandstone and minor carbonate and local stromatolitic chert (**Figure 15.20**). The basal contact with the Fleming Sandstone is gradational (Haines *et al* 1999). Depositional environments were generally shallow and reducing, with periodic exposure. Evaporitic conditions prevailed during the deposition of the lower half of the unit. Haines (1994) interpreted the Fleming Sandstone–Koolatong Siltstone contact as a parasequence boundary correlative of the Masterton Sandstone–Mallapunyah Formation and Kurala Sandstone–Slippery Creek Siltstone contacts of the McArthur and Habgood groups, respectively. Subsequently, Haines *et al* (1999) suggested that the Koolatong Siltstone correlates with most of the Umbolooga Subgroup of the McArthur Group.

The *Strawbridge Breccia* is a resistant ridge-forming unit of chert breccia after stromatolitic carbonate rocks, deposited in a shallow-water, probably intertidal setting. Haines (1994) interpreted an unconformity above the Strawbridge Breccia and suggested that it is a tectonic-related sequence boundary that may extend to the southern McArthur Basin, possibly represented there by an inferred hiatus between the Mitchell Yard and Teena Dolostone members.

The *Vaughton Siltstone* comprises a succession of mudstone, minor sandstone, black shale and dolostone interbeds, deposited mostly in a subtidal environment with a fluvial unit at the base. Black carbonaceous shale with up to 10% pyrite is also present in the lower parts of the formation and it might correlate with the economically important Barney Creek Formation of the McArthur Group (Plumb and Derrick 1975).

The *Conway Formation* is a relatively thin, resistant, ridge-forming unit, consisting of dolomitic siltstone, sandstone and mudstone, followed in the upper part by several prominent chert beds. Geochronological data on the Yarrawirrie Formation shows that the Conway Formation correlates with the Hot Springs Member of the Lynott Formation, with which it shares many lithological similarities (Haines *et al* 1999).

Figure 15.20. Domical stromatolites in dolostone bed within upper Koolatong Siltstone (53L 568700mE 8553000mN, after Haines *et al* 1999: plate 21).

The *Zamia Creek Siltstone* is a recessive unit, comprising mudstone, laminated dolostone and minor sandstone, deposited under subtidal to very shallow evaporitic settings. Haines (1994) correlated the Zamia Creek Siltstone with the Umbolooga Subgroup of the McArthur Group (Reward Dolostone). However, geochronological data from the Yarrawirrie Formation suggest that it as a possible correlative of the upper Lynott and Yalco formations (Haines *et al* 1999).

The *Yarrawirrie Formation* comprises fluvial to shallow-marine polymictic conglomerate (*Ngilipitji Conglomerate Member*) near the base, followed by stromatolitic dololutite, silty dolostone and dolarenite; these were deposited in a shallow-marine to lacustrine environment. Pietsch *et al* (1994) reported a SHRIMP U-Pb single zircon age of 1621 ± 21 Ma from tuffaceous rock in the Yarrawirrie Formation, suggesting a correlation with the Batten Subgroup, possibly the Stretton Sandstone (Haines *et al* 1999).

The *Baiguridji Formation* comprises mainly fine-grained sandstone, mudstone and dolostone, deposited in subtidal, partly storm-influenced environment. It has also been correlated with the Stretton Sandstone of the Batten Subgroup (Haines 1994, Haines *et al* 1999).

The *Bath Range Formation* is the most widely outcropping formation of the Balma Group. It is dominantly arenaceous, with subordinate carbonate rocks and tuffaceous beds. The latter are more common near the base and have yielded a SHRIMP U-Pb zircon age of 1599 ± 11 Ma (Pietsch *et al* 1994). This date overlaps with a SHRIMP date of 1589 ± 3 Ma for the upper Balbirini Dolostone. Depositional environments for the basal part were subtidal and storm dominated. Coarser-grained sandstone higher in the succession was deposited in very shallow, higher-energy, intertidal conditions (Haines *et al* 1999).

Vizard Group

Units assigned to the Vizard Group (Abbott *et al* 2001) were previously included in the Vizard Formation of the McArthur Group (Dunn (1963c). The Group is exposed over an area of 100 km^2, about 50 km southeast of Roper Bar. Its distribution is partly controlled by the Urapunga Fault Zone, which Rawlings (1999) attributed to structural imbrication during post Roper Group inversion. The Vizard Group is about 300 m thick and is divided into a lower unit, the Saint Vidgeon Formation, consisting predominantly of stromatolitic carbonates, and an upper unit, the Nagi Formation, consisting mostly of fine-grained siliciclastic rocks (**Table 15.9**). The Mount Birch Sandstone (Nathan Group) overlies the Vizard Group with a regional unconformity. SHRIMP U-Pb zircon dates from tuffaceous beds in the Vizard Group (Page *et al* 2000, see below) provide a firmer basis for a correlation with the Umbolooga Subgroup of the McArthur Group.

The *Saint Vidgeon Formation* comprises a succession of dolostone, dolomitic and tuffaceous siltstone, potassium-metasomatised sedimentary rocks and chert. Coxco Needles, acicular gypsum pseudomorphs and stromatolites are evident in places. The uppermost part of the formation consists of thinly bedded silty dololutite and fine dolomitic sandstone, pyritic black shale, and rare interbeds of medium-grained dolomitic sandstone. A silicified unit that locally preserves conical stromatolites commonly caps the formation. By analogy with Winefield's (1999) Barney Creek depositional cycle, the entire unit is marine. SHRIMP U-Pb zircon dating of a tuff bed, about 30 m above the base of the formation, has yielded an age of 1640 ± 4 Ma; this is indistinguishable from age determinations of the Barney Creek Formation (Page *et al* 2000).

The *Nagi Formation* is a succession of fine-grained arkose and shale, dolomitic sandstone and siltstone, K-metasomatised sedimentary rocks and tuff, and chert. This unit was deposited under fluvial to shallow-marine environments. It was formerly mapped as part of the Vizard Formation (Dunn 1963c). The Mount Birch Sandstone (Nathan Group) overlies the Nagi Formation with a regional unconformity. Zircons from a tuff bed near the base of the formation have yielded a SHRIMP U-Pb age of 1634 ± 4 Ma (Page *et al* 2000). Thus, the Nagi Formation correlates with the upper McArthur Group (cf Lynott Formation: 1636 ± 4 Ma).

Other units of the Glyde Package

Outside the Batten, Walker and Urapunga Fault zones, the Glyde package rarely outcrops and is locally absent. Possible stratigraphic equivalents in the northeastern McArthur Basin are the Jalma Formation, Mount Bonner Sandstone and Durabudboi beds.

The *Jalma Formation* is a succession of sandstone, mudstone and minor carbonate, restricted to the central northeastern McArthur Basin. It unconformably overlies the Coast Range Sandstone and locally, the Grindall Formation, and is overlain with a probable unconformity by the Balbirini Dolostone. Based on stratigraphic position, the Jalma Formation may correlate with part of the Parsons Range Group or the Balma Group (Haines *et al* 1999).

The *Mount Bonner Sandstone* comprises fluvial conglomerate and sandstone, exposed on the northern part of the northeastern McArthur Basin. It rests unconformably on most units of the Spencer Creek Group and is, in turn, unconformably overlain by conglomerate, sandstone and dolostone of the Balbirini Dolostone (Nathan Group). On the basis of lithofacies similarities and stratigraphic position, Rawlings *et al* (1997) correlated the Mount Bonner Sandstone with the Jalma Formation and proposed that these two formations represent greatly attenuated lateral facies variants of the Parsons Range, Habgood and Balma groups.

The *Durabudboi beds* comprise mainly laminated mudstone and minor dolomitic rocks, poorly exposed in the northern part of the northeastern McArthur Basin. These were previously assigned to the Cretaceous succession. The Durabudboi beds lie beneath the Roper Group and may be a part of the lower Roper Group, but correlation with the Habgood Group (or perhaps an attenuated equivalent of part of that succession) is favoured (Rawlings *et al* 1997, Rawlings 1999).

MESOPROTEROZOIC

Favenc Package

The Favenc Package comprises a regionally extensive 50 to 1600 m-thick succession of stromatolitic dolostone–sandstone, deposited in a shallow-water, marginal-marine, peritidal-shelf and/or continental-sabkha environment (Rawlings 1999). Mafic volcanics are also known in the Urapunga area (Abbott *et al* 2001). The package includes the widespread Nathan Group, deposited over most of the McArthur Basin, and the Mount Rigg Group in the northeast. Sediments of the Favenc Package unconformably overlie the Glyde Package successions and are in turn unconformably overlain by Wilton Package strata. The Favenc Package corresponds to the P8 interal of Ahmad (2000).

The age of Favenc Package is constrained by SHRIMP zircon dating of the lower and upper Balbirini Dolostone from the type section within the Batten Fault Zone, at 1613 ± 4 Ma and 1589 ± 3 Ma, respectively (Page *et al* 2000). The significant difference between these dates suggests a major break in the Nathan Group at this stratigraphic level. Rawlings (2000) indicated that the lower part of the Balbirini Dolostone may be actually part of the McArthur Group and that a major unconformity might occur within the Nathan Group. Further work is needed to clarify this situation.

Nathan Group

Jackson *et al* (1987) recognised a regional unconformity within the upper part of the McArthur Group, as revised by Plumb and Brown (1973). They erected the Nathan Group to encompass those formations above this hiatus, but older than the unconformably overlying Roper Group. The Nathan Group includes a relatively thin and lenticular basal siliciclastic and often conglomeratic unit, overlain by thicker carbonate and siliciclastic rocks.

In the Batten Fault Zone, the Nathan Group is divided into three formations (**Table 15.10**) and attains a thickness of about 1600 m. The basal *Smythe Sandstone* comprises a 250 m-thick succession of fluvial conglomerate, sandstone and minor sandy dolarenite. Conglomerate clasts were derived from the underlying McArthur Group. The *Balbirini*

Unit and thickness	Lithology	Depositional environment	Stratigraphic relations
VIZARD GROUP			
Nagi Formation 220 m	Arkose, shale, dolomitic sandstone and siltstone, K-metasomatised sedimentary rocks and tuff, chert	Unit 1: Fluvial floodplain to peritidal; Unit 2: storm-dominated shelf; Unit 3: peritidal carbonate	Disconformably overlies Saint Vidgeon Formation; overlain unconformably by Mount Birch Sandstone
Saint Vidgeon Formation 110 m	Dolostone, dolomitic and tuffaceous siltstone, tuff, chert	Upward-fining and -deepening succession, from shallow-marine into locally anoxic shale facies	Base not seen; overlain disconformably by Nagi Formation

Table 15.9. Stratigraphic succession of the Vizard Group after Abbott *et al* (2001).

Dolostone gradationally overlies the Smythe Sandstone and comprises mainly dolarenite, stromatolitic dololutite, silty dololutite, dolomitic shale and K-metasomatised mudstone (**Figure 15.21**). This succession was deposited in a shallow-marine to continental-sabkha environment. The overlying *Dungaminnie Formation* is a succession of siltstone and fine-grained sandstone followed by stromatolitic dolostone. This unit is restricted to a syncline around the top of the Abner Range. The lower part of the formation was deposited in slightly deeper-water conditions in comparison to the upper part, which is considered to have been deposited under conditions similar to those of the Balbirini Dolostone.

In the southeastern McArthur Basin, the Nathan Group (**Table 15.10**) is represented by the *Karns Dolostone*, which is up to about 700 m thick and comprises a succession of fluvial to shallow-marine stromatolitic and evaporitic carbonate rocks, with lesser sandstone, mudstone and conglomerate near the base. It unconformably overlies various units of the Tawallah Group and is unconformably overlain by the Roper Group. It was interpreted by Roberts

Unit, thickness and age	Lithology	Depositional environment	Stratigraphic relations
URAPUNGA FAULT ZONE (NATHAN GROUP)			
Walmudga Formation 250 m	Oolitic, banded and stromatolitic chert (silicified carbonate rocks), quartz sandstone, siltstone and shale	Peritidal carbonate ramp and subtidal high-energy sand flat	Lower contact is conformable; upper contact is regional unconformity marked by pronounced palaeoregolith
Yalwarra Volcanics 80–115 m	Basalt, peperite, volcanigenic sandstone and conglomerate; minor siltstone and chert	Lacustrine or marine shoreline setting within lava-dominated terrane	Sharp, but not obviously unconformable lower contact; gradational conformable upper contact
Knuckey Formation 150 m?	Dolomicrostone, dolomitic siltstone and sandstone, stromatolitic dolostone, mudstone and chert	Peritidal, from subtidal to supratidal	Lower and upper contacts are both conformable
Mount Birch Sandstone ca 5–100 m	Dolomitic and quartz sandstone; conglomerate near base	Fluvial, braided stream	Unconformable on Vizard Group and on Urapunga Granite/Mount Reid Rhyolite; upper contact gradational and conformable
SOUTHERN McARTHUR BASIN (NATHAN GROUP)			
Dungaminnie Formation <240 m	*Upper*: Laminated sandy dolarenite and dololutite; stromatolitic, intraclasts, ooids and ripples *Lower*: Thinly bedded fine sandstone and siltstone with rare conglomerate lenses	Shallow-water to emergent; terrestrial mainly fluvial	Conformably overlies Balbirini Dolostone and unconformably overlain by Roper Group
Balbirini Dolostone <1500 m 1613 ± 4 Ma 1609 ± 3 Ma	Dololutite, dolomitic siltstone and shale, silty dololutite more common in lower part of unit and frequently containing evaporite pseudomorphs and in places cauliflower cherts; conical, large columnar, stratiform and domal stromatolites; diagnostic ooid dolostone beds; rare thin sandstone beds	Shallow-marine to emergent (continental playa or sabkha)	Unconformably overlies Batten Subgroup and unconformably overlain by Roper Group
Smythe Sandstone <100–250 m	Massive, coarse polymict conglomerate, pebbly lithic (chert) sandstone, typically poorly sorted and prominently cross-bedded; sandstone, minor sandy dolarenite	Terrestrial - mainly fluvial (alluvial fan and debris flow)	Unconformably overlies Batten Subgroup and unconformably overlain by Roper Group
Karns Dolostone <700 m	Quartz arenite and dolarenite with cross-beds and ripples; gypsum and halite casts, cauliflower chert pebble beds and chert clasts common; stromatolitic dolostone with thin interbeds of dolarenite and quartzarenite (ooids and intraclast breccia)	Shallow-marine to emergent; terrestrial mainly fluvial	Unconformable on Tawallah/ McArthur groups and unconformably overlain by Roper Group or Bukalara Sandstone
NORTHWEST McARTHUR BASIN (MOUNT RIGG GROUP)			
Dook Creek Formation < 220 m	Stromatolitic and intraclastic dolostone, mudstone and siltstone; laminated very fine sandstone and coarse siltstone	Peritidal, from shallow-subtidal to supratidal; storm-dominated marine shelf in upper part	Lower contact conformable; upper contact inferred to be disconformable or conformable
Jamberline Sandstone Member 200+ m	Medium to coarse and pebbly quartz sandstone, chert-clast conglomeratic sandstone; minor dolomitic siltstone	Proximal fluvial and shallow-marine	Sharp, probably erosive base; upper contact conformable
Bone Creek Sandstone 20–30 m	Medium to coarse quartz sandstone; scattered granules and pebbles of quartz, jasper and chert	Probably shallow-marine	Conformable on Margaret Hill Conglomerate, or unconformable on West Branch Volcanics/Gundi Sandstone/McCaw Formation
Margaret Hill Conglomerate 0–300 m	Thickly to very thickly bedded polymictic pebble, cobble and boulder conglomerate; purple lithic sandstone and granule conglomerate	High-energy alluvial fan or proximal braided stream	Unconformable on West Branch Volcanics; conformable overlain by Bone Creek Sandstone

Table 15.10. Stratigraphic succession of the Nathan Group and equivalents across the McArthur Basin constructed after Abbott *et al* (2001), Pietsch *et al* 1991, Kruse *et al* (1994) and Rawlings *et al* (1997).

et al (1963) to be a shelf equivalent of the McArthur Group in the Batten Fault Zone, whereas Jackson *et al* (1987) and Pietsch *et al* (1991) correlated it with the Nathan Group.

In the Urapunga Fault Zone, the Favenc Package is represented by a succession of dolostone, chert, and dolomitic sandstone, siltstone, sandstone, conglomerate, and mafic volcanic rocks. It unconformably overlies the Vizard Group and locally rests directly on the Mount Reid Rhyolite and Urapunga Granite (see **Other Palaeoproterozoic inliers**). The whole succession was previously assigned to the Balbirini Dolostone of the Nathan Group (Jackson *et al* 1987) but has been subsequently subdivided by Abbott *et al* (2001) into four named units. The *Mount Birch Sandstone* comprises a succession of dolomitic and quartz sandstone with a lenticular basal conglomerate. It is interpreted to be of fluvial origin and is probably a braided stream deposit. The unit is correlated with the Smythe Sandstone in the Batten Fault Zone and with the Bone Creek Sandstone of the Mount Rigg Group in the northwestern McArthur Basin. The *Knuckey Formation* [lower part of the former Kookaburra Creek Formation of Dunn (1963c)] is a succession of dololutite, dolomitic siltstone and sandstone, stromatolitic dolostone, shale, mudstone and chert, deposited in subtidal to supratidal environments. The Knuckey Formation conformably overlies the Mount Birch Sandstone and is overlain conformably by the Yalwarra Volcanics. It is correlated with the lower Balbirini Dolostone and lower Dook Creek Formation. The *Yalwarra Volcanics* comprises a succession of basalt and peperite that alternates with prominent ridges of volcanigenic sandstone. Oolitic chert is interbedded with the uppermost sandstone of the Yalwarra Volcanics and indicates a gradation into the overlying Walmudga Formation. Basaltic volcanism of this age is not known elsewhere in the McArthur Basin and the Yalwarra Volcanics may reflect a local extensional event and associated tectonic uplift across the crest of the Urapunga Fault Zone (Abbott *et al* 2001). The *Walmudga Formation* conformably overlies the Yalwarra Volcanics and comprises oolitic, laminated, and stromatolitic chert (silicified carbonate rock), fine- to medium-grained quartz and feldspathic sandstone, dolomitic siltstone, and purple-brown mudstone and shale. Lithic arkose and granule conglomerate are present locally. This succession corresponds to the former Kookaburra Creek Formation above the Yalwarra Volcanics. The depositional environments include peritidal carbonate-ramp, and tidal sand flat.

Figure 15.21. Conical stromatolites (transverse sections) in lower Balbirini Dolostone (53L 585200mE 8509000mN, after Haines *et al* 1999: plate 21).

In the northeastern McArthur Basin and in the Walker Fault Zone, rocks formally assigned to the 'Kookaburra Creek Formation' and Blue Mud Bay Beds by Plumb and Roberts (1965) are now mostly assigned to the *Balbirini Dolostone* (Haines *et al* 1999). Most outcrops in this area are silicified and are dominated by white to grey chert, commonly displaying relict textures after shallow-water carbonates, with scattered interbedded sandstone. The primary lithologies are interpreted to consist of interbedded ooidal, intraclastic, stromatolitic and evaporitic dolostone interbedded with minor sandstone. On the basis of lithological similarities and the presence of ooid-rich dolostone, Haines *et al* (1999) suggested that the succession in this area probably only represents the upper part of the Balbirini Dolostone, as defined at the type section in the Abner Range area (Jackson *et al* 1987).

Mount Rigg Group

The Mount Rigg Group (**Table 15.10**) is a succession of dolomitic and siliciclastic rocks, unconformably overlying the Katherine River Group and separated from the overlying Roper Group with a well defined regional unconformity. It consists of three formations: the Margaret Hill Conglomerate, Bone Creek Sandstone and Dook Creek Formation. These formations are exposed in a 30 km-wide, northeast-trending belt in the northwestern McArthur Basin and are estimated to be about 600–800 m thick (Sweet *et al* 1999). Plum and Derrick (1975) correlated the Mount Rig Group with the McArthur Group, but on the basis of lithology and diagnostic columnar stromatolites, it was subsequently correlated with the Nathan Group (Plumb 1985, Jackson *et al* 1987, Walter *et al* 1988, Sweet *et al* 1999).

A succession of poorly sorted conglomerate, sandstone and polymictic pebble to cobble conglomerate, deposited as alluvial fan or proximal braided stream systems in the upper reaches of Waterhouse River north of Beswick, has been defined as the *Margaret Hill Conglomerate* by Kruse *et al* (1994). Similar conglomerate, forming the base of the Bone Creek Formation further north, was described by Sweet *et al* (1999).

The *Bone Creek Sandstone* (previously Bone Creek Formation) is dominated by shallow-marine, white to pale yellow, thickly bedded, medium- to coarse-grained quartzic sandstone (locally glauconitic), with local debris flow or talus conglomerate and breccia at the base.

The *Dook Creek Formation* makes up the bulk of the Mount Rigg Group and comprises dololutite, dolomitic siltstone and sandstone, stromatolitic and oolitic dolostone, siltstone, and quartz sandstone, deposited in peritidal to shallow-marine settings (**Figure 15.22**). It overlies the Bone Creek Sandstone with a conformable, gradational contact and is overlain, with a regional unconformity, by the Limmen Sandstone of the Roper Group; a palaeoregolith is developed below the Roper Group unconformity.

Wilton Package

The Wilton Package (Roper Superbasin of Jackson *et al* 2000) comprises the regionally extensive Roper

Group (aerial extent 145 000 km²), which is widespread throughout the McArthur Basin. It corresponds to the P̱9 interval of Ahmad (2000) and is correlated with other Mesoproterozoic successions of northern Australia, eg the South Nicholson Group (South Nicholson Basin) and the Renner Group (Tomkinson Province). The widespread distribution of these correlated strata may justify separate basin or sub-basin (incorporating the Beetaloo Sub-basin) status. The Roper Group comprises a upward-coarsening cyclic succession of mainly marine mudstone alternating with sandstone (**Table 15.11**). Minor lithologies include pedogenic sedimentary breccia, fluvial sandstone, micritic and intraclastic limestone, and ooidal ironstone. Sequence stratigraphical observations have been used to identify six large-scale upward-coarsening cycles (Jackson *et al* 1988, Abbott and Sweet 2000). Post-depositional mafic sills and dykes were emplaced during a regional extensional event. The rocks of the Roper Group are essentially flat lying and the preserved thickness ranges from 1500 m over most areas to greater than 3 km further south in the Beetaloo Sub-basin (Silverman *et al* 2007). This thickening is confirmed by the southern McArthur Basin seismic transect (Rawlings *et al* 2004). Individual formations show remarkable lateral continuity and can be traced over most of the McArthur Basin. Abbott *et al* (2001) gave a thickness of 1.8 km for the succession in the Urapunga area.

Plumb and Wellman (1987) suggested that the Roper Group was deposited during a sag phase of basin development with a depocentre in the Beetaloo Sub-basin. Jackson *et al* (1987) considered that the Roper Group represents an epicontinental basin succession, distinct from the McArthur Basin. Jackson *et al* (1999) proposed the term Roper Superbasin and included the South Nicholson Basin as a part of it.

The *Beetaloo Sub-basin* is centered about 300 km southeast of Katherine and extends over an area of 15 000 km² (**Figure 15.1**, **15.23**). It represents a thick succession of the Roper Group and is defined by a pronounced gravity low, seismic profiles, drilling and magnetotelluric data (Plumb and Wellman 1987, Lanigan *et al* 1994). The sub-basin is a largely flat-lying depocentre with uplifted erosional margins, consisting of three sandstone to mudstone successions. The lower two successions are assigned to the Roper Group and are

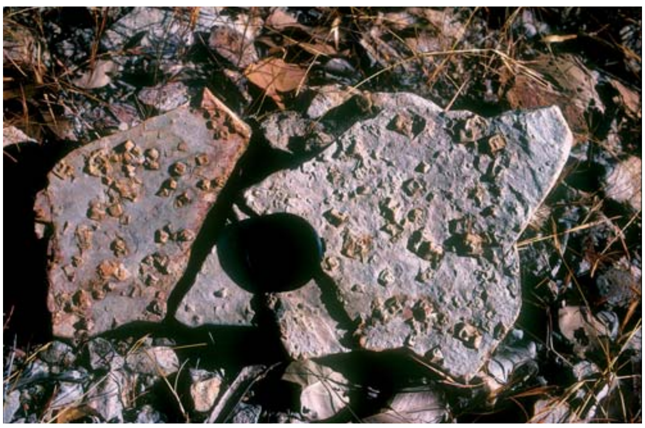


Figure 15.22. Halite casts on bedding surface of fine sandstone of Dook Creek Formation. Roper River area; precise location unknown (after Abbott *et al* 2001: figure 10).

unconformably overlain by the informally named 'Jamison sandstone' and 'Hayfield mudstone'. These units may be as young as Neoproterozoic (Lanigan *et al* 1994), in which case they would not form part of the McArthur Basin (*sensu stricto*). This succession is successively overlain by volcanic rocks of the Kalkarindji Province, and by Neoproterozoic–Palaeozoic Georgina Basin and Mesozoic Carpentaria Basin strata (**Figure 15.24**). For the purpose of this publication, the Beetaloo Sub-basin is considered to be part of the Roper Group succession of the McArthur Basin. This sub-basin has attracted significant petroleum exploration activity (see **Petroleum**).

The age of the Roper Group is constrained by a Rb-Sr determination of 1429 ± 31 Ma for diagenetic illite in the McMinn Formation (Kralik 1982) and a SHRIMP U-Pb zircon date of 1492 ± 4 Ma for a tuffaceous bed within the lower Mainoru Formation (Jackson *et al* 1999). A minimum age of 1324 ± 4 Ma comes from SHRIMP dating of baddeleyite from the Derim Derim Dolerite (Abbott *et al* 2001). The unconformity at the base of the Roper Group is considered to be related to the Isan Orogeny (1580–1560 Ma) and Jackson *et al* (1999) estimated a break in deposition of 80–90 My.

Dunn (1963c) assigned the upper part of the Roper Group to the Maiwok Subgroup, but the lower formations were not included in a subgroup. Abbott *et al* (2001) defined the name Collara Subgroup to describe the formations from the base to the top of the Hodgson Sandstone (**Figure 15.25**). The Collara Subgroup is characterised by a high proportion of tidal-platform sandstone relative to the Maiwok Subgroup, which is mudstone dominated.

Collara Subgroup

Depending on location, the basal unit of the Collara Subgroup is the Phelp Sandstone, Mantungula Formation or Limmen Sandstone. The *Phelp Sandstone* consists of white quartz sandstone, siltstone and minor conglomerate, deposited under fluvial conditions. The formation is best developed in the northwestern Roper River region in the northwestern McArthur Basin. The conformably overlying *Mantungula Formation* is a recessive unit of mudstone and siltstone, with a local basal conglomerate. The *Limmen Sandstone* comprises fluvial to shallow-marine, quartz-rich to sublithic, fine- to coarse-grained sandstone, locally incorporating basal granule- to pebble-rich intervals. The *Mainoru Formation* includes red and green mudstone, glauconitic and micaceous siltstone and sandstone, glauconitic sandstone, limestone, and calcareous mudstone. Based on lithology, the formation was divided by Abbott *et al* (2001) into six formally named members, namely the Showell, Wooden Duck, Mountain Valley Limestone, Nullawun, Wadjeli, and Gibb members. The *Mountain Valley Limestone Member* is lithologically distinctive and comprises green laminated mudstone and limestone, deposited under shallow-marine to tidal-flat environments. Other members represent mudstone separated by sandstone intervals. The *Wadjeli Sandstone Member* includes intervals of oolitic ironstone (**Figure 15.26**). Other members consist of mudstone and sandstone. The gradationally overlying *Crawford Formation* is a mostly fine-grained micaceous and glauconitic sandstone unit with subsidiary siltstone and mudstone.

The overlying *Abner Sandstone* in the Roper River Region was divided into four mappable members (Dunn

Unit, thickness and age	Lithology	Depositional environment	Stratigraphic relations
Derim Derim Dolerite 1324 ± 4 Ma	Medium to coarse dolerite		Sills and some dykes intrude Roper Group
ROPER GROUP			
MAIWOK SUBGROUP			
Chambers River Formation <300 m	Thinly to medium bedded, laminated micaceous siltstone and mudstone; minor very fine sandstone	Storm-dominated shelf	Probably conformable on Bukalorkmi Sandstone
Bukalorkmi Sandstone 10–20 m	Thinly to medium bedded, trough cross-stratified, well sorted, fine quartz sandstone	Coastal tidal platform	Contact with Kyalla Formation is sharp and probably erosional (disconformable)
Kyalla Formation ca 250 m	Interbedded siltstone, sandstone and mudstone	Storm-dominated shelf	Gradational and conformable on Sherwin Formation
Sherwin Formation Up to 100 m	Interbedded sandstone, siltstone and mudstone; local pisolitic ironstone lenses	Fluvial to marginal marine	Gradational and conformable on Moroak Sandstone
Moroak Sandstone 2.5–420 m	Thinly to medium bedded, medium to fine quartz sandstone; coarse-grained and quartz-granule intervals	Coastal tidal platform	Disconformable on Velkerri Formation
Velkerri Formation 330 m	Grey and black mudstone and siltstone; minor fine glauconitic sandstone	Distal shelf	Conformable on Bessie Creek Sandstone
Bessie Creek Sandstone ca 20–56 m	Fine to medium, locally coarse and granule-rich quartz sandstone	Coastal tidal platform	Disconformable on Corcoran Formation
Corcoran Formation ca 180–225 m	Laminated green-grey to black mudstone and siltstone; minor fine sandstone	Distal shelf, and storm-dominated shelf	Grades up from Munyi Member
Munyi Member 13–23 m	Red to brown ferruginous sandstone, siltstone, mudstone, conglomerate and pisolitic ironstone	Shallow-marine to fluvial	Disconformable to conformable on Hodgson Sandstone
COLLARA SUBGROUP			
Hodgson Sandstone 30–130 m	White to pink, fine to coarse, strongly trough cross-bedded quartz sandstone	Coastal tidal platform	Overlies Jalboi Formation with gradational, or in some areas, erosive contact
Jalboi Formation 117–230 m	Interbedded fine sandstone and siltstone, alternating with medium to thick beds of medium quartz sandstone	Storm-dominated shelf	Disconformable on Crawford Formation
Arnold Sandstone 0–123 m	White cross-bedded quartz sandstone	Coastal tidal platform	Overlies Crawford Formation with minor disconformity; overlain unconformably by Jalboi Formation
Crawford Formation 0–235 m	Thickly bedded, fine micaceous and glauconitic sandstone; thinly interbedded sandstone, siltstone and mudstone; minor trough cross-bedded medium quartz sandstone	Storm-dominated shelf	Conformable on Showell Member of Mainoru Formation; overlain by Arnold Sandstone with sharp, probably erosive contact, or by Jalboi Formation with disconformable contact
Mainoru Formation 1492 ± 4 Ma 1493 ± 4 Ma	Shale and siltstone, glauconitic and micaceous sandstone, micritic and intraclastic limestone, calcareous and non-calcareous mudstone		
Showell Member 40–155+ m	Laminated calcareous mudstone; scattered glauconite, sulfides, and carbonate nodules; laminated limestone near base	Distal to storm-dominated shelf	Conformable on Wooden Duck Member; overlain conformably by Crawford Formation or disconformably by Jalboi Formation
Wooden Duck Member 55–350+ m	Greyish-green mudstone and fine micaceous glauconitic sandstone	Storm-dominated shelf	Conformable on Mountain Valley Limestone Member; overlain conformably by Showell Member
Mountain Valley Limestone Member 55–80 m	Green laminated mudstone interbedded with intraclast limestone	Shallow-marine, tidal flat	Conformable on Nullawun Member; overlain conformably by Wooden Duck Member
Nullawun Member 71.5 m	Massive red-brown mudstone and mudstone breccia	Non-marine mudstone, probably fluvial floodplain deposits; brecciated during palaeosol formation	Apparently disconformable on Limmen Sandstone; conformably overlain by Mountain Valley Limestone Member
Wadjeli Sandstone Member 15 m	Medium bedded, medium to fine sandstone; minor ironstone and ferruginous sandstone	Storm-dominated shelf to coastal tidal platform	Conformable on Gibb Member; overlain conformably by Nullawun Member
Gibb Member 0–250 m	Dark grey and olive-black mudstone, fine sandstone	Storm-dominated marine	Conformable between Limmen Sandstone and Wadjeli Sandstone Member
Limmen Sandstone 20–100 m	Fine to very coarse and granule-rich quartz sandstone; minor micaceous siltstone	Fluvial to shallow-marine shoreline sandstone	Erosive lower contact with Mantungula Formation, conformable upper contact with Gibb Member
Mantungula Formation <100–150 m	Mudstone, siltstone	Storm-dominated marine shelf	Apparently conformable on Phelp Sandstone; contact with Limmen Sandstone appears to be erosive
Phelp Sandstone <40–80 m	Quartz sandstone and siltstone; minor conglomerate and breccia	Fluvial and shallow-marine	Overlies Nathan Group with regional unconformity; overlain conformably by Mantungula Formation

Table 15.11. Stratigraphic succession of the Roper Group after Abbott *et al* (2001).

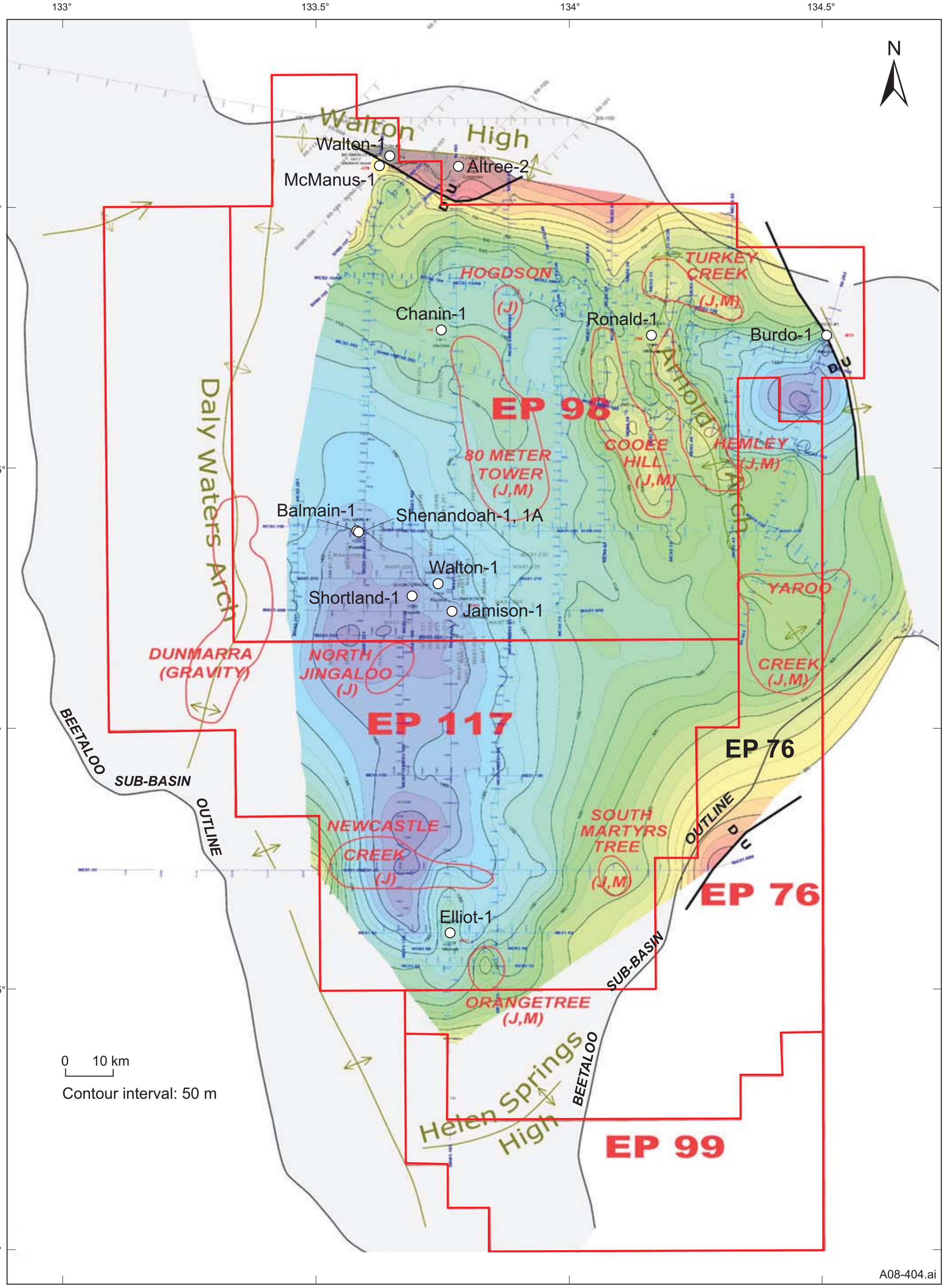


Figure 15.23. Tectonic elements of the Beetaloo Sub-basin. Basin-wide structure map of Moroak Sandstone, as interpreted from seismic and well data. Cold colours (blues) represent basin depocentres and hot colours (reds) are highs (after Silverman *et al* 2007).

1963a, b, c): the Arnold Sandstone, Jalboi, Hodgson Sandstone and Munyi members. Haines *et al* (1993) assigned the Munyi Member to the base of the Corcoran Formation, rather than to the top of the Abner Sandstone. Abbott *et al* (2001) raised the other three former members to formation rank. An unconformity separates the Jalboi Formation from the units beneath it. The use of the term Abner Sandstone is now restricted to an undifferentiated succession in the Abner Range, in the southern McArthur Basin.

The *Arnold Sandstone* is a thin unit of white, thickly bedded, mainly medium-grained quartz sandstone, which is strongly planar cross-bedded. The *Jalboi Formation* consists of mudstone, siltstone, and sandstone. It is locally disconformable on the Arnold Sandstone and/or the Crawford Formation.

The *Hodgson Sandstone* is a resistant unit dominated by quartz-rich sandstone. The lower contact is conformable and gradational with the Jalboi Formation. The upper contact, with the Munyi Member of the Corcoran Formation, was considered to be disconformable by Haines *et al* (1993).

Maiwok Subgroup

The term Maiwok Subgroup was assigned by Dunn (1963a, c) and Randal (1963) to include Roper Group strata above the Bessie Creek Sandstone. Walpole *et al* (1968) noted that the Maiwok Subgroup is distinguished by a greater proportion of finer-grained units than the lower Roper Group and by the presence of oolitic ironstone. Abbott *et al* (2001) redefined the subgroup to include the Corcoran Formation and all younger units up to and including the Chambers River Formation. They noted that the finer-grained succession dominates from the top of the Hodgson Sandstone, rather than from the top of the Bessie Creek Sandstone.

The *Corcoran Formation* comprises a succession of laminated mudstone, siltstone and minor sandstone, deposited in a marine shelf environment. The basal *Munyi Member* is a succession of dark red- to brown-weathering, locally ferruginous sandstone, siltstone, mudstone, minor conglomerate and minor pisolitic ironstone.

The *Bessie Creek Sandstone* comprises fine- to medium-, locally coarse-grained and granule-rich quartz sandstone. The sandstone units are mainly thinly to medium bedded and are trough cross-stratified. In a region of low dip in the Roper River Region, the formation caps mesas and buttes. The most spectacular such occurrence, colloquially named the 'Ruined City', is characterised by joint-bounded, karstically weathered towers up to 50 m high (**Figure 15.27**).

The *Velkerri Formation* comprises grey and black mudstone and siltstone, with calcite nodules and pyrite stringers, which was deposited in a distal shelf setting (Abbott *et al* 2001). In BMR drillhole Urapunga-4 (nominated as the type section), the Velkerri Formation is 330 m thick and it attains a thickness of 880 m to the south in the Beetaloo Sub-basin.

The *McMinn Formation* consists of interbedded blocky quartz sandstone, tabular micaceous sandstone, siltstone and shale. It was originally subdivided into four members; these were, in ascending order, the Moroak Sandstone Member, Sherwin Ironstone Member, Kyalla Member and Bukalorkmi Sandstone Member (Dunn 1963 a, b, c). All of these are now assigned formation status and were defined by Abbott *et al* (2001). The *Moroak Sandstone* consists of an upward-coarsening thinly to medium bedded, medium- to fine-grained quartz sandstone that contains coarse-grained and quartz-granule-rich intervals up to 1 m thick near the base. As defined by Dunn (1963c), it included an overlying succession of interbedded sandstone, siltstone, and mudstone. Abbott *et al* (2001) included this overlying succession as a part of the Sherwin Formation. The *Sherwin Formation* is characterised by the presence of oolitic ironstone, but is dominated volumetrically by interbedded sandstone, siltstone and mudstone. The upper boundary is defined as the last occurrence of oolitic ironstone. Significant low-grade ironstone deposits are known from this formation and were drilled by BHP in the 1950s (Cochrane 1955, Bennett and Heaton 1958, Salamy 1958, Vivian 1962; see **Mineral resources**). The *Kyalla Formation* overlies the Sherwin Formation and comprises interbedded siltstone, sandstone and mudstone; the upper part is sandstone rich. The *Bukalorkmi Sandstone* is the youngest of the quartz sandstone formations in the Roper Group and is mapped in the Roper River region. Possible correlates may exist in the Beetaloo Sub-basin (Abbott *et al* 2001).

In the Roper River region, the *Chambers River Formation* is the youngest unit of the Roper Group. It is dominated by thinly to medium bedded, laminated micaceous siltstone and mudstone, and subordinate very fine-grained sandstone. This unit is not recognised elsewhere, but possible correlates occur in the Beetaloo Sub-basin (Abbott *et al* 2001).

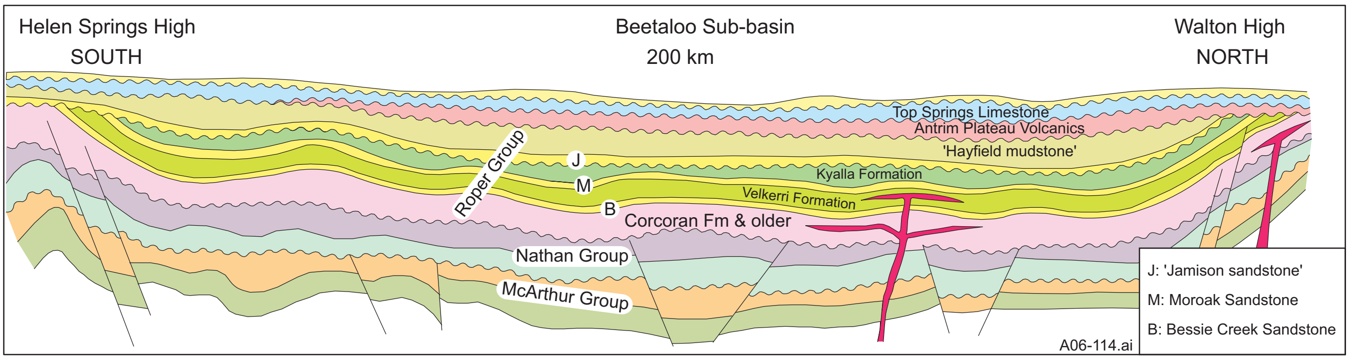


Figure 15.24. Schematic cross-section through the Beetaloo Sub-basin (after Silverman *et al* 2007).

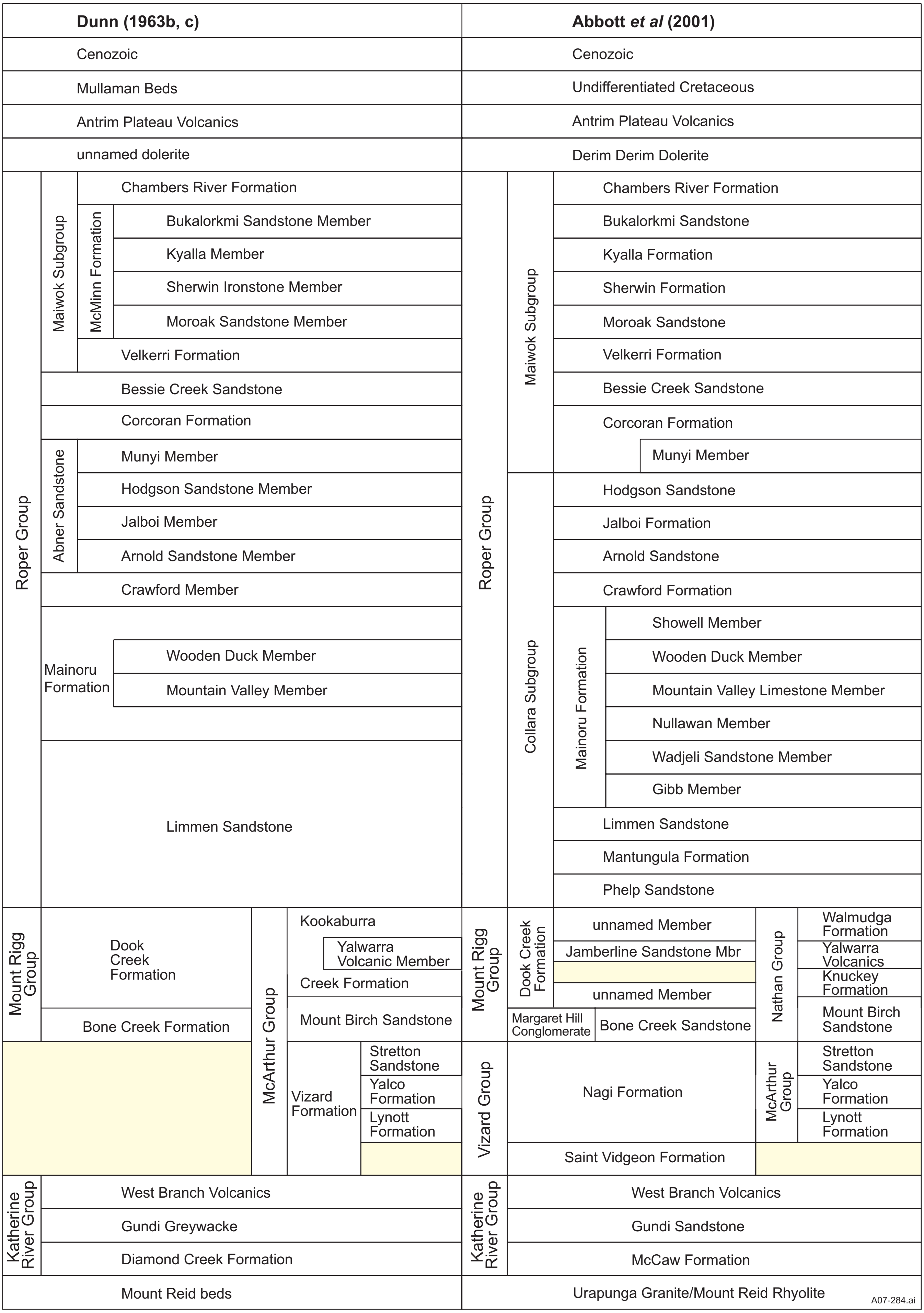


Figure 15.25. Comparison of Dunn (1963b, c) and Abbott *et al* (2001) stratigraphic nomenclature of Roper Group (after Abbott *et al* 2001). Stratigraphic position of Margaret Hill Conglomerate (Kruse *et al* 1994) within Mount Rigg Group is also shown.

Derim Derim Dolerite

Dolerites intruding the Roper Group are quite uniform in composition and mineralogy, and have collectively been named the Derim Derim Dolerite (Abbott *et al* 2001). They have a strong magnetic response, due to high magnetite contents, and form prominent features on aeromagnetic images. The dolerites are fine- to coarse grained, and consist mainly of plagioclase, clinopyroxene and opaque minerals. The dolerite weathers to produce eluvial and colluvial heavy mineral concentrates rich in ilmenite and titanomagnetite.

U-Pb SHRIMP dating of baddeleyite from a sample of the Derim Derim Dolerite has yielded an age of 1324 ± 4 Ma (Abbott *et al* 2001). This provides the best estimate for the age of intrusion of the dolerite suite, and supersedes the previous minimum age of 1280 Ma by McDougall *et al* (1965). The SHRIMP date also provides a maximum age for post-Roper Group deformation, because the dolerites were deformed with the Roper Group and were clearly intruded before the deformation event (Abbott *et al* 2001).

MINERAL RESOURCES

The McArthur Basin is one of the most significant base metal provinces of Australia and forms part of the Carpentaria Zinc Belt, extending from Mount Isa in the south to Milingimbi in the north. A number of world-class base metals deposits are known from this belt, including Mount Isa, Hilton, George Fisher and Century in Queensland and McArthur River (formerly HYC: 'Here's Your Chance') in the Northern Territory.

The McArthur Basin hosts over three hundred mineral occurrences, but significant mining activity has taken place only at McArthur River, Merlin and Redbank (**Figure 15.28**). Mineral commodities include base metals (lead, zinc, silver, copper), uranium, iron ore, manganese, barite and phosphate. Diamondiferous kimberlite pipes (Merlin, AB021 and E.Mu) intruded the succession during the Palaeozoic.

Deposit types include: (a) stratiform, sedimentary base-metals deposits hosted in pyritic organic rich shale and siltstone eg McArthur River; (b) stratabound, discordant base-metals deposits, eg Coxco, Cooley and Ridge; (c) copper-bearing breccia pipes, eg Redbank; (d) copper in shear zones and veins; (e) uranium deposits within sandstone or volcanic rocks, eg Westmoreland deposits; (f) stratiform oolitic ironstone occurrences within the Sherwin Formation eg Roper River iron ore; (g) irregular manganese occurrences associated with the Karns Dolostone and Echo Sandstone, eg Calvert Hill deposits; (h) sedimentary phosphate occurrences within the Echo Sandstone/Karns Dolostone; and (i) hard-rock heavy-mineral concentrations in dolerites, and associated eluvial and colluvial deposits. The McArthur Basin and in particular, the Beetaloo Sub-basin, is also prospective for petroleum and possibly for Century-style base metals deposits.

Stratiform Zn-Pb-Ag deposits

These deposits comprise fine-grained pyrite, galena and sphalerite, preferentially concentrated in pyritic bituminous shale. They are considered to have formed either synchronously with sedimentation at the sediment–water interface or by early diagenetic processes, involving low-temperature hydrothermal fluids.

The deposits are stratiform and stratabound. The HYC Pyritic Shale Member of the Barney Creek Formation hosts the only known economic occurrences. These deposits are similar to the Mount Isa deposit, but whereas the latter is weakly metamorphosed and the sulfides are relatively coarse-grained, the currently known deposits in the McArthur Basin are unmetamorphosed. Consequently the sulfides are extremely fine-grained and seldom exceed 10 µm.

McArthur River (HYC)

Traces of silver, lead and copper are reported to have been discovered on McArthur River Station as early as the mid 1880s. The gossan of the McArthur River deposit (**Figure 15.29**) was discovered in 1955 by Mount Isa Mines Ltd, but it was not until 1959, when the second round of drilling was undertaken, that the significance of this gossan was revealed. Metallurgical problems related to the extremely fine-grained nature of the ore prevented economic exploitation until 1995, when MIM Ltd started mining and processing ore from underground operations. In August 2005, McArthur River Mining (MRM) announced its intention to convert the McArthur River mine to an open-cut operation and this was

Figure 15.26. Pisolitic ironstone from type section of Wadjeli Sandstone Member of Mainoru Formation (53L 481500mE 8382600mN, after Abbott *et al* 2001: figure 18).

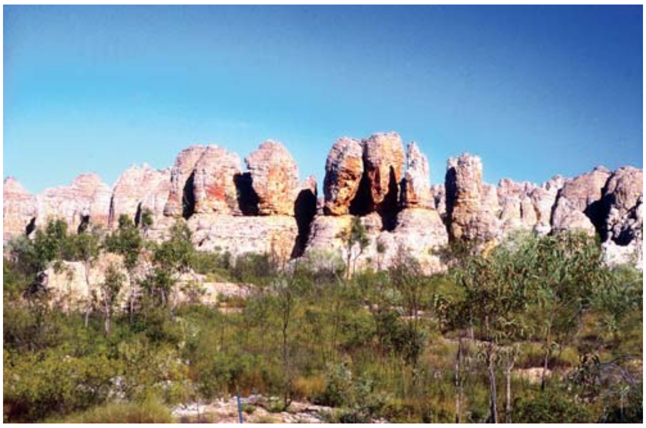


Figure 15.27. Sandstone karst topography of flat-lying Bessie Creek Sandstone in headwaters of Mangkardanyiranga Creek, 55 km northeast of Ngukurr settlement (after Abbott *et al* 2001: figure 25).

approved by the Northern Territory Government in October 2006. In August 2006, the McArthur River Mine commenced operating a test open pit. This contributed ore for sampling and processing, as underground operations were reduced. The test pit was subsequently extended in April 2007, when underground mining ceased. Total production from the mining operation to June 2008 was recorded at 1.7 Mt Zn, 0.42 Mt Pb and 16 Moz Ag. As of 30 June 2007, McArthur River had total resource of 144 Mt at 11.2% Zn, 4.8% Pb and 48 g/t Ag; Total reserves were recorded as 46.3 Mt at 9.6% Zn, 4.2% Pb and 43 g/t Ag.

The relatively pristine state of the McArthur River deposit has made it a model for sediment-hosted stratiform base metal deposits, and a number of detailed studies are available (Croxford 1968, Croxford and Jephcott 1972, Lambert and Scott 1973, Croxford *et al* 1975, Murray 1975, Lambert 1976, Williams and Rye 1974, Walker *et al* 1977, Williams 1978a, b, 1979, 1990, Rye and Williams 1981, Logan 1979, Eldridge *et al* 1993, Hinman 1996, Large and McGoldrick 1998, Large *et al* 1998). The following discussion relies heavily on these studies.

The HYC Pyritic Shale Member of the Barney Creek Formation hosts the mineralisation at McArthur River (**Figure 15.19b**). The pyritic carbonaceous shale was probably deposited in an area of active subsidence associated with a growth fault. Other smaller sub-basins, which may or may not have had active faults, are shown in **Figure 15.30**. Metal precipitation resulted from reduction in anoxic, organic-rich sub-basins (Large *et al* 2002). Orebody layering suggests that the introduction of metalliferous brines into the basin was as a series of intermittent pulses. The HYC Pyritic Shale Member contains base metals with abundant sulfides only within these sub-basins, and outside these, it is usually represented by a succession of thinly bedded, weakly pyritic, dolomitic bituminous shale.

The generalised geology around the McArthur River deposit is shown in **Figure 15.31** and a schematic cross-section is given in **Figure 15.32**. The McArthur River mineralisation covers an area of a few square kilometres and ore is localised in the basal 80 m of the Barney Creek Formation. The ore succession is divided into eight orebodies separated by low-grade intervals of poorly bedded or fragmented pyritic and dolomitic shale interbeds, or dolomitic breccia (**Figure 15.33**).

The sulfides are associated as fine-grained bands of sphalerite and galena within thinly laminated beds of dark bituminous and tuffaceous shale (**Figure 15.34**). The mineralisation consists predominantly of pyrite, galena and sphalerite, along with minor arsenopyrite and chalcopyrite. Two generations of pyrite have been

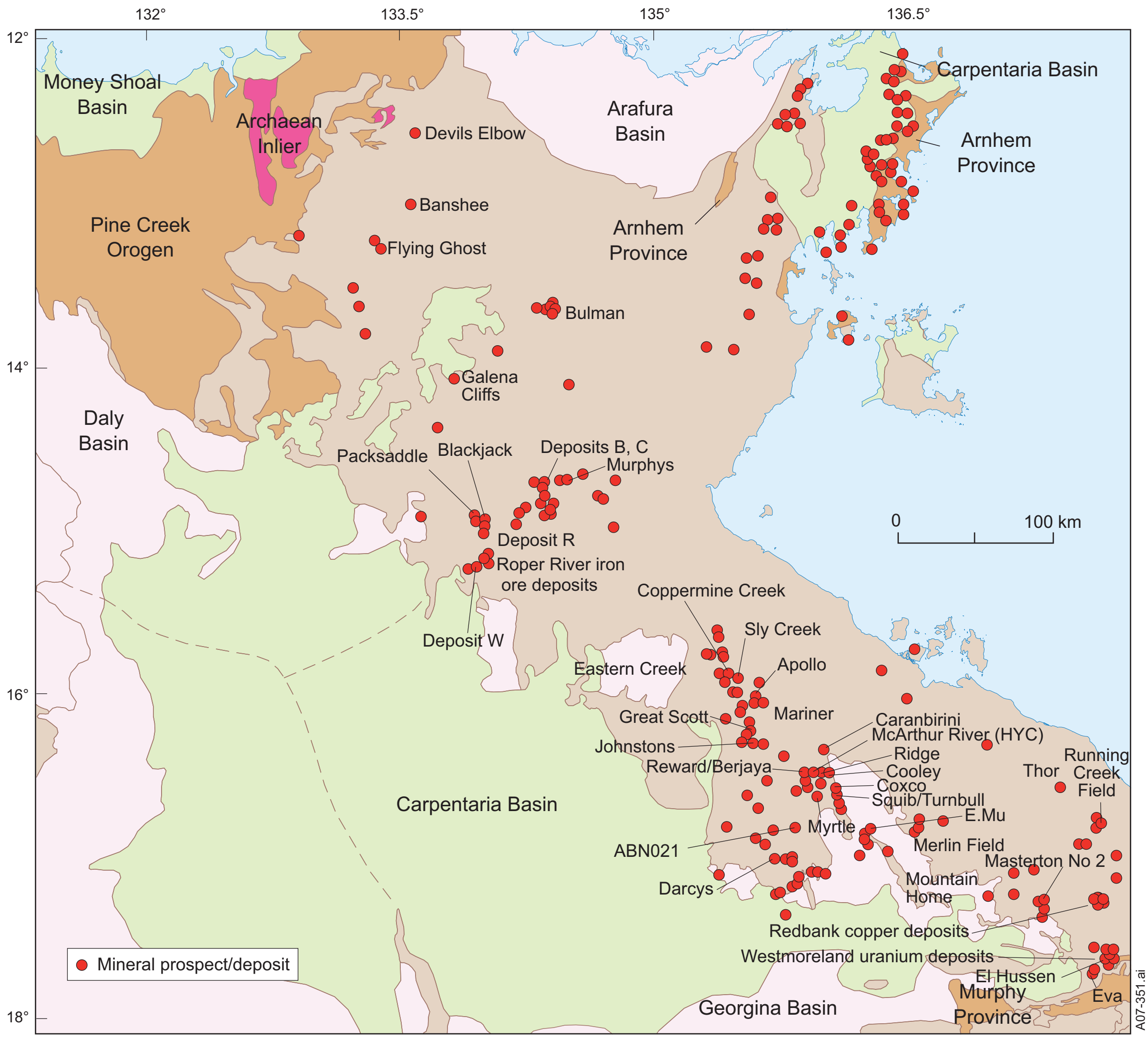


Figure 15.28. Location of significant mineral occurrences in McArthur Basin area (from NTGS MODAT database).

identified. The earlier generation (Py_1) is present as 1–15 µm-sized euhedral and spherical grains, and the later pyrite (Py_2) occurs as overgrowths on Py_1 or as infillings within it. Sphalerite occurs as monomineralic layers up to 1 mm thick, as elongate bodies up to 0.2 mm in diameter, and as fine-grained disseminations. Galena is observed as monomineralic layers up to 0.05 mm thick, as streaks in sphalerite layers and as fine-grained disseminations. Chalcopyrite is present as minute elongate bodies in sphalerite. Mutual relationships suggest a paragenetic sequence, in which Py_1 was followed by Py_2, with galena and sphalerite forming later than Py_2.

Isotopic studies

Conventional sulfur isotope analyses of sulfide separates indicated that $\delta^{34}S$ values of pyrite ($Py_1 + Py_2$) increase from -3.9‰ at the footwall to 14.3‰ at the top of the mineralised

Figure 15.29. Gossan at McArthur River deposit, consisting of silicified inter-ore breccia, smithsonite and hemimorphite [1.5 km northeast of McArthur River airstrip (53K 617800mE 8182600mN)].

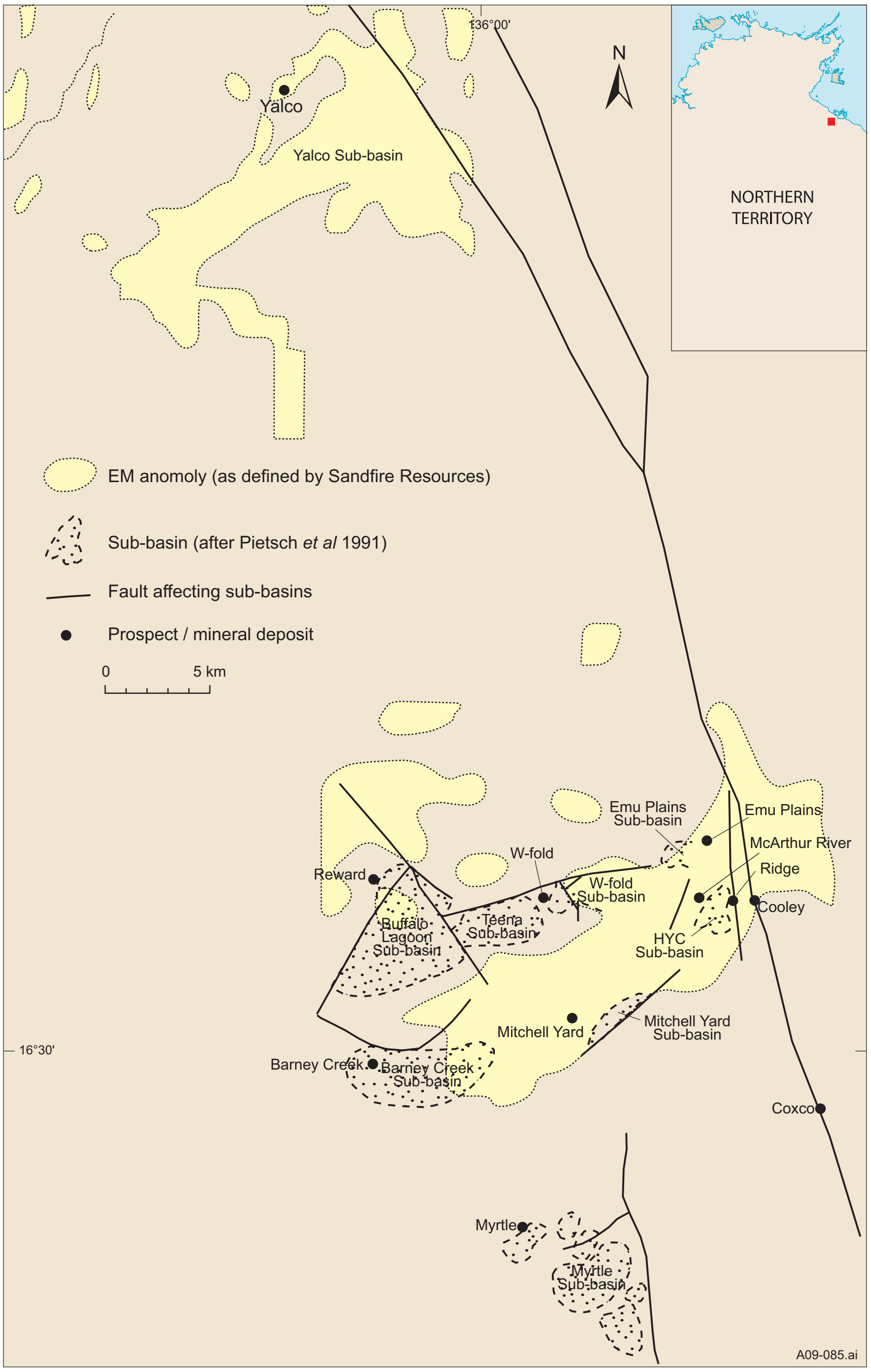


Figure 15.30. Sub-basins in vicinity of McArthur River deposit (after Pietsch *et al* 1991) and AEM anomalies interpreted as sub-surface shale in vicinity of McArthur River and Yalco deposits (derived from Sandfire Resources NL, Presentation for the general meeting of shareholders 19/06/08, see **Figure 15.36**).

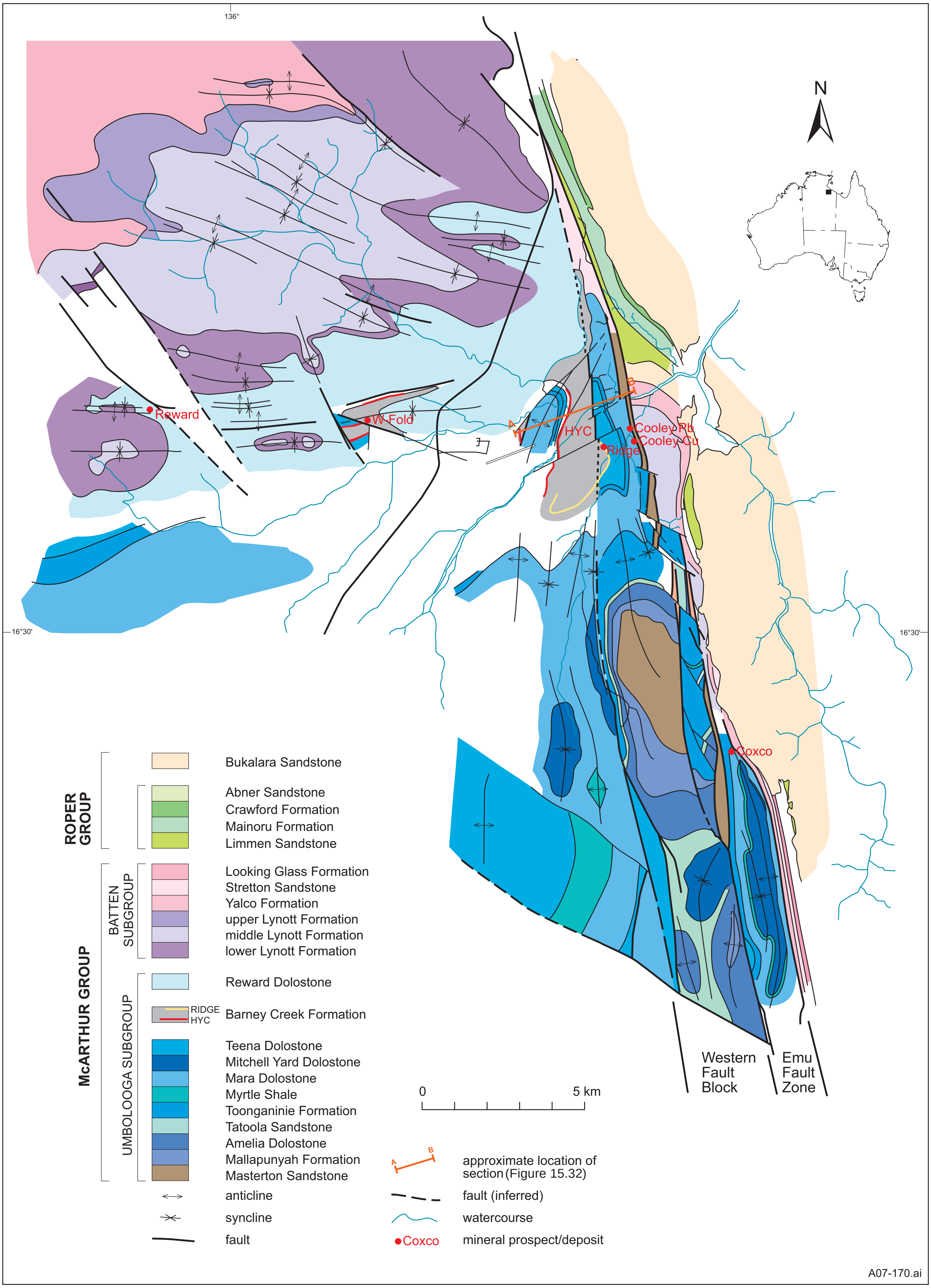


Figure 15.31. Surface geology in vicinity of McArthur River deposit (after Hinman 1995).

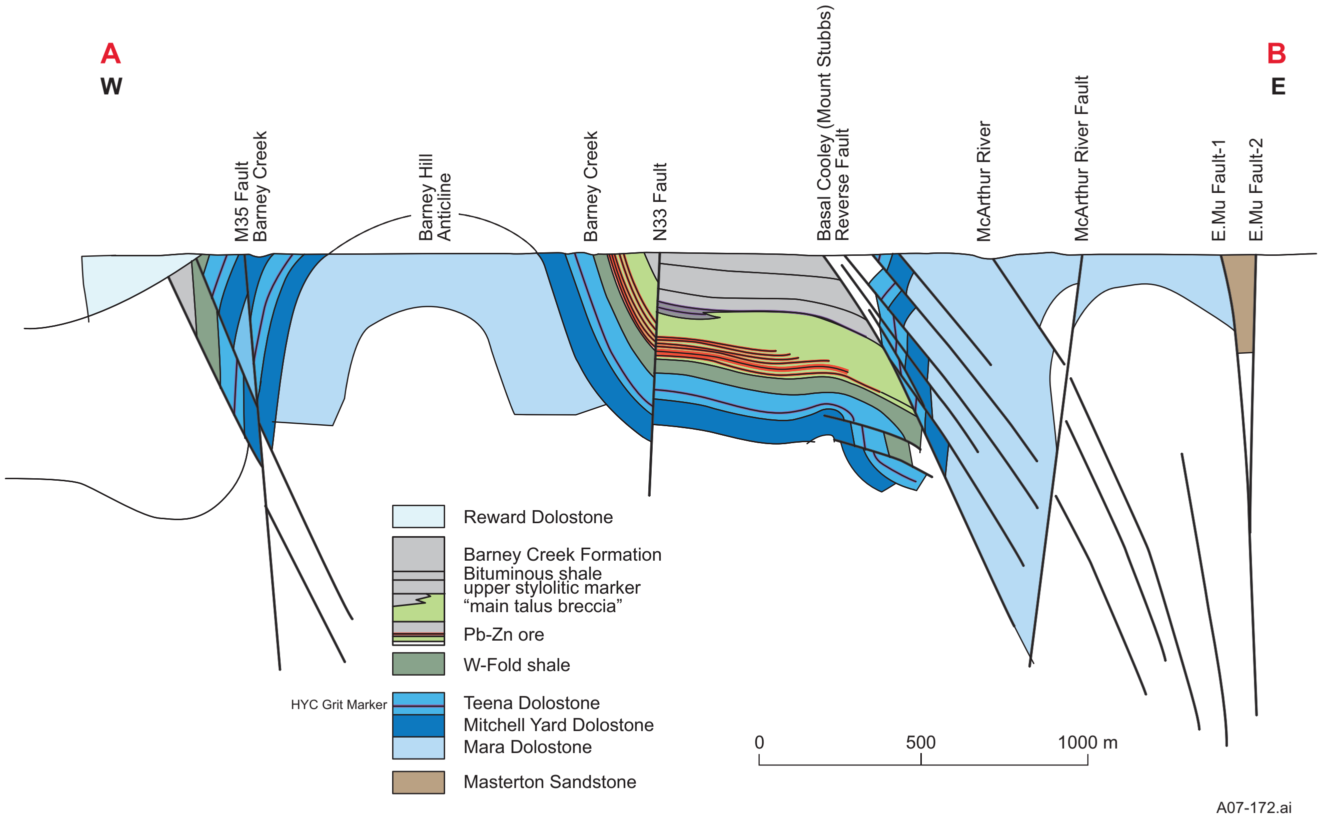


Figure 15.32. Slightly modified cross-section through McArthur River deposit, as interpreted by Hinman (1995).

section, whereas those of galena and sphalerite are constant at -1.2 to 5.7‰ and 3.3 to 8.9‰, respectively. The galena-sphalerite pair gave a temperature range of 100–260°C (Smith and Croxford 1973). Sulfur isotope compositions using SHRIMP ion microprobe analysis (Eldridge *et al* 1993) of individual sulfide grains indicated that both Py_1 and Py_2 may be biogenic in origin, with $\delta^{34}S$ values ranging from –3 to +15‰ for Py_1 and -5 to +45‰ for Py_2. The lead, zinc and copper sulfides have a relatively restricted isotopic range of –5 to +9‰. The sulfur isotope data thus suggest that neither of the two pyrite types are related to the lead zinc mineralisation and it seems unlikely that the early pyrite was the local source of sulfur for metal precipitation (Eldridge *et al* 1993).

The $\delta^{13}C$ values for the carbonaceous material ranges between -31.0 to -27.5‰ and may be good evidence of biological activity. The $\delta^{13}C$ and $\delta^{18}O$ values of carbonate rocks range from -3.8 to 0.3‰ and 17.7 to 24.6‰, respectively, and are typical for marine carbonates. These $\delta^{13}C$ and $\delta^{18}O$ values show a collinear trend and suggest a temperature of 120–170ºC (Rye and Williams 1981).

Large *et al* (2001) reported on an extensive halo of ^{18}O-enriched and ^{13}C-depleted rocks surrounding the orebody and this corresponds to the lithogeochemical halo of elevated Fe, Mn, Zn, Pb and Tl (see below).

Alteration halos

Lithogeochemical studies of shale-hosted deposits in the Carpentaria Zinc Belt have resulted in the identifications of well developed Fe-Mn halos around several deposits (Large and McGoldrick 1998). The McArthur River orebody is surrounded by well developed ankerite-ferroan dolomite and manganese carbonate halos.

The ankerite-ferroan dolomite halo is developed within the dolomitic sediments surrounding the deposit and can be traced for about 15 km along the favourable pyritic shale facies at the base. The most ankerite-rich compositions occur in the ore zone and along the base of the HYC Pyritic Shale Member. This ankerite ferroan dolomite halo is associated with Zn, Pb and Tl enrichment within the dolomitic sediments and is characterised by Zn >1000 ppm, Pb >100 ppm and Tl >4 ppm.

The manganese carbonate halo is represented by a narrow zone of manganese-rich ferroan dolomite surrounding the deposit and extends about 23 km west of the deposit. The manganese content of the dolomite increases systematically towards the deposit.

These halos are considered to be related to the release of cool Fe- and Mn-bearing brines into developing sedimentary basins, both prior to and subsequent to the Zn-Pb mineralising episode (Large and McGoldrick 1998).

Fluid-flow modelling

Garven *et al* (2001) modelled the large-scale fluid migration that produced the McArthur River deposit. They considered three scenarios: (1) topographically induced flow, when parts of the basin were exposed and elevated above the Batten Fault Zone, (2) density driven flows when the basin was mostly submarine, and (3) transient flows associated with fault rupture during periods of transpiration. Numerical modelling suggested that the Emu and Tawallah faults greatly controlled the flow of fluid in the area. Fluid descended through the western edge via the Tawallah Fault, migrated laterally to the east through the clastic and volcanic succession of the upper Tawallah Group, leached metals from these successions and ascended up through the Emu Fault, then discharged onto the basin floor.

Chemical modelling

Chemical modelling (Large *et al* 2002, Cooke *et al* 2000) shows that a neutral to moderately alkaline, oxidised (SO_4 > H_2S), low temperature (100–250°C) fluid could have carried sufficient metals to form the McArthur River deposit. Precipitation would have been by reduction.

Genesis

Earlier genetic models for the deposit emphasised syngenetic characteristics and postulated metal precipitation on the seafloor from metalliferous exhalations (Cotton 1965, Croxford 1968, Murray 1975). The contrasting behaviour of $\delta^{34}S$ values of pyrite and base metal sulfides led Smith and Croxford (1973) to suggest a dual source for sulfur: one for pyrite and the other for galena and sphalerite. They suggested that pyrite formed diagenetically, whereas galena and sphalerite were precipitated elsewhere and accumulated syngenetically at the sites of diagenetic pyrite formation. Croxford *et al* (1975) modified this model by postulating that Py_2 formed after Py_1, galena and sphalerite by post-depositional reactions.

Williams (1978a, b) showed that Py_2 formed before galena and sphalerite, and that the $\delta^{34}S$ values of galena, sphalerite and pyrite are in some way related. He proposed an epigenetic model, in which Py_1 formed during early diagenesis. Later mineralising fluids were introduced from the Western and/or Emu faults and precipitated Py_2, galena and sphalerite through reduction of SO_4^{-2} in solution and oxidation of organic matter in the sediments. Williams (1990) modified the above model and suggested a two-fluid 'permeation model' in which two fluids passed into and spread through the unconsolidated sediments beneath the McArthur River lake or lagoon. The uppermost iron-rich, reduced fluid deposited iron monosulfides. The lower fluid was rich in Pb and Zn, but poor in reduced sulfur, and dissolved iron monosulfides to precipitate galena and sphalerite. Numerous studies have been undertaken to explain or experimentally reproduce the laminations present in the McArthur River ore and host rocks. These are reviewed in Bubela (1981). Eldridge *et al* (1993) carried out mineralogical and SHRIMP-based sulfur isotopic studies and reinforced the epigenetic model.

Large *et al* (1998, 2002) carried out extensive, isotopic, sedimentological, mineralogical and hydrological

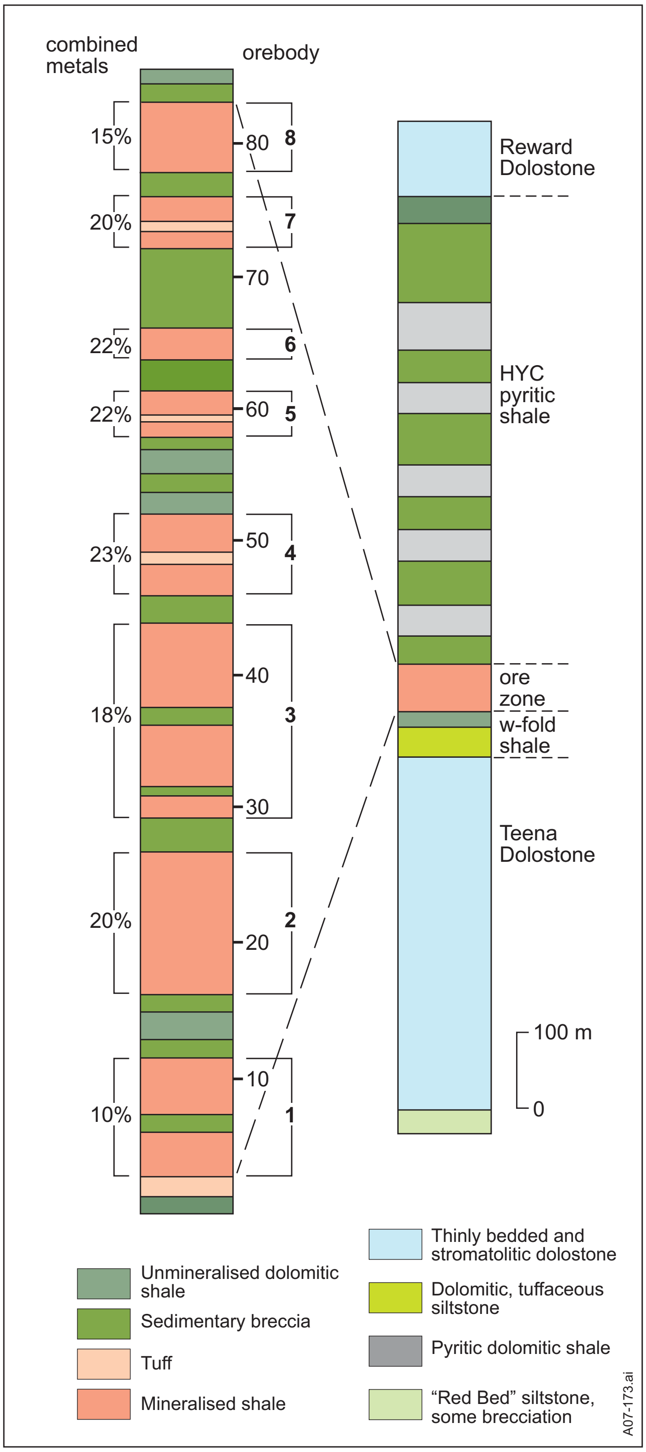


Figure 15.33. Stratigraphic section through McArthur River deposit, showing ore lenses (1–8), with grade combined metal (%) and inter-ore sedimentary mass flow breccia (after Large *et al* 1998).

Figure 15.34. Thinly bedded to laminated sphalerite and galena ore typical of the main ore body at McArthur River mine (J Dunster collection).

studies on the McArthur River deposit and surrounds. They favoured a synsedimentary model, with metals precipitating in intermittent pulses on the sea floor (**Figure 15.35**). They proposed that deep seismic events lead to the following ore cycles: fault movements; sediment breccia deposition sourced from faults; episodic release of hot metalliferous brines along faults; and metal sulfide deposition in muds and turbidites adjacent to faults (Large *et al* 1998). Metals were transported in sulfate-rich oxidised brines at 150–250°C and deposition occurred due to thermochemical reduction by organic matter and diffusion of H_2S from the anoxic water columns to the metalliferous brine layer.

Symons (2007) carried out palaeomagnetic analysis of 273 specimens from the ore zones and host rocks at the McArthur River deposit. The characteristic remnant magnetisation in the ore zone is due to pyrrhotite and magnetite, and is 2–3 My younger than the primary age of the host rock; this supports an epigenetic origin for the ore zone sulfides.

Yalco

During the 1980s, *Yalco* was explored by various JVs. In 1994, MIM Exploration drilled three diamond holes totalling 708.7 m at Yalco to test weak soil anomalies. No economic grades were intersected, but the drilling was not deep enough to intersect the Barney Creek Formation. The Yalco area was subsequently explored by an Anglo American Exploration Australia/North Ltd JV during 2003–2005 (Kennedy *et al* 2005). Drilling intersected a bituminous pyritic shale interpreted as Caranbirini Formation, rather than the HYC Shale Member of the Barney Creek Formation.

Sandfire Resources NL drilled a broad EM anomaly at the Yalco prospect during 2007 (**Figure 15.36**). The hole intersected 50 m of carbonaceous pyritic shale of the HYC Shale Member, containing micro-veinlets of galena, but lacking any economic mineralisation (Sandfire Resources NL, Quarterly report for the period ended 30 September 2007).

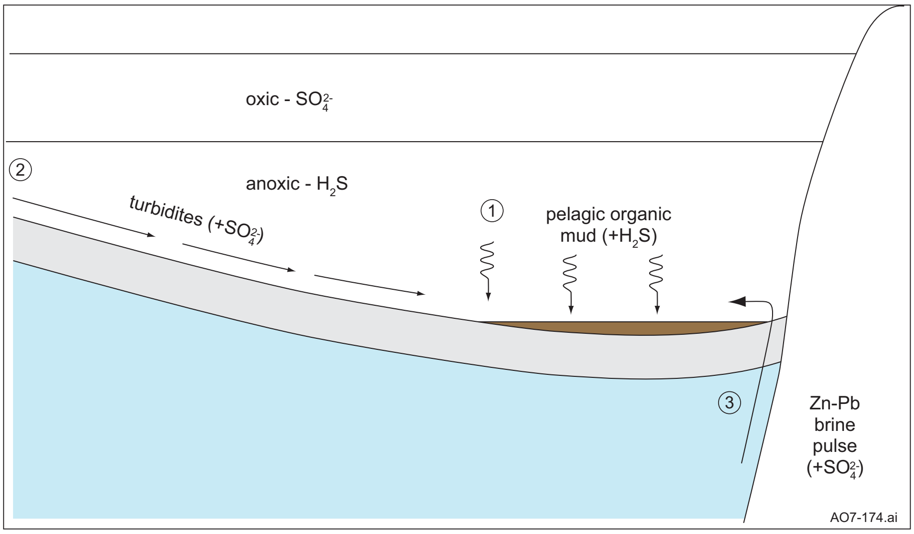


Figure 15.35. Diagrammatic representation of three stages of ore formation at McArthur River deposit (after Large *et al* 1998): (1) Pelagic mud from anoxic water column; (2) oxic quartz-carbonate turbidity flows from basin margins; (3) Zn-Pb-bearing brine pulses migrating along active proximal faults.

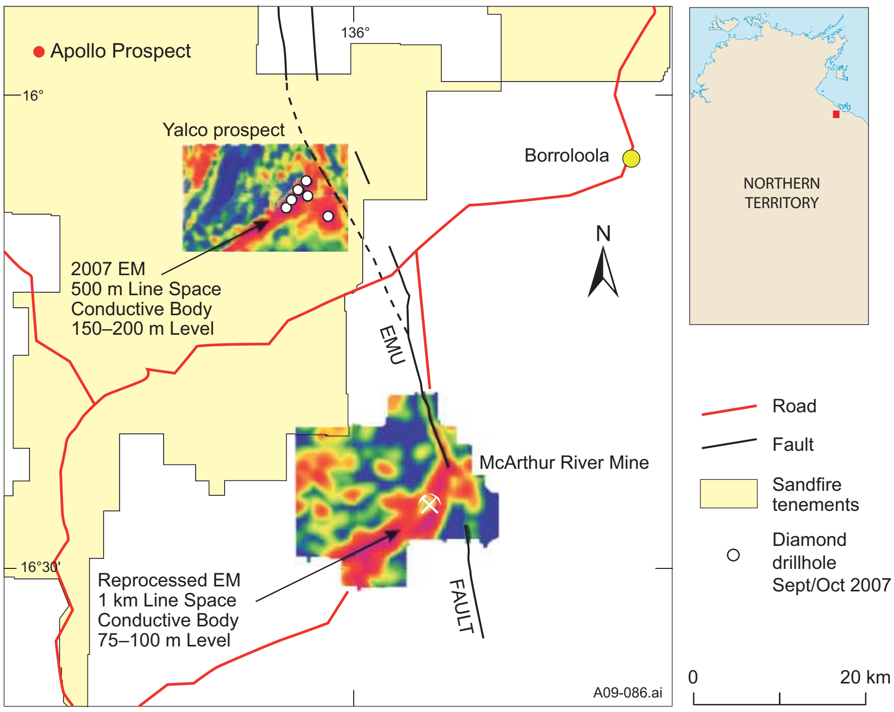


Figure 15.36. AEM-derived conductivity depth slices over Yalco and McArthur River (after Sandfire Resources NL, Presentation for the general meeting of shareholders, 19/06/08).

W-Fold

The W-Fold deposit (Murray 1952, Fricker 1962, Rawlins 1967, Walker *et al* 1977) is located about 5 km west of McArthur River (**Figure 15.30**) and contains stratiform Pb-Zn concentrations in the HYC Pyritic Shale Member. Two deep diamond drillholes, 1 500 m apart, intersected some 200 m of HYC Pyritic Shale Member and 70 m of the W-Fold Shale Member. One hole intersected a 30 m-thick zone containing 3% Zn, including 2 m of 9% Zn. The second hole intersected some 40 m of 2.2% Zn, which includes a basal 3 m of 9.5% Zn (Murray 1975). Wickens Hill DDH1 intersected a 7.46 m-thick ore zone, averaging 7.76% Zn, 1.7% Pb and 5 g/t Ag.

The mineralisation is similar to the McArthur River deposit and consists of very fine-grained pyrite, sphalerite and galena, forming delicately laminated to massive bands, concordant with the shale bedding. Much of the sphalerite is present as up to 0.5 mm-thick pale straw-yellow laminae, interbedded with dolomitic shale. Coarse-grained red sphalerite with scattered galena crystals is present in a few thin beds, which may also host concretionary base metal sulfides (Murray 1975). Inter-ore breccias like those found in the McArthur River deposit are not present in the W-Fold deposit.

Emu Plains

The Emu Plains Pb-Zn prospect is a subsurface deposit about 3 km north of the McArthur River deposit (**Figure 15.30**). Two diamond drillhole intersections have returned assays averaging 2% Zn and 0.7% Pb over 50 m (Walker *et al* 1977). Emu DDH12 intersected the HYC Pyritic Shale Member in the interval 54–140 m, recording assays of 1% Zn over 7 m (CEC 1977). The mineralisation is very similar in style to the McArthur River deposit and is at the same stratigraphic level.

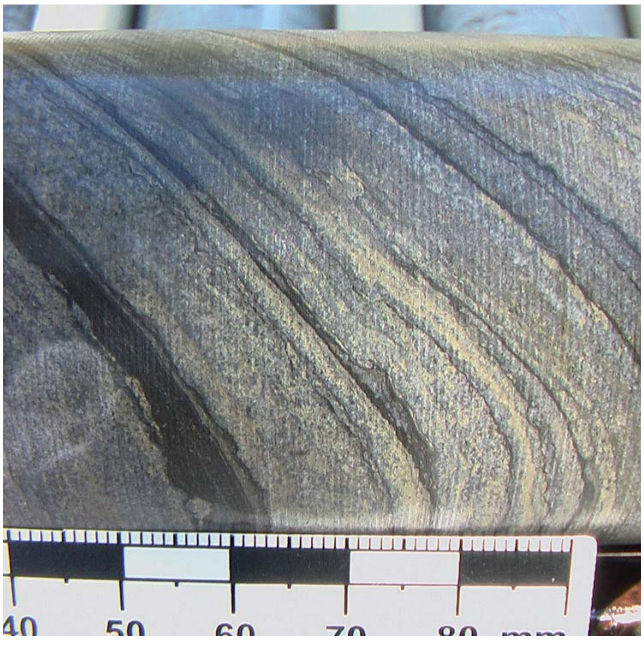


Figure 15.37. Banded sphalerite in drill core from Myrtle prospect (Rox Resources Ltd, drillhole MY16: 189.1 m, 53K 610080mE 8167065mN).

Berjaya

The Berjaya Zn (Pb-Cu) prospect (Kneale *et al* 1979, Bornman 1982) is situated about 18 km west of the McArthur River deposit (**Figure 15.28**) and was discovered during a geophysical survey. Follow-up geological mapping, geochemical sampling (soil and rock), geophysical (IP) surveys and diamond drilling (5 holes totalling 586 m) delineated minor stratiform base metal mineralisation within laminated pyritic and carbonaceous shale of the Caranbirini Member. Pyrite is present as discrete, disseminated fine grains, forming 0.5 mm-thick laminae or occupying small fractures. Sphalerite is commonly located in dolomite veins and vugs within dolomitic breccias, as intersected by drillhole BJ1 (54.7–55.3 m), which assayed 4.63% in the interval 54.7–55.3 m, and averaged 0.87% Zn and 740 ppm Pb in the interval 16–27 m, including 1.77% Zn over 1 m.

Mitchell Yard

The Mitchell Yard Pb-Zn prospect (Fricker 1962) is situated in the vicinity of the informally named Mitchell Yard sub-basin (**Figure 15.30**), about 8 km southwest of the McArthur River deposit. Low-grade stratiform Pb-Zn mineralisation was intersected within pyritic shale of the Barney Creek Formation, which occupies the hinge area of an open to tight syncline, cut by a northeast-trending fault. Assays of 0.7–1.1% Zn have been recorded in drill core intersections, as well as visible galena within dolostones of the Mitchell Yard Member at the surface.

Myrtle

The Myrtle Zn-Pb prospect, located 19 km south-southwest of the McArthur River deposit (**Figure 15.28**), contains significant stratiform zinc-lead mineralization within the Barney Creek Formation in the Myrtle Sub-basin, at depths of up to 500 m. The prospect was first identified by a regional geophysical survey (IP), conducted by Carpentaria Exploration Company Ltd in 1966, which located a significant anomaly (Shaw 1968). Follow-up work delineated a 1.7 km-long east–west-trending anomaly. Myrtle DDH1 was subsequently drilled to test the anomaly, and intersected over 100 m of the Barney Creek Formation, containing a 35.7 m zone assaying 0.6% Zn, 0.09% Pb and 6.2 g/t Ag (Shaw 1968). Pyrite is the dominant sulfide, typically forming laminae within carbonaceous shale. Sphalerite and galena are visible as monomineralic veinlets or as fine to medium grains within carbonate veins (Shannon *et al* 1980). More recent drilling by Rox Resources Ltd has identified significant lead-zinc mineralisation in multiple intervals. Rox has announced a JORC-compliant resource estimate of 43.6 Mt at 4.09% Zn and 0.95% Pb, for 5.03% Zn + Pb at a cut-off grade of 3% Zn + Pb. At a higher cut-off grade of 5% Zn + Pb, the resource is 15.3 Mt at 5.45% Zn and 1.4% Pb, for 6.84% Zn + Pb (Rox Resources Ltd, ASX Announcement, 15 March 2010). The orebody remains open to the north and west. High-grade mineralisation occurs as sphalerite, galena and pyrite in a well bedded calcareous shale (**Figure 15.37**), interpreted to be the HYC Pyritic Shale, or an equivalent unit. Mineralisation is similar in style to that of the McArthur

River deposit, but has a coarser grain size (Rox Resources Ltd, ASX Announcement, 28 August 2008).

Barney Creek Sub-basin

The Barney Creek Sub-basin is an east–west-elongated basin, located about 17 km southwest of the McArthur River deposit (**Figure 15.30**). A broad magnetic low with an associated resistivity low suggested an attractive exploration target (Rawlins 1967). Follow-up diamond drilling intersected low grade (0.42% Zn and 0.12% Pb over 10 m) stratiform base metal mineralisation within pyritic shale of the Barney Creek Formation.

Mountain Home (Glyde Sub-basin)

The Mountain Home prospect is located in the Glyde Sub-basin, some 60 km south of the McArthur River deposit (Staples 1978, Wilkins 1980, Davidson and Dashlooty 1993). The area lies between two bounding faults: the Emu and Cowdrey faults. An equivalent of the HYC Pyritic Shale Member has been intersected in several drillholes, and generally consists of black dolomitic and pyritic, carbonaceous shale, which ranges in thickness from 0–50 m. Pyrite is present as disseminated framboidal clumps and frequent thin massive bands and clots. Sphalerite often forms visible grains in dolomitic slump breccias and carbonate veins.

Century-style base metals deposits

The McArthur Basin has potential for Century-style base metals mineralisation. Century is located 250 km northwest of Mount Isa in Queensland and is a stratiform zinc-lead-silver deposit hosted within turbiditic siliclastic black shale and siderite-rich siltstone of the middle Proterozoic Lawn Hill Formation, a succession of shale, siltstone and sandstone overlain by Cambrian limestone. This deposit is believed to have been formed via the influx of an oxidised metal-bearing fluid into a pre-existing, zoned hydrocarbon reservoir, leading to the deposition of base metals by thermochemical sulfate reduction (Broadbent *et al* (1988). Although no deposits of this type have yet been identified in the McArthur Basin, potential hydrocarbon-bearing host rocks are widespread within the McArthur Group (see **Petroleum**) and occur in areas that have been subjected to mineralised fluid flows. Prospective strata include palaeo-hydrocarbon reservoirs, such as intervals of the Barney Creek Formation and Coxco Dolostone Member that have been reported as containing extensive bitumen and other hydrocarbons (Thomas 1981).

Discordant Pb-Zn-Ag±Cu deposits

These deposits occur as open space-filling of coarse-grained pyrite, galena and sphalerite+chalcopyrite in brecciated dolostone, and were generated by low- to moderate-temperature hydrothermal fluids. A number of these are associated with karstification close to silicified regolith, with the brecciation produced by hydraulic fracturing. Many are regarded as classic Mississippi Valley-style deposits. The Umbolooga Subgroup contains almost all of these deposits, with the majority occurring in the Reward or Emmerugga dolostones. Vein-style deposits are few, are generally confined to the lower McArthur and Tawallah groups, and are usually chalcopyrite rich. They were probably produced by moderate-temperature hydrothermal fluids.

Cooley prospects (Cooley I, II and III)

These prospects are located immediately to the east of the McArthur River deposit (**Figure 15.30**). Outcropping mineralisation is present only at the Cooley I deposit; at the other two deposits, mineralisation has been intersected in drillholes. All are situated close to the Emu Fault in brecciated Emmerugga Dolostone (Walker *et al* 1977). Cooley II is closest to the Emu Fault and is primarily a copper deposit, with subordinate lead and zinc. Walker *et al* (1977) assigned the brecciated host carbonate to the Mara Dolostone Member of the Emmerugga Dolostone. Cooley I and III are mainly lead and zinc deposits. Williams (1978a) and Rye and Williams (1981) gave a detailed description of these deposits and the following summary is mainly based on their work.

The outcropping Emmerugga Dolostone succession at the Cooley I deposit strikes north–south, dips moderately to the west and consists of well bedded stromatolitic dolostone. Northwest-striking, steeply northeast-dipping and up to 1 m wide dolomite 'dykes' traverse the succession. These dykes carry galena-bearing sparry dolomite veins running parallel to the 'dyke' walls (**Figure 15.38**). Some crosscutting galena-dolomite stringers and pods are also present. In places, the Emmerugga Dolostone is brecciated and carries galena-sphalerite pods as breccia infill. Williams (1978a) identified two types of breccias in the drill core samples. The first generation breccia (Br_1) consists of angular dolostone clasts, up to 1 m in size, in a dark matrix of dolomite grains, pyrite and carbonaceous material. The second generation breccia (Br_2) consists of angular clasts of Br_1 in a matrix of dolomite and sulfides (veins or disseminations), with interlocking laths of barite, or dolomite pseudomorphs after barite and carbonaceous material. The Br_1 breccias are interpreted to be due to movements on the Emu Fault/ Western Fault, debris slumping, or solution collapse.

Figure 15.38. Mineralised dolomite dyke crosscutting Emmerugga Dolostone at Cooley 1 prospect. Galena is associated with sparry dolomite forming thin darker layers traversing from bottom to top of the photograph within yellow dolomite. (53K 619600mE 8182300mN).

Exposed breccias at the Cooley I deposit probably belong to this phase of brecciation. The Br_2 breccias are interpreted to be due to solution collapse following the introduction of mineralising solutions into porous Br_1 breccias. The origin of the dolomite 'dykes' is not discussed, but they may represent channelways for the mineralising solutions, or may be neptunian dykes.

The sulfides are relatively coarse grained and were deposited sequentially in the order of pyrite + marcasite + barite + dolomite, then Cu sulfides, galena + sphalerite, with Cu-bearing sulfides occurring close to the Emu Fault, mostly at the Cooley II deposit.

Sulfur isotopic ratios of pyrite, sphalerite and galena show a range and behaviour similar to those of the McArthur River deposit, with pyrite having large variations, and galena and sphalerite nearly constant. The galena-sphalerite sulfur isotope geothermometer gives a temperature of 290°C for the Cooley I deposit (and 275°C for the Cooley II deposit (Williams 1978a).

The $\delta^{13}C$ and $\delta^{18}O$ values of ore-stage dolomite define a linear trend and individual deposits yield distinctive values that become heavier away from the Emu Fault. Modelling of $\delta^{13}C$ and $\delta^{18}O$ data provides temperatures of 310°C for the Emu Fault zone, 300–290°C for the Cooley I deposit, 275–250°C for the Cooley II deposit and 240–185°C for the Cooley III deposit.

Murray (1975) visualised the mineralisation originating as sulfide mud in lagoons. Williams (1978a) and Rye and Williams (1981) considered the mineralisation to be epigenetic and suggested that the mineralising fluids issued from the Emu Fault and flowed westward. This would explain the observed decrease in Cu/Pb+Zn ratios and temperatures away from the Emu Fault.

Ridge deposits (Ridge I, Ridge II)

These subsurface prospects are located east of the McArthur River and Cooley deposits. At the Ridge I deposit, the mineralisation is within brecciated Cooley Dolostone Member, whereas at the Ridge II deposit, the upper half is within the HYC Pyritic Shale Member and the lower half is in brecciated Cooley Dolostone Member. Murray (1975), Williams (1978a), Logan (1979), and Rye and Williams (1981) have described the deposits and the following summary is largely based on these studies.

The sulfides are coarse grained and occur in the breccia matrix as open-space infills at Ridge I and the lower half of Ridge II. In the upper half of Ridge II, the sulfides are fine grained and similar in texture to the McArthur River orebody. The main ore minerals are pyrite, galena, sphalerite and minor chalcopyrite, and the paragenetic sequence is similar to that in the Cooley deposits. As with the Cooley deposits, two types of breccias (Br_1 and Br_2) have been identified.

Stratiform mineralisation in the upper half of the Ridge II deposit is situated directly above the breccia-filled mineralisation and, like the McArthur River orebody, is within the basal part of the HYC Pyritic Shale Member.

The stable isotope variations and systematics of the Ridge deposits are similar to those in the Cooley deposits, but calculated temperatures are lower. A galena-sphalerite sulfur isotope geothermometer gave a range 120–180°C for the Ridge II deposit. Modelling of carbon and oxygen isotope data on ore-stage dolomite gave temperatures of 175–190°C for the Ridge I deposit and 225–190°C for the Ridge II deposit (Rye and Williams 1981).

Coxco (Cox and Cooks)

The Coxco deposit is located some 10 km southeast of the McArthur River mine (**Figure 15.28**). The name Coxco is derived from two adjacent mines, Cox and Cooks, discovered in the late nineteenth century and worked for high-grade oxidised ore using a number of shallow shafts and pits. No production records are available. The deposit was extensively drilled by Carpentaria Exploration Company Pty Ltd (CEC), and reserves were quoted to be several million tonnes averaging 2.5% Zn and 0.5% Pb by Walker *et al* (1983), who also provided a detailed description of the deposit. Additional drilling and resource estimations have been carried out on the deposit by CEC and North Ltd, but not published.

The mineralisation is hosted by the Reward Dolostone, which is unconformably overlain by the Lynott Formation and unconformably underlain by the Mara Dolostone Member of the Emmerugga Dolostone. The Reward Dolostone–Lynott Formation contact is a siliceous zone, probably representing a palaeoweathering surface, and consists of quartz, void-filling chalcedony and goethite. Close to the Mara Dolostone Member–Reward Dolostone unconformity, the Mara Dolostone Member contains fine-grained, laminated, discordant quartz-dolomite veins.

The Reward Dolostone and upper part of the Mara Dolostone Member contain lenses and dykes of breccia, consisting of angular pieces of host rock in a fine-grained matrix of dolomite, quartz, clay, organic matter, feldspar, chert, iron sulfides, collophane, mica and dolomite pseudomorphs after barite. These breccia lenses have a sharp contact with the host rock and are interpreted as infills of solution cavities developed during an episode of karstification. Another kind of breccia, interpreted as crackle breccia, is preferentially developed in the Reward Dolostone immediately below the silicified zone. It is clast supported, with rounded to angular fragments, and there are no exotic rock lithologies. It originated by brittle deformation as a result of hydraulic fracturing (Walker *et al* 1983).

Two stages of Pb-Zn mineralisation have been identified (**Figure 15.39**): stage I comprises sphalerite, marcasite, pyrite and galena, and occurs as colloform and crystalline crusts and fragments within the karst breccia matrix; stage II comprises sphalerite, marcasite, pyrite and galena and occurs as veins and as matrix in the crackle breccia. Comb structures are common in stage II mineralisation, showing pyrite and marcasite near the base, followed by sphalerite, followed by galena. Stage II mineralisation crosscuts the Reward Dolostone, silicified zone, void infills, stage I mineralisation and the basal Lynott Formation, and was therefore formed after the lithification of the Lynott Formation.

Two-phase (water+vapour) primary fluid inclusions in stage II sphalerite and dolomite have freezing temperatures in the range -22.2 to -27.8°C, suggesting high-salinity brines. Homogenisation temperatures are in the range 100–169°C.

The galena-sphalerite sulfur isotope geothermometer gives a range of 128–191°C, which is consistent with the fluid inclusion homogenisation temperatures.

Lead isotope ratios are similar to those of the McArthur River deposit and suggest ore-fluid derivation from basinal brines, although some samples have a more radiogenic component, suggesting possible leaching of the McArthur Group sediments themselves.

Carbon and oxygen isotope data on bituminous matter and dolomite show that the former is mainly biogenic ($\delta^{13}C$ -37.7 to -32.5‰). The host dolomite shows a wide spread in the $\delta^{18}O$ values of 19.8 to 24.7‰, but a narrow range of $\delta^{13}C$ values (-3.0 to 0.1‰). Two samples of stage II dolomite gave $\delta^{18}O$ values of 18.2 and 20.4‰ and $\delta^{13}C$ values of 0.8 and -1.3‰. These values are dissimilar to those of ore stage mineralisation in the Cooley and Ridge deposits.

The proposed genetic model (Walker *et al* 1983) suggests the formation of stage I mineralisation in karstic cavities by the mixing of metal-bearing brines with reduced sulfur-bearing groundwaters. Stage II fluids represent basinal brines at temperatures of 100–170°C; precipitation took place due to a biological sulfate reduction by hydrocarbons at the site of metal deposition. Most workers regard the Coxco deposit as a Mississippi Valley type.

Squib

This prospect is hosted by the brecciated Mara Dolostone Member and is situated about 4 km southeast of Coxco. Mineralisation, comprising malachite, azurite and chalcopyrite, is patchy and is exposed in four small pits within an area of 25 x 5 m. The prospect is situated alongside a branch of the Emu Fault, which separates the Mara Dolostone Member from the Yalco Formation. The faulted contact is silicified and is composed of massive to brecciated chert resembling the silicified zone at the Reward Dolostone–Lynott Formation contact in the Coxco deposit. This silicified zone has an irregular contact with the Mara Dolostone Member, and may represent a regolith, but is not mineralised (Pietsch *et al* 1991, Ahmad and Ferenczi 1993).

Mineralisation is confined to brecciated Mara Dolostone Member just below the silicified zone. Unlike Coxco, secondary copper minerals are the dominant form of mineralisation. No information is available on the primary mineralisation, but presumably much of the secondary copper minerals are derived from the oxidation of chalcopyrite.

Turnbull

The geological setting of this prospect is similar to that of the Squib prospect. It is situated in brecciated Mara Dolostone Member, adjacent to the silicified zone at the faulted Mara Dolostone Member–Yalco Formation contact. Minor production from a shallow shaft has taken place. Within the shaft, galena occurs as colloform concretions in the matrix-supported breccia and minor malachite is also present as encrustations. The breccia–dolostone contact is irregular, but sharp. The breccia resembles the karstic breccia at the Coxco deposit and the mineralisation is similar to the stage I mineralisation at the Coxco deposit (Ahmad and Ferenczi 1993).

Reward

The Reward prospect is located about 15 km west of the McArthur River mine (**Figure 15.30**) and was mined by underground methods, producing a few hundred tonnes of ore probably in late 1950s. Mineralisation is within the Reward Dolostone and underlies a silicified zone consisting of massive to brecciated chert/jasper. The silicification is pervasive and generally structureless. In places, some remnant bedding is present. The silicified zone appears to be similar to that at the Coxco, Turnbull and Squib deposits and probably represents a regolith. Below the silicified zone there is a yellow ochreous zone, about 2 m thick. The contact between these two zones is irregular, but sharp. The yellow ochreous zone is underlain by red-brown, ferruginous gossanous material, containing cerussite, pyromorphite and minor malachite.

In one of the costeans, there is a small outcrop of heavily fractured, unsilicified Reward Dolostone. The

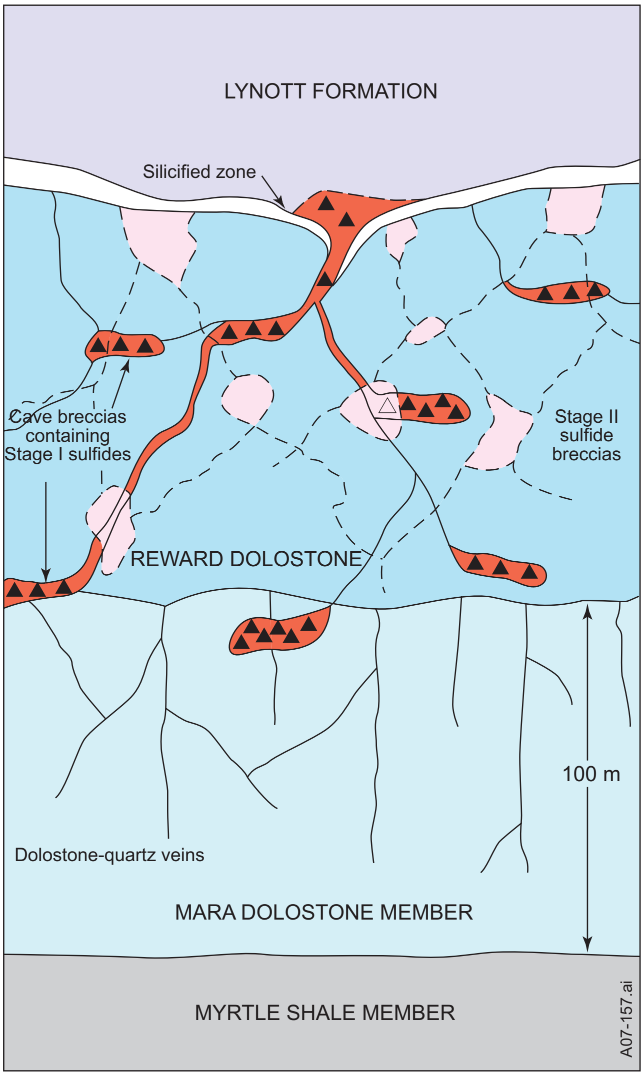


Figure 15.39. Coxco prospect: relationship between cave breccias with stage I sulfides and later stage II sulfide breccias (after Walker *et al* 1983).

fractures are filled by galena, dolomite and sphalerite. Galena and dolomite stringers are also seen at a few other places in the Reward Dolostone in close proximity to the mine (Ahmad and Ferenczi 1993).

Mariner

The Mariner lead prospect (Nenke 1977, 1979, Logan 1980a, b, BHP 1982a, b) is located about 20 km northeast of Bauhinia Downs Station. Anomalous Pb geochemical results were also obtained, 4 km to the north (Mariner North). Both prospects are within chert breccia, stromatolitic dolostone and dolomitic mudstone of the Tooganinie Formation.

The mineralisation is located in a possible regolith directly under the Roper Group–McArthur Group unconformity (Logan 1980b). Surface mineralisation consists of cerussite within weathered cherty material, which assayed up to 11.9% Pb (Nenke 1979), while a laminated chert sample from Mariner North assayed 1.5% Pb (Nenke 1977). The best drilling intersection (Mariner RDH1) assayed 7.9% Pb over 16 m (14–30 m), including 13% Pb over 7 m (Nenke 1979).

Great Scott

The Great Scott Pb-Zn-Cu prospect (Rawlins 1972, Nenke 1979) is located about 14 km south-southeast of Mariner. This prospect lies within stromatolitic dolostone of the Tooganinie Formation. Galena is the principal ore mineral, found as coarse disseminations or infilling small fractures or vugs within dolostone over a 5 km strike length. In the central portion of the prospect, galena appears to be confined to stromatolitic dolostone beds, 1–2 m thick. Chip samples have returned assays up to 3% Pb and 2.2% Zn (Nenke 1979).

Bald Hills (Bulburra)

The Bald Hills Pb-Zn prospect (Brown 1908, Fricker 1962, Murray 1952) is located about 15 km west of the McArthur River deposit and was discovered in the early 1900s. Exploration work, including drilling, has indicated that the bulk of the mineralisation is near the surface and very erratic. The old workings consist of a 3 m shaft and several shallow pits. Mineralisation consists of coarse-grained galena and sphalerite with minor chalcopyrite, infilling fractures and vugs within brecciated dolostone of the Reward Dolostone. A chip sample assayed 11% Pb and 20 g/t Ag, while subsurface drilling has intersected 10 m of 1.2% Pb and 6.5% Zn (AMS DDH2) and 5.5 m of 2% Pb and 7.8% Zn (AMS DDH1).

Barney Creek and Barneys

Barney Creek and Barneys are both carbonate-hosted lead prospects in the vicinity of the McArthur River deposit. Barney Creek was first inspected and sampled by Brown (1908); a chip sample of secondary ore assayed 53.3% Pb and a galena-rich sample assayed 83.3% Pb and 200 g/t Ag. The mineralisation at Barney Creek consists of coarse-grained galena infilling vugs within dolarenites of the Mara Dolostone Member. At Barneys, the mineralisation consists of coarse-grained galena infilling fractures and voids within brecciated dololutite of the Teena Dolostone.

Caranbirini

Caranbirini Zn-Pb-Ag prospect (Staples 1978, Wilkins and Staples 1979, Wilkins 1980) is located about 20 km north-northwest of the McArthur River deposit (**Figure 15.28**). Mineralisation is subsurface and has been intersected in drillholes. It comprises medium- to fine-grained sphalerite, with minor galena and chalcopyrite infilling breccia voids and fractures within dolomite breccia of the Cooley Dolostone Member equivalent. Best intersections assayed 7.25% Zn, 0.85% Pb and 9.5 g/t Ag over 3 m (DD83 CA3, 663–666 m), and 0.5 m of 22.4% Zn and 2.5% Pb in DD82 CA1 (Allnutt and Bubner 1986).

Buffalo Lagoon

Buffalo Lagoon lead prospect is situated about 15 km west of the McArthur River deposit It is a subsurface deposit, comprising coarse-grained galena within fractured dolostone of the Mitchell Yard Dolostone Member which assayed 3.22% Pb (Shaw 1968).

Apollo Prospect

The Apollo Prospect (Nenke 1977) is located some 15 km southeast of the Eastern Creek prospect and is hosted within the Amelia Dolostone. Galena, cerussite and minor chalcopyrite are the primary ore minerals. Secondary ore minerals include pyromorphite and malachite. Mineralisation occurs as disseminations, blebs, veins, fracture infills and occasional karst infills within white chertified dolostone and carbonaceous mudstone. Mineralisation extends over >2500 m by 900 m, and is up to 40 m thick (Ward 1983). Surface samples contain up to 37% Pb with subordinate copper. The best intersections were 15 m of 2.15% Pb, including 2 m of 8.4% Pb and 4 m of 3.35%Pb and 14g/t Ag (Nenke 1979).

Base metal sulfides were probably precipitated from hydrothermal brines emanating along local fault zones. Carbonaceous material in the Amelia Dolostone probably acted as the reducing agent, providing a trap for these sulfides (Haines *et al* 1993).

Eastern Creek

Eastern Creek Pb-Cu-Ba prospect (Muir *et al* 1985, Nenke 1977) is located about 15 km south of Nathan River, within finely bedded organic-rich dolomitic and pyritic mudstone of the Balbirini Dolostone, at the unconformity surface with the overlying Roper Group (**Figure 15.28**). This area is characterised by an abundance of barite mineralisation, which extends northward along the Limmen Bight River to The Four Archers. Mineralisation comprises galena, and lesser chalcopyrite and malachite, occurring as coarse disseminations, veins and small pods of galena within an 8 m-thick zone of solution collapse breccia over a strike length of 1300 m (Johnston 1972, 1974). Best drillhole intersections were 8.3 m at 2.55% Pb, including 2 m at 4.5% Pb.

Johnston (1974) suggested an early diagenetic origin involving two stages: (a) deposition of galena and minor chalcopyrite and pyrite into open space fractures, vugs and pore spaces; followed by (b) precipitation of barite and minor base metals in the remaining spaces, together with partial remobilisation of galena. Simpson and Dennis (1982) suggested that mineralisation is related to the unconformity surface.

Muir *et al* (1985) carried out fluid inclusion mineralogical and stable isotope studies. Fluid inclusion data on mostly secondary inclusions indicated a pressure-corrected temperature for barite and vein dolomite in the ranges 95–138°C and 158–168°C, respectively. Sulfur isotopes for galena and minor chalcopyrite range from 3.6 to 11.2‰, whereas for barite, they range from 18.4 to 24.7‰. Muir *et al* (1985) proposed that the Eastern Creek mineralisation involved two distinct brines. The first fluid contained Fe and sulfate and formed in the void spaces at the top of the Balbirini Dolostone during vadose diagenesis and by the dissolution of evaporites. The second basinal brine, rich in Ba, Pb, Cu and H_2S, came into contact with the lower temperature, stationary earlier fluid, precipitating galena and chalcopyrite.

Bulman mineral field

The Bulman mineral field (**Figures 15.28**, **15.40**), comprising 10 recorded mineral occurrences, was discovered in early 1900 and worked intermittently until 1925. Between 1908 and 1911, the deposits produced 10 t of high-grade lead ore before mining was abandoned owing to rapidly decreasing lead grades with depth (Patterson 1965). Minor production again took place in 1925. A combined resource for seven of the deposits has been estimated as 1.2 Mt at 6.5% Pb and 0.93 Mt at 11% Zn (Nasca 1969). Admiralty Resources NL conducted a drilling program in June–July 2008, via its wholly owned subsidiary Bulman Resources Pty Ltd. The drillholes intersected shallow, flat-lying localised zones of zinc-lead mineralisation hosted by dolomitic and calcareous sediments above an intrusive dolerite contact. Drillhole BEL0001 intersected 3 m at 11.63% Zn and 5.02% Pb from 15 m. Other intersections are highly variable and range from 3–11 m at 0.16% Zn to 8 m at 2.20% Zn and 3 m at 0.49% Zn (Admiralty Resources NL, ASX Announcement, 10 October 2008).

The mineralisation at Bulman is within flat-lying or gently dipping, laminated stromatolitic dolostone, chert, fine-grained sandstone, and cherty breccia of the Dook

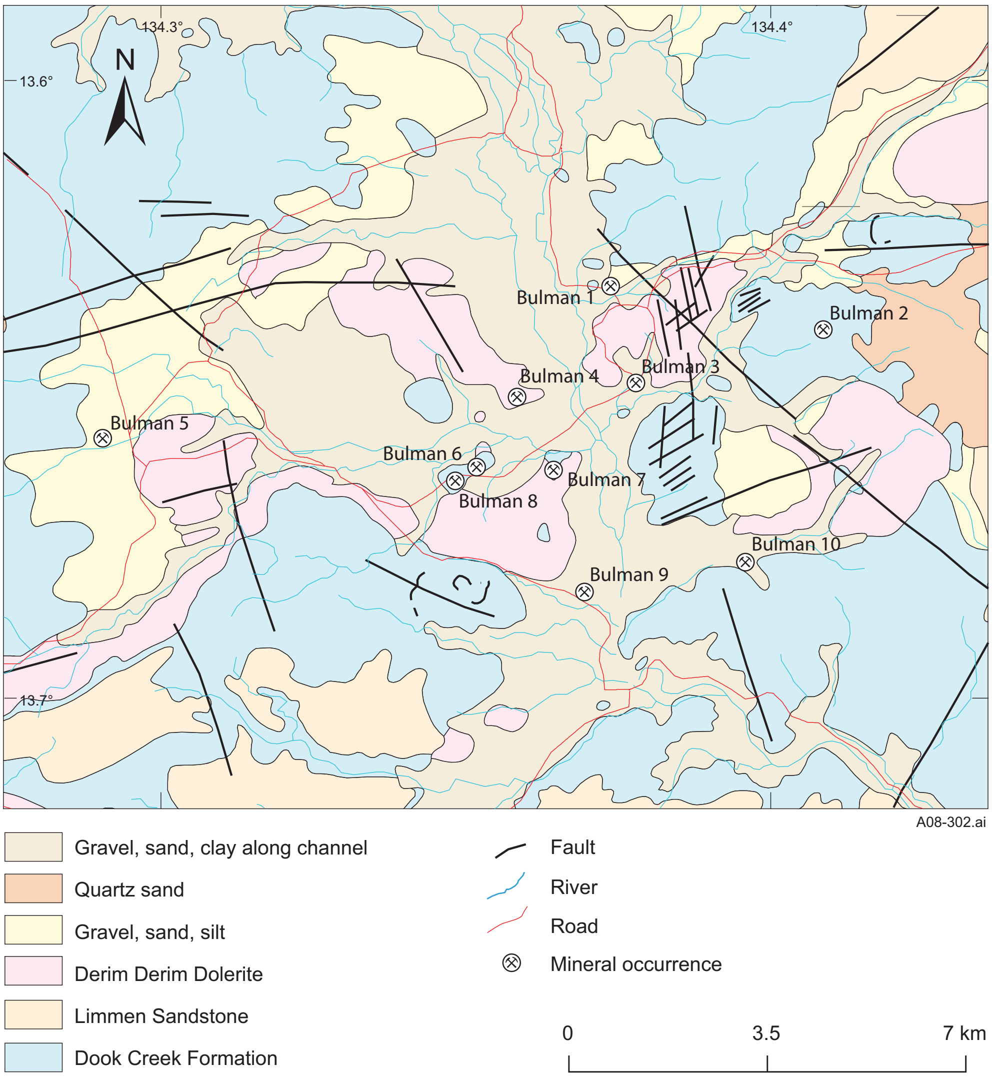


Figure 15.40. Geology of the Bulman mineral field.

Creek Formation. Sills of Derim Derim Dolerite intrude the dolostone. The most prominent structural feature is the Bulman Fault, which can be traced over a distance of about 300 km.

Almost all of the mineral occurrences are in carbonate rocks, which have been contact metamorphosed by a dolerite sill. The carbonate rocks within a 50 m-wide contact zone show extensive contact metamorphic effects ranging from slight recrystallisation to extensive development of serpentinite and talc (Nasca 1969). Minor ore minerals are also known from non-metamorphosed carbonate rocks.

Three types of mineral occurrences can be distinguished. The first type, which is represented in the majority of the old workings, consists of small but rich pods of high-grade galena and sphalerite in cavities along bedding planes (**Figure 15.41**). The second type consists of a 0.3–0.6 m-thick surface crust of high-grade zinc ore, averaging 20% Zn and 3% Pb (Patterson 1965); ore minerals comprise cerussite, galena, hydrozincite, smithsonite and willemite. The third type forms the bulk of the base-metal resource in the Bulman mineral field and appears to offer the most potential for further discoveries. It is represented by subsurface stratiform lead-zinc mineralisation at several levels (**Figure 15.41**). The average zinc to lead ratio is 3:1 and silver content is usually less than 30 g/t (Nasca 1969).

Nasca (1969) proposed that the base metals were derived from an igneous source (dolerite) and were transported in silica-rich fluid, to be precipitated as a result of falling temperature and pressure. This model appears unlikely, as a number of dolerite sills intrude the McArthur Basin succession and mineralisation does not occur along the contacts with theses sills. Sweet *et al* (1999) suggested that the Bulman occurrences could have formed from the

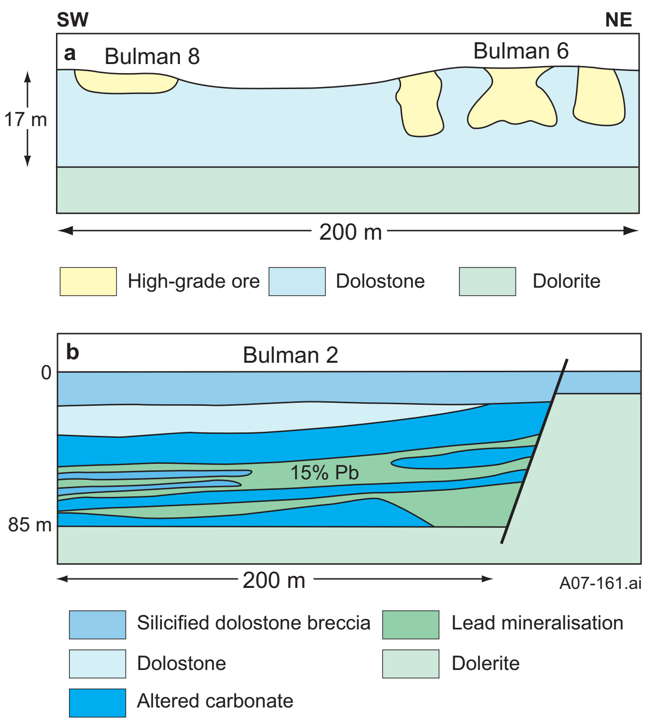


Figure 15.41. Bulman mineral field. (**a**) Stratabound occurrences (Bulman 6 and 8); and (**b**) stratiform lodes at Bulman 2 (simplified after Nasca 1969).

modification and remobilisation of an extensive, but low-grade syngenetic deposit as a result of dolerite intrusion.

Sulfur-isotope analyses on three galena samples (Sweet *et al* 1999, Muir *et al* 1985) indicated small $\delta^{34}S$ variations of +11.6 to +17.3‰. Muir *et al* (1985) considered these values to be consistent with a genetic model similar to that proposed for the Eastern Creek prospect.

Thor prospect

Thor prospect is located adjacent to the Calvert River crossing on the Borroloola–Wollogorang track and is within the Karns Dolostone. It was discovered during mapping and prospecting in 1979 and was subsequently drilled (Janecek 1980, Dennis 1981, Barrett 1982). The mineralisation comprises coarse-grained galena and sphalerite veins and disseminations, closely associated with bitumen vugs. This is hosted in porous and cavernous dolostone and sandstone facies of the lower Karns Dolostone. Surface grab samples assayed up to 36% Zn, 17% Pb and 62 g/t Ag. However, drilling indicated only moderate grades at depth over narrow intervals. The best intersection was 13.4 m at 3.21% Zn and 0.39% Pb (Janecek 1980).

Copper-bearing breccia pipes

Copper-bearing breccia pipes are known from the Redbank area (**Figure 15.42**) near the southern edge of the southeastern McArthur Basin (Orridge and Mason 1975, Rod 1978, Knutson *et al* 1979, Ahmad and Wygralak 1989, 1990, Wall and Heinrich 1990, Redbank Mines Ltd, ASX Announcements, 18 July 2007, 8 January 2008 and 10 January 2008). Minor vein-type mineralisation is also present in the Redbank area. Both mineralisation types are closely associated and are possibly genetically related. Most pipes are within the Gold Creek Volcanics, but in an area close to Wollogorang Station, pipes are also known from within the Wollogorang Formation and Settlement Creek Dolerite. A volcanic plug piercing the Seigal Volcanics (**Figure 15.12**), about 2 km north of the Kings Ransom uranium prospect, possibly also belongs to this category (Ahmad and Wygralak 1989). Over 50 breccia pipes are known from the Redbank area and at least 10 of these contain copper mineralisation, with chalcopyrite as the main primary mineral. The most significant mineralisation is documented from the Bluff, Sandy Flat, Stanton, Redbank, Azurite, Prince and Punchbowl occurrences. The pipes comprise various proportions of microbreccia, dolomite, quartz, chlorite, celadonite, haematite, K-feldspar and apatite, with minor barite, rutile and galena. Pyrobitumen has been noted in some occurrences and is probably derived from the underlying sedimentary units. The distribution of mineral occurrences may be controlled by east-trending lineaments that are traversed by northeast- and northwest-trending faults.

The breccia pipes are steeply plunging cylindrical structures, 4 to 75 m in diameter, with a vertical extent of at least 330 m. They appear as circular features on aerial photographs and are often covered by spinifex and devoid of large trees. Pipe boundaries are commonly represented by a complex of minor shears and narrow zones of fracturing extend beyond the limits of the pipes (Orridge and Masson 1975). Rod (1978) considered the pipes to have crooked stems and mushroom-like caps, which have forced the overlying sediments and volcanics into dome-like structures. In the Redbank field, rocks within the pipes commonly dip inward and are generally collapsed to a level more than 100 m below their normal stratigraphic position.

Copper is normally the only commodity present in economic concentrations. However, anomalous Co concentrations are known from some occurrences, and the Stanton and Running Creek pipes, further to the north, contain significant Ni and Co, in addition to copper (Manzies *et al* 1996, Manzies and Morris 1996, Rawlings 2006).

Redbank field

The first copper discovery in the Redbank area was at the *China Girl* prospect in ca 1900. Further copper was

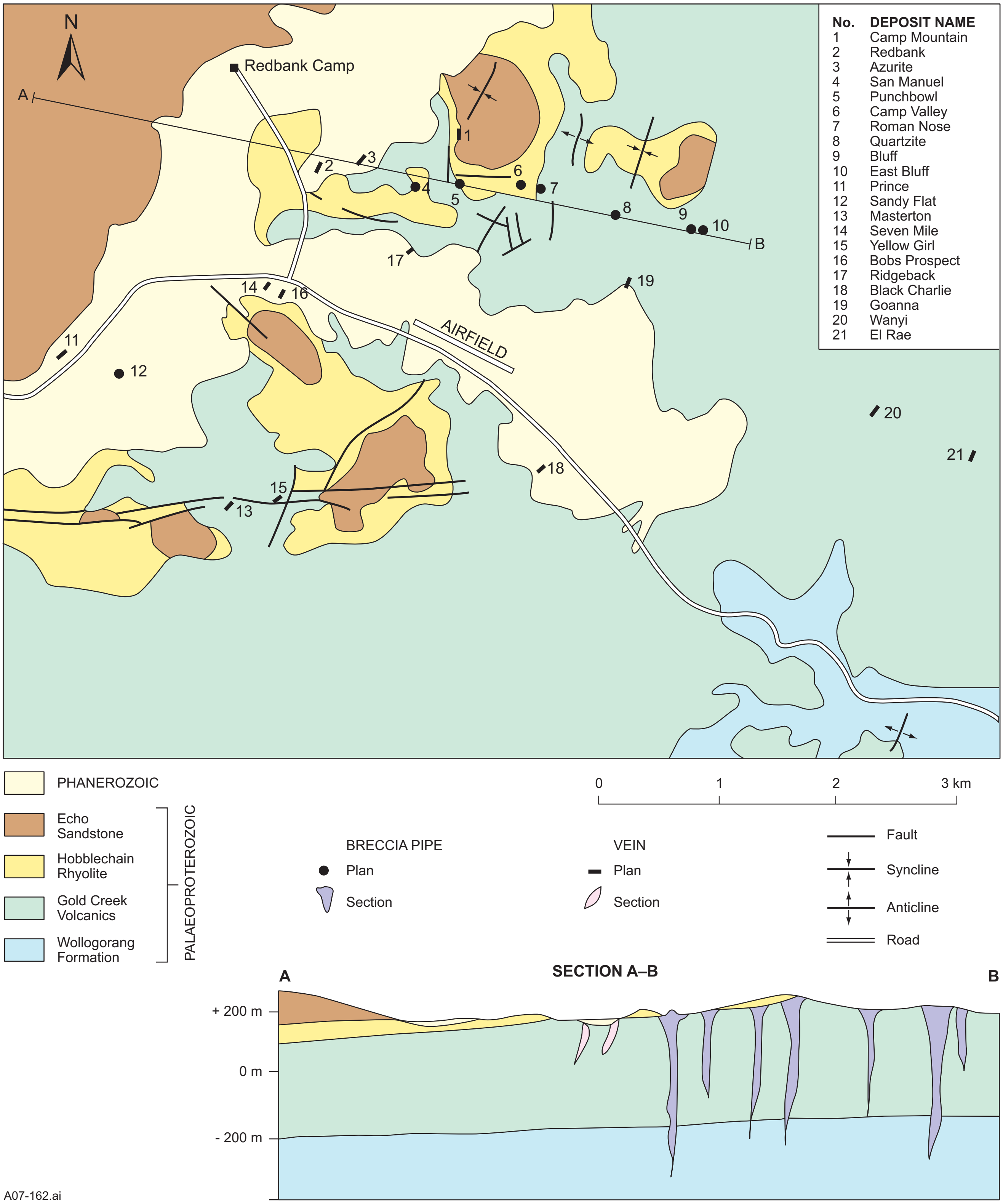


Figure 15.42. Geology of Redbank copper field (after Ahmad and Wygralak 1987).

discovered at *Packsaddle* and *Bauhinia* in1912. From 1916 onward, WR Masterton discovered and delineated most of the prospects in the Redbank field and mined these via a number of small open cuts. Total production by Masterton was more than 1220 t of ore from 1916 until 1957, largely from the *Azurite*, *Redbank* and *Prince* deposits. A number of exploration companies have subsequently examined the area. NEWAIM Pty Ltd, Harbourside Oil NL, Triako Mines NL and CRA Ltd conducted significant geological investigations, including drilling, resource estimation, geophysical surveys and geological mapping during the 1970s.

Knutson *et al* (1979) showed that the Redbank pipes contain both autochthonous and allochthonous breccias (**Figure 15.43**). The former is confined to the outer part of the pipe and comprises very angular fragments of the local rocks, eg Gold Creek Volcanics (**Figure 15.44**). The allochthonous breccia is present in the axial zone of the pipe and comprises large, subrounded fragments of the underlying Wollogorang Formation and volcanic rocks. The matrix in both breccias is similar and comprises dolomite, calcite, quartz, K-feldspar, apatite, celadonite, haematite, rutile and clay minerals. Chalcopyrite is the predominant ore mineral but some pyrite, galena, sphalerite and covellite are also present. The mineralogy of the Sandy Flat pipe has been studied by McLaughlin *et al* (2000).

The oxidised zone extends to a depth of about 30 m and contains high-grade mineralisation, ranging from 1.7 to 5.8% Cu. The main minerals in the oxidised zone are malachite, azurite, chalcocite and chrysocolla.

A JORC-compliant estimate of the total resources at Sandy Flat, Bluff, Redbank and Punchbowl is 6.24 Mt at 1.5% Cu for 95 900 t of contained metal. This includes an indicated resource of 2.76 Mt at 1.6% Cu and an inferred resource of 3.48 Mt at 1.5% Cu (Redbank Copper Ltd website: www.redbankcopper.com.au, accessed Oct 2010). There are a number of advanced targets located near the minesite area as well as regional targets, and it is possible that exploration will result in increased oxide and sulfide resources. An open cut mining operation commenced in March 2006, and was suspended in September 2008. The company plans to recommence mining in 2013 and known resources are expected to support an initial 10-year operation.

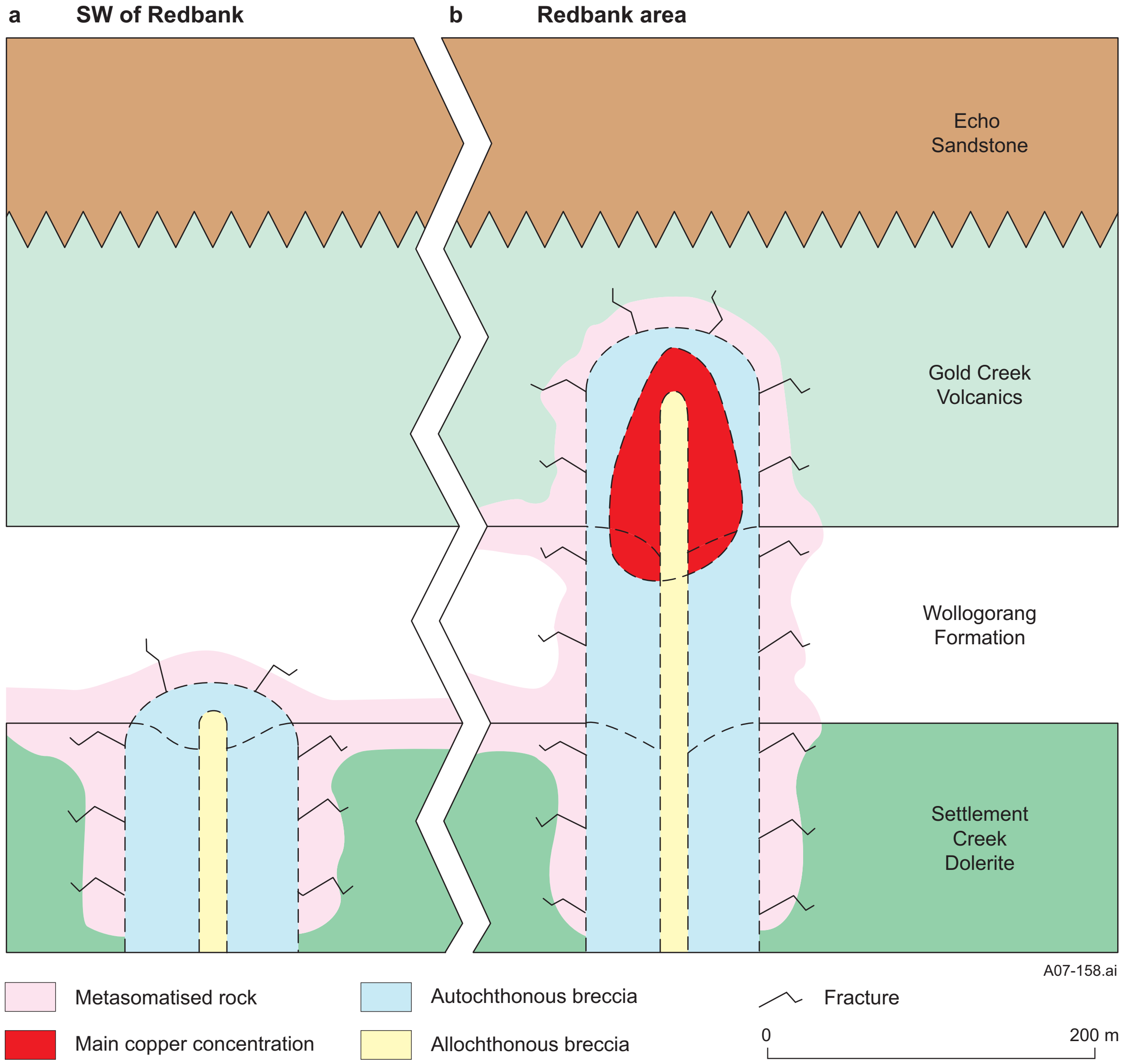


Figure 15.43. Sketches showing geological relationships and spatial distribution of breccia types in Redbank area. (**a**) Tom Springs and Eagles Nest, southwest of Redbank mines and (**b**) Redbank breccia pipes at Sandy Flat and Bluff (modified after Knutson *et al* 1979).

Sandy Flat

The breccia pipe at Sandy Flat is concealed by soil and laterite. it was discovered by Harbourside Oil NL in 1969 and detailed drilling was carried out by NEWAIM Pty Ltd in 1971. The diameter of the pipe is about 60 m at the surface; it tapers down to a diameter of about 30 m near the Gold Creek Volcanics–Wollogorang Formation contact, at a depth of about 200 m. Drill intersections suggest that the breccia pipe continues well into the Wollogorang Formation.

A high-grade supergene zone, containing chalcocite and malachite, extends down to about 30 m below the surface. Chalcopyrite is the main primary mineral, occurring as disseminations, veinlets and fracture fillings associated with strong chloritic alteration (Bell 1974). The interface between the Gold Creek Volcanics and Wollogorang Formation is mineralised and this mineralisation possibly extends beyond the pipe boundaries.

Bluff

The Bluff breccia pipe was discovered by NEWAIM Pty Ltd / Harbourside Oil NL in 1971 as a result of surface soil sampling. There is also a strong vegetation anomaly over a circular spinifex-covered depression, which represents the pipe. Weak surface mineralisation in brecciated trachyte can be traced for about 300 m, mainly as malachite stains on joints and fractures. The Bluff pipe has been extensively drilled. It is about 100 m in surface diameter and tapers down to about 30 m at a depth of about 270 m, well into the Wollogorang Formation. The ore-grade mineralisation plunges 70° due north (Bell 1974), with high-grade mineralisation present as fracture fillings and disseminations in brecciated rocks.

Figure 15.44. Copper-stained breccia from Sandy Flat pipe, consisting of trachyte clasts in chalcopyrite-bearing pyrobitumen matrix (A Wygralak collection).

Large unmineralised blocks of volcanic rocks are present within the centre of the pipe.

Knutson *et al* (1979) provided sulfur, carbon and oxygen isotope data, and proposed that the deposits were formed as a result of the explosive release of hydrothermal fluids from potassic magma bodies at depth. Wall and Heinrich (1990) suggested a fluid-mixing model, involving copper-rich basinal brines derived from above or lateral to the deposit and more-reduced hydrocarbon-bearing fluids, sourced from the underlying Wollogorang Formation.

Punchbowl

The Punchbowl deposit was discovered by Triako Mines NL in 1974 by following up a Cu soil anomaly in a topographic depression. A kaolin-quartz-calcite alteration zone associated with fine-grained chalcopyrite extends for several hundred metres around a rhyolite intersected in drillholes. One of the early diamond holes returned 36.6 m at 1.0% Cu from 11.6 m (Triako Mines 1975).

Running Creek field

The *Stanton* and *Running Creek* prospects are located some 55 km northwest of Wollogorang Station and are hosted within the upper Gold Creek Volcanics (**Figure 15.28**). The Running Creek occurrence was probably discovered at the same time as the Redbank pipes and subsequently mined for a negligible tonnage from shallow workings. In the late 1970s, WJ Fisher identified eight anomalous circular features in this general area and carried out geochemical sampling. Subsequent exploration by CRA Exploration in 1990 lead to the discovery of seven discrete prospects (Palmer *et al* 1995, Menzies and Morris 1996, Menzies *et al* 1996, Harvey 1997). The total indicated resource at Stanton is 800 000 t at 0.15% Co, 0.08% Ni and 0.15% Cu (Hydromet Corp Ltd, ASX Announcement, 2 February 2001). Stanton also has rare anomalous intersections of gold, including 6 m at 0.2 g/t (Palmer and Fisher 1992). Pb and Zn are also locally anomalous, with the best intersection 8 m at 0.48% Zn at the nearby *Felix* prospect (Menzies *et al* 1996). No resource is estimated for Running Creek.

Ore minerals at Stanton are mainly of disseminated siegenite and chalcopyrite in the primary zone (**Figure 15.45**), and malachite, azurite, chalcocite, native

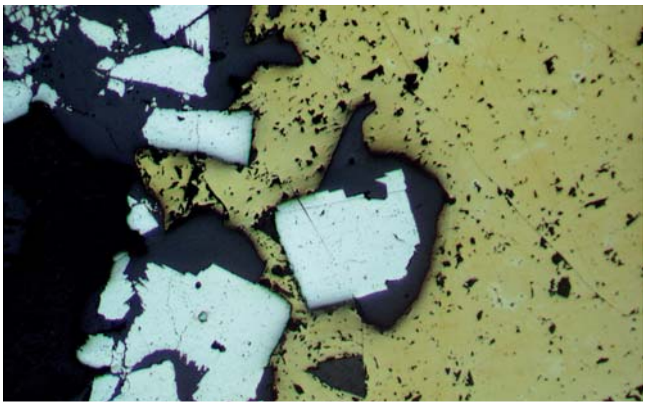


Figure 15.45. Large, euhedral, cubic siegenite crystals, partially enclosed by massive chalcopyrite at Stanton deposit (after Rawlings 2006: figure 76). Field of view about 1.5 mm wide. Drillhole DD94RC33, 129 m depth, 53K 793500mE 8148300mN.

copper and asbilite (a manganese-base metal oxide) in the oxidised zone (Menzies *et al* 1996). Primary sulfides occur as disseminations and in quartz-dolomite veins. Gangue minerals include chlorite, K-feldspar, pyrobitumen, celadonite, pyrite, haematite and siderite. Live oil shows and bleeds have been recorded from several drillholes (Menzies *et al* 1996).

The pipes have steep radial dips and stratigraphic juxtapositions that imply faulting and downward movement of the pipe interiors. Breccia ranges from monomictic to polymictic, and comprises clasts of sandstone, mudstone and basalt in a mud-sand matrix (Rawlings 2006). The breccia pipes apparently continue down-plunge, perhaps into the underlying Wollogorang Formation.

Breccia pipes in the Running Creek area are interpreted to be contemporaneous with: (i) folding of the Gold Creek Volcanics; (ii) the development of a disconformity at the base of the Pungalina Member and; (iii) emplacement of the Hobblechain Rhyolite and Packsaddle Microgranite (Rawlings 2002).

Rawlings (2006) considered that brecciation was localised within: (i) a transtensional jog associated with a north-northeast-trending, steeply northwest-dipping strike-slip (wrench) fault or; (ii) a dilational boundary between two gravity-driven slide blocks. Furthermore deformation is attributed to emplacement of the Packsaddle Microgranite and its unexposed equivalents (Rawlings 1997). This structural model contrasts with earlier hypotheses that the breccia pipes at Redbank formed by hydrothermal and magmatic explosions, associated with the emplacement of postulated, deep-seated carbonatite magma bodies (Orridge and Mason 1975, Rod 1978, Knutson *et al* 1979).

Fluid inclusion studies (Menzies *et al* 1996, Morris *et al* 1996) have shown that the brines were relatively low temperature (110–120°C) and highly saline (>20 wt% NaCl equivalent). The data shows a tail of elevated homogenisation temperatures (120–350°C), and the presence of liquid oil in the fluid inclusions favours the existence of a hot, reducing fluid [D Rawlings, Toro Energy Ltd (formerly NTGS) unpublished data].

A two-fluid model was considered by Rawlings (2006) for the genesis of Stanton and other prospects in the Running Creek area: an oxidised saline brine (generated in the Gold Creek Volcanics and carrying the metal constituents) and a reduced, hydrocarbon-bearing fluid (originating in the underlying Wollogorang Formation). Metal precipitation was considered to be due to the reduction of metal-bearing oxidised waters.

Vein-type copper occurrences

As well as the copper-bearing breccia pipes in the southeastern McArthur Basin, there are a number of occurrences where copper minerals occur in veins and fault infills. Production from theses veins has been insignificant and there are no detailed studies on these vein-type occurrences.

At *Johnstons* mine (**Figure 15.28**), copper-lead mineralisation is hosted within a subvertical, north-northeast-trending shear zone in the lower McArthur Group (Tooganinie Formation). The main mineralised shear is about 1 m wide and can be discontinuously traced for over 150 m along strike. Several minor sub-parallel fractures are exposed in pits and costeans in the footwall. Malachite is the dominant ore mineral observed at the surface, staining and infilling fractures within brecciated shale and dolarenite. Chalcocite, azurite, chrysocolla, cerussite, pyromorphite and anglesite are also present. The primary ore consists of coarse-grained galena and pyrite, with minor chalcopyrite and arsenopyrite infilling fractures and voids between the brecciated dolomitic fragments (CEC 1977). A grab sample from the lead ore dump assayed 55.2% Pb and 214.6 g/t Ag (Marlow 1963) and 36.9% Pb and 600 g/t Ag (NTGS sample No 9740), whereas samples from the copper dump assayed 37.9% Cu (Marlow 1963) and 32.7% Cu (NTGS sample No 9739). Johnstons DDH 1, drilled by CEC, intersected a 1.5 m section that assayed 1.8% Pb, 1400 ppm Zn and 10 g/t Ag, including a 0.6 m section of 4% Pb (Marlow 1963).

The *Coppermine Creek* prospect (also known as Gordons, Mulhollands or Tawallah Prospect) is located some 2 km southeast of the Eastern Creek prospect and is hosted by a sideritic carbonate-mudstone interval within the Amelia Dolostone (**Figure 15.28**). Mineralisation is present as patchy disseminations, veins and blebs of pyrite and chalcopyrite, together with the secondary minerals chalcocite, malachite and azurite. Minor mineralisation also occurs as fracture- and breccia void-infills within the adjacent east–west-trending fault zone that separates the Amelia Dolostone from Mainoru Formation and Limmen Sandstone. CEC Pty Ltd (Marlow 1963) drilled a diamond hole to test the subsurface extent of mineralisation. The best intersection was 17 m of 0.5% Cu, including a 30 cm interval of 8.25% Cu. Sandfire Resources NL drilled an IP anomaly at this prospect and intersected veinlet chalcopyrite between 160 m and 175 m over a possible strike length of >1.5 km, (Sandfire Resources NL, ASX Announcement, 1 November 2006).

The *Sly Creek* prospect (also known as the Casey R Claim) is hosted within an interval of diagenetic sideritic carbonate, assigned to the Amelia Dolostone (**Figure 15.28**). It was worked for a small unspecified tonnage in the late 1950s. Copper mineralisation is in the form of blebs, veins and disseminations of chalcopyrite, bornite, chalcocite, malachite and azurite (Haines *et al* 1993).

Darcys Copper prospect (**Figure 15.28**) is located about 5.6 km northwest of Mallapunyah homestead and was explored by CEC in 1966 (Rawlins 1967). It is hosted within dolomitic siltstone of the Reward Dolostone. Mineralisation comprises masses of chalcocite, cuprite, malachite and azurite. The cupriferous siltstone lies beneath an unconformity within the Reward Dolostone.

The *Margoo* copper prospect (Kneale *et al* 1979, AO Australia 1980) is located about 29 km west of Balbirini Station and is hosted within dolomitic siltstone assigned to the Mara Dolostone Member. It can be traced for over 70 m along strike. Malachite is the dominant ore mineral present, with minor amounts of cuprite and chalcocite.

The *Tawallah Pocket* copper prospect (Rawlins 1972) was discovered by CEC during a regional stream sediment survey in 1969–1970. Drilling intersected minor chalcopyrite in calcite veins (0.03% Cu over 47 m) within recrystallised carbonaceous dolostone of the Amelia Dolostone (CEC 1977).

At the *Kilgour* prospect, malachite, chalcocite, bornite and chalcopyrite are present as joint- and terra rossa-filled cave breccias in the Amelia Dolostone, immediately below the unconformity with the Bukalara Sandstone. Mineralisation at the *Yah Yah* mine is also within the Amelia Dolostone, below the disconformity with the Tatoola Sandstone (Plumb *et al* 1990).

A number of small vein-type copper occurrences are also present within the Seigal Volcanics (Ahmad and Wygralak 1989). Judging from their surface expression and historic mining activities, the *Dianne, Vulcan* and *St Barb* prospects appear to be insignificant. Mineralisation comprises secondary copper minerals filling fractures and shears within the Seigal Volcanics.

Uranium (±gold±PGE)

The McArthur Basin hosts a number of small uranium-gold deposits in the region surrounding the Murphy Inlier of the Murphy Province. Most prospective occurrences of this group that have an established resource (Westmoreland uranium deposits) are in adjoining areas of Queensland. Almost all of the occurrences are in the lower Tawallah Group (Westmoreland Conglomerate and Seigal Volcanics) and in adjacent, unconformably underlying older rocks (Cliffdale Volcanics; see **Murphy Province**). Several occurrences of uranium (±gold±PGE) are also known within sandstone of the Kombolgie Subgroup on the western margin of the McArthur Basin, in western Arnhem Land.

The total inferred resources for deposits within the Westmoreland Conglomerate in Queensland have been estimated at 17 400 t averaging 1.2 kg/t U_3O_8 (Rheinberger *et al* 1998). The Eva deposit, hosted by the Cliffdale Volcanics in the Northern Territory, contains 54 500 t at 0.62 % U_3O_8 (Lally and Bajwah 2006).

Occurrences in the lower Tawallah Group

Arthur Blackwell discovered a radioactivity anomaly near Pandanus Creek in 1955. He pegged the area as Cobar II (later Cobar 2) and put down a shaft and drive in the same year. Also in 1955, RT Norris discovered surface uranium minerals at several locations which he collectively called Pandanus Creek. Norris pegged several Authorities to Prospect and in June 1958, the Eva prospect was discovered by his niece, Eva Clarke. The Eva mining lease was pegged in 1958 and the North Broken Hill Propriety Company explored it under option from 1959 to 1960. The general area was further explored by both syndicates of small prospectors and the large mining companies. A Bureau of Mineral Resources airborne radiometric survey led to follow-up ground work by MIM Ltd and Northern Australian Uranium Corporation. Queensland Mines Ltd explored in this area from the late 1960s to the early 1970s (Taylor *et al* 1968, Hills 1970, Hills and Thakur 1975). From 1980 to the early 1990s, Kratos Uranium Ltd, Uranerz Australia Ltd, Urangesellschaft Australia Ltd, Queensland Mines Limited and CRA Exploration conducted further exploration. As a result of these efforts, some 35 uranium occurrences in the Northern Territory and 19 occurrences in Queensland were identified. Several or the more significant prospects were held by the Newcrest Coronation Hill JV while the Federal Government moratorium on new uranium mines was in place. A resurgence in uranium exploration in the mid-2000s rekindled interest in the region and future discoveries are possible.

Historical production from the region was limited to small-scale mining operations at *Eva* and *Cobar 2* (also called *Cobar II*) in the Northern Territory, and totalled 34.6 t U_3O_8. An association of uranium with gold had been known for sometime, but was only investigated from 1981 onward, with the reporting of high-grade assays, ranging from 1–16 g/t, in the NE Westmoreland occurrence (Kratos Uranium NL 1981). Ahmad (1982) reported assays as high as 103 g/t Au and averaging at 15 g/t for mullock samples from the Eva Mine.

Ahmad (1987) classified uranium occurrences on both sides of the Northern Territory–Queensland border into five types (A–E), based on their hydrological and geological settings (**Figure 15.46**).

Type A

These deposits lie at the contact between the Westmoreland Conglomerate and the Cliffdale or Seigal Volcanics. In sub-type A_1 occurrences, the contact between the Cliffdale Volcanics and Westmoreland Conglomerate is a reverse fault. In sub-type A_2 deposits, the contact between the Westmoreland Conglomerate and Seigal Volcanics is conformable. The overlying volcanics, Westmoreland Conglomerate, or both units may be mineralised adjacent to the contact. Mineralisation is seldom more than a few metres in width, but anomalous radioactivity occurs for several tens of metres along the strike of the contact (Ahmad 1987). Examples of subtype A_1 deposits are *Redrock, Jackson Pit, Jim Beam, Jacques* and *Southern Comfort* prospects. Examples of subtype A_2 deposits are *El Hussen* and *McGuinness.*

Type B

In these deposits, mineralisation occurs as sub-horizontal and sub-vertical lenses in the Westmoreland Conglomerate, adjacent to highly altered, generally subvertical dolerite dykes (possibly coeval with the Seigal Volcanics) that may also be mineralised. Several of these dykes cut the Nicholson Granite and Cliffdale Volcanics, but no uranium mineralisation has been reported where they cut rock types other than the Westmoreland Conglomerate.

Uranium mineralisation is associated with three major northeast-trending lineaments, called the NE Westmoreland, Redtree and El Nashfa dyke zones. The last two are in Queensland and contain the largest known uranium resources in the region.

The NE Westmoreland dyke zone in the Northern Territory contains narrow and discontinuous mineralised zones with uranium averaging from 0.04 to 2.4 % U_3O_8 and gold grades from 1 to 16 g/t (Stewart 1990) at the *Mageera, Intermediate* and *Oogoodoo* prospects.

In Queensland, the Redtree dyke zone extends over a strike of 20 km, and hosts the *Moongooma, Namalangi, Redtree, Junnagunna* and *Wanigarango* prospects. Rheinberger *et al* (1998) provided descriptions of the main deposits.

The inferred resources for the three largest deposits are: *Redtree* – 10.2 Mt at 0.126 % U_3O_8, Junnagunna – 5400 t at 0.098 % U_3O_8, and Huarabagoo – 1.8 Mt at 0.169 % U_3O_8 (Rheinberger *et al* 1998).

Mineralisation within the dyke zones is associated with a proximal alteration assemblage of quartz-sericite ± kaolinite in sandstone, and haematite-quartz in dolerite. Mineralisation distal to dyke zones is associated with chlorite and minor haematite alteration. The primary ore consists mainly of uraninite, with varying amounts of autunite, ningyoite, bassetite and coffinite. Uranium minerals are either interstitial to sand grains or occur as fracture coatings in sandstone and within haematite-quartz veins in dolerite (Ahmad and Wygralak 1989, Rheinberger *et al* 1998). Gold is also present, but grades are generally erratic.

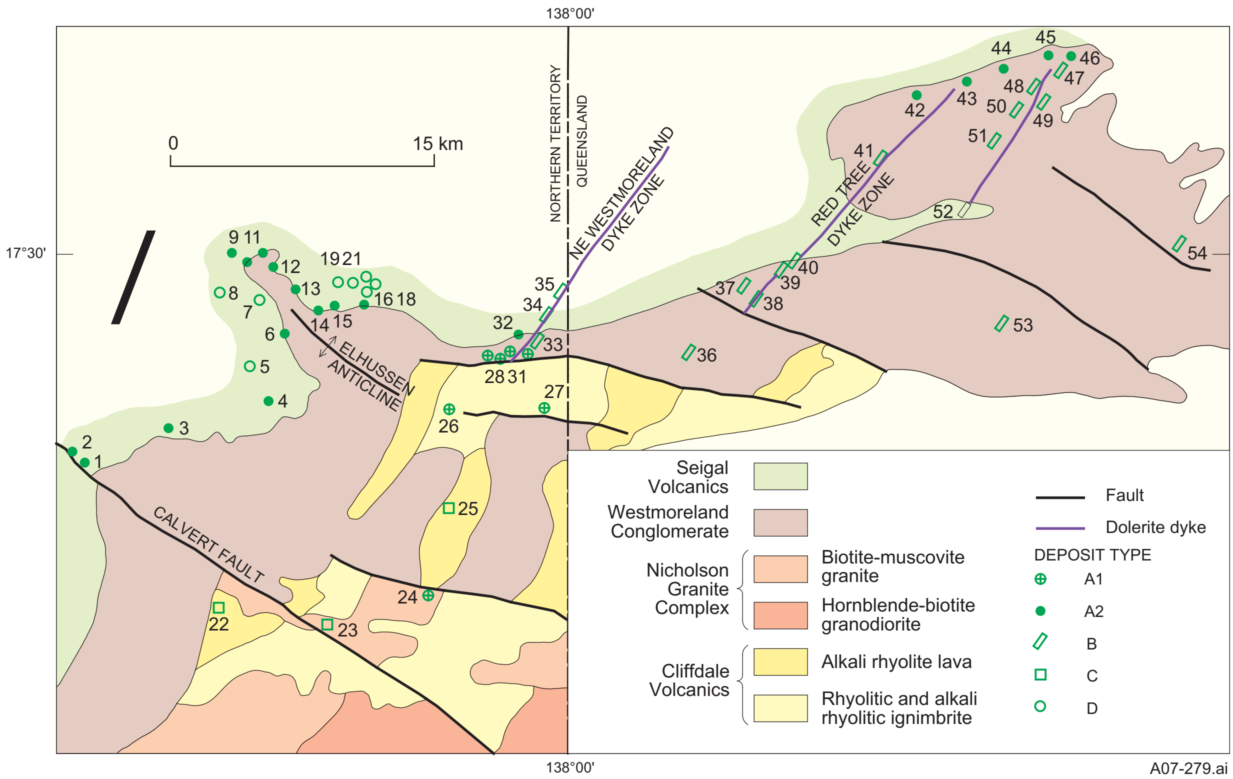
Type C

Type C deposits are hosted by intensely altered Cliffdale Volcanics close to the exhumed unconformity with the overlying Westmoreland Conglomerate. *Eva* (Pandanus Creek) is the only significant uranium deposit of this type in the region (Morgan 1965, Ahmad 1982); see **Murphy Province**.

Other Type C occurrences are *Crippled Horse*, which is associated with a subvertical quartz-filled fault zone, and *Duccios*, which has no apparent structural control.

Type D

Type D occurrences are related to fractures in the lower part of the Seigal Volcanics, up to 200 m above the contact with underlying Westmoreland Conglomerate. They include



URANIUM OCCURRENCES

1 Calvert South
2 Calvert North
3 Debbil-Debbil
4 White Label
5 Horse Pocket
6 El Hussen
7 Monte Carlo
8 Fata Morgana
9 White Horse
10 Black & White
11 McGuiness
12 Corio
13 Kookaburra
14 Hidden Valley
15 Waterfall Creek
16 Rocky Creek
17 Old Parr
18 Cobar 2
19 Kings Ransom
20 White Heather
21 Johnny Walker
22 Eva Mine
23 Una May
24 Red Rock
25 Crippled Horse
26 Duccios
27 Maniws
28 Southern Comfort
29 Jacques
30 Jim Beam
31 Jackson Pit
32 NE Westmoreland (contact lode)
33 NE Westmoreland (Mageera)
34 NE Westmoreland (Intermediate)
35 NE Westmoreland (0ogoodoo)
36 Moongooma
37 Redtree
38 Namalangi
39 Huarabagoo
40 Junnagunna
41 Wanigarango
42 Embayment
43 Pats Find
44 Pioneer
45 Vaudeville
46 Broadway
47 Amphitheatre
48 Yankee
49 El Sharm
50 Flying Fox
51 El Nashfa
52 Long Pocket
53 Tjaumbi
54 Buck Hill

Figure 15.46. Regional geological setting of uranium deposits in Westmoreland area (modified from Ahmad and Wygralak 1987).

Cobar 2, *Old Parr* and *Kings Ransom*. Other occurrences of this type are small zones of anomalous radioactivity that generally relate to secondary uranium minerals in vertical fractures. Newton and McGrath (1958) noted that mineralised fractures in this type of occurrence are generally intensely silicified and include some haematite. Very little other information is available.

Type E

These uranium occurrences are hosted by the Murphy Metamorphics and are associated with faults and fractures. Drilling has indicated minor mineralisation at *Anomalies 1*, *3* and *4901* (see **Murphy Province**).

Geochronology

U-Pb dating of uraninite from Cobar 2, Eva and Namalangi indicated two periods of uraninite deposition, at 820 Ma and 430 Ma (Hills and Richards 1972). Subsequent U-Pb dating of uraninite from Namalangi by Pidgeon (1985) indicated a single mineralisation event at 812 ± 55 Ma. The 820 Ma age of uraninite in the Westmoreland-Murphy region is consistent with similar dates for several deposits in the Alligator River uranium field (AURF) in the Pine Creek Orogen. However, in the case of ARUF deposits, more recent dating of uraninite has yielded significantly older ages of mineralisation and it is therefore possible that the 820 Ma date is part of a widespread remobilisation event, rather than the time of primary mineralisation.

Genesis

Newton and McGrath (1958) and Morgan (1960) proposed that uranium was deposited from hydrothermal fluids related to the Nicholson Granite. It is now known that this granite is older and unconformably underlies the Westmoreland Conglomerate which is the host to most uranium occurrences. Hills and Thakur (1975) considered that deposits associated with the Redtree dyke zone were hypogene in origin. Schindlmayr and Beerbaum (1986) and Rheinberger *et al* (1998) proposed that hot oxidised uranium-bearing fluid was derived from granite and volcanic rock. This fluid ascended along major structures into the overlying Westmoreland Conglomerate. Uranium precipitation occurred there as a result of reduction at sandstone–volcanic or sandstone–dyke contacts, or from mixing with cooler descending groundwater, or at permeability barriers.

On the basis of thermoluminescence studies, Hochman and Ypma (1984) concluded that the original uranium content of the Westmoreland Conglomerate was about 10 ppm, compared to current concentrations of 4–6 ppm. Ahmad and Wygralak (1989) noted that fluid within the Westmoreland Conglomerate was oxidised and capable of leaching uranium. They emphasised the hydrological setting of the uranium deposits and concluded that uranium was leached by groundwater and deposited at interfaces with reducing lithologies.

Polito *et al* (2005) carried out paragenetic, stable isotopes and geochronological studies at the Junnagunna deposit. They showed that oxygen and hydrogen isotopic ratios from syn-mineralisation illite are compatible with uranium deposition by a basinal brine with $\delta^{18}O$ fluid and δD fluid values of 4 ± 3 and –33 ± 10‰ respectively. These values are consistent with evolved evaporated seawater, but not with hot oxidised fluids derived from underlying uraniferous granites or volcanic rocks, as previously suggested. Illite crystal habits indicated that the uraninite-illite-haematite assemblage formed at 200 ± 50ºC. $^{40}Ar/^{39}Ar$ ages of illite and $^{207}Pb/^{206}Pb$ ages of uraninite indicate that mineralisation occurred between 1655 ± 83 Ma and 1606 ± 80 Ma, coincident with major tectonic events in northern Australia, and was later remobilised between ca 1150 and 850 Ma.

Occurrences in the lower Kombolgie Subgroup

Anomalous uranium, gold and PGE values have been obtained from rock chip samples and drillhole samples of units in the Kombolgie Subgroup at various prospects in western Arnhem Land (**Figure 15.28**). At *Devils Elbow* (**Figure 15.47**), assays up to 5.8% U_3O_8, 38.1 g/t Au and 28.02 g/t Pd were obtained from surface samples, in which mineralisation was related to fractures within altered amygdaloidal basalt of the Nungbalgarri Volcanics (Taylor 1990). However, the best intersection from drilling was 0.095% U_3O_8 over 5 m from 116 m depth (**Figure 15.48**). At *Flying Ghost* and *Casper/Banshee*, similar high uranium, gold and PGE values from surface samples were not repeated in drillhole samples. Uranium is associated with zones of intense fracturing filled with goethitic clays in the Gumarrirnbang Sandstone near its contact with the Gilruth Volcanics (Drever *et al* 1998).

Iron ore

Iron ore was first discovered in the McArthur Basin in 1911 at the *Murphys* prospect on the Roper River, west of Urapunga. At this prospect, a series of concordant siliceous lenses, up to 100 m long and 7 m thick, contain massive to disseminated haematite in arkosic sandstone of the Mount Birch Sandstone, at the unconformity with the Mount Reid Rhyolite. Bulk sampling by BHP Ltd indicated that sections of the deposit contain up to 54% Fe

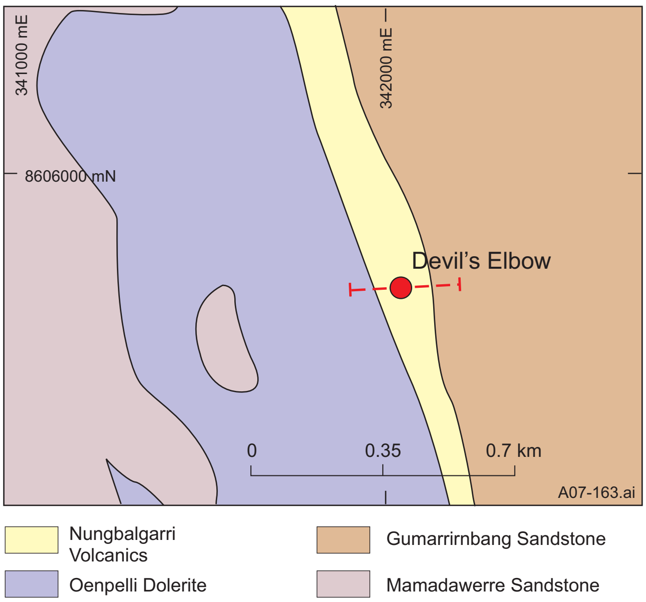


Figure 15.47. Surface geology of Devils Elbow U-PGE occurrence. Dashed red line shows location of cross-section in **Figure 15.42**.

over 5 m and 51% Fe over 11 m (Hickey 1987). This area is currently under application by Australian Ilmenite Resources Pty Ltd.

The *Kipper Creek* iron prospect was discovered 11.5 km east-northeast of Murphys by Carpentaria Exploration Company Ltd in the early 1960s. An oolitic ironstone interval at the base of the Wadjeli Sandstone member occurs sporadically at surface over a 75 km strike length. Shallow diamond drilling was undertaken to test a 10 km strike length. Two ironstone beds were intersected. The lower is oolitic haematite with interstitial siderite. It is an average of 0.8 m thick with an average of 40.4% Fe. The upper bed is 0.9 m thick, oolitic and pisolitic with siderite and calcite cement, and averages 31.0% Fe over the area drilled (Williams 1962). This area is currently under application by Australian Ilmenite Resources Pty Ltd.

Ironstone in Sherwin Formation

Between 1955 and 1961, BHP Ltd investigated 27 iron ore prospects in the Sherwin Formation to the southwest of Murphys prospect (Cochrane 1955, Bennett and Heaton 1958, Salamy 1958, Cochrane and Edwards 1960, Vivian 1962). The best of these prospects were given letter names (**Figure 15.49**). Interest in these deposits was briefly revived in early 1990s, when some of the occurrences were sampled and mapped (Orridge 1993, Ferenczi 1997), but it was not until recently that the potential of the Sherwin Formation iron ore was seriously considered and JORC-compliant resources have now been established for some of the deposits. The Sherwin Formation iron deposits are currently being explored in four project areas (**Figure 15.49**).

The old BHP prospects A to P in the *Sherwin Creek/ Mount Scott* area are held by North Australian Iron Ore Pty Ltd, a wholly owned subsidiary of Sherwin Iron Ltd, but there has been only limited work in this area to date. At least four distinct ironstone beds and lenses have been identified. The upper three ironstone units (upper, middle and lower beds) consist of low-grade (average 38% Fe), ferruginous oolitic sandstone with a high silica content (average 42% SiO_2). A soft, ochreous oolitic ironstone bed near the base of this succession has better economic potential than the harder, upper ironstone intervals, as it is higher in iron and contains less silica (Ferenczi 2001). BHP's prospects Q, R. S and Z are under application by Australian Ilmenite Resources Pty Ltd. A schematic cross-section, based on information from drillholes, by Ferenczi (2001) is reproduced in **Figure 15.50**.

The *Hodgson Downs* project area (**Figure 15.49**) contains the former BHP T to Y prospects. At W Deposit (**Figure 15.51**), Sherwin Iron has delineated a Mineral Resource of 100 Mt at 48% Fe using a 40% Fe cut-off and an SG of 2.7 (Sherwin Iron Ltd, ASX Announcement, 19 October 2010). At the Hodgson Downs deposits generally, the Sherwin Formation forms a distinctive mappable unit up to 8 m thick that can be discontinuously traced for some 25 km around the southern and eastern margins of a shallow northeast-plunging syncline.

Southeast of the original BHP work, Western Desert Resources Ltd has established JORC-compliant resource estimates of 90.7 Mt, 12.3 Mt, 72 Mt and 14.2 Mt at their *Roper Bar* project areas D, E, E (South) and F (not to be confused with the original BHP prospects of the same name). The respective grades are 37.2%, 44.0%, 39% and 49.5% Fe (Western Desert Resources Ltd, ASX Announcements, 15 October 2010, 23 November 2010). Western Desert Resources also has tenements over the Sherwin Formation in the *Mountain Creek* project area.

The Sherwin Formation ironstone typically comprises lenses of massive oolitic to pisolitic beds (**Figure 15.52**),

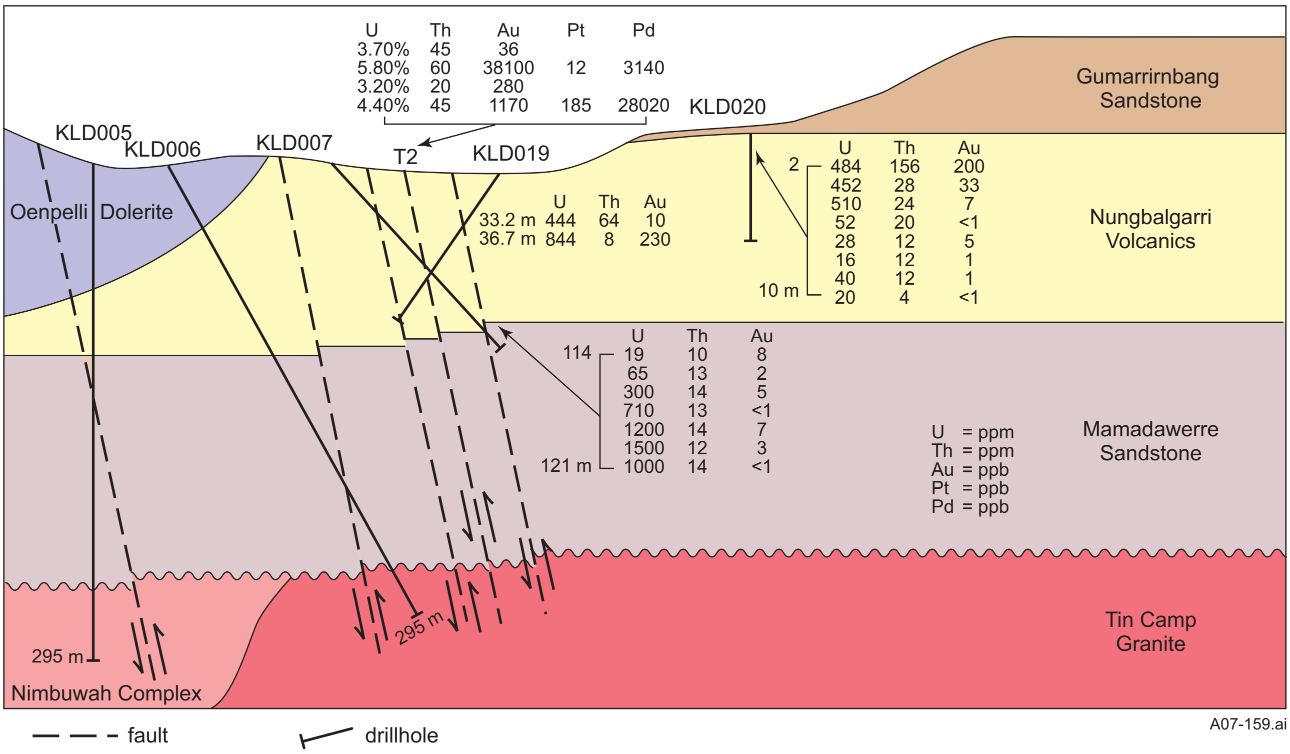


Figure 15.48. Geological cross-section at Devils Elbow U-PGE occurrence, western Arnhem Land (modified from Drever *et al* 1998).

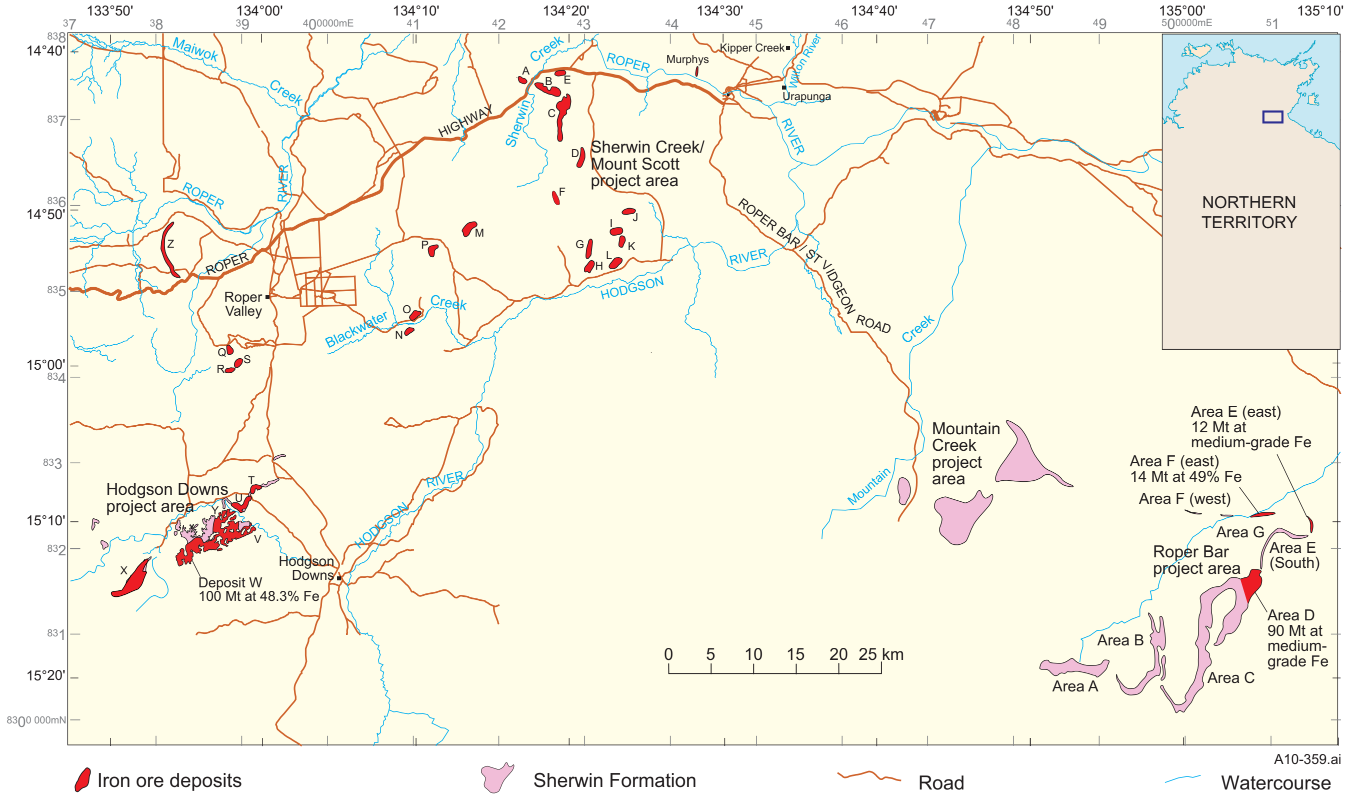


Figure 15.49. Iron ore occurrences in Roper Bar area (data from Ferenczi 2001, Sherwin Iron Ltd, ASX Announcements, 19 October 2010, 16 November 2010, Western Desert Resources Ltd, ASX Announcement, 15 October 2010). Outcrop of Sherwin Formation shown only in vicinity of Hodgson Downs, Mountain Creek and Roper Bar project areas.

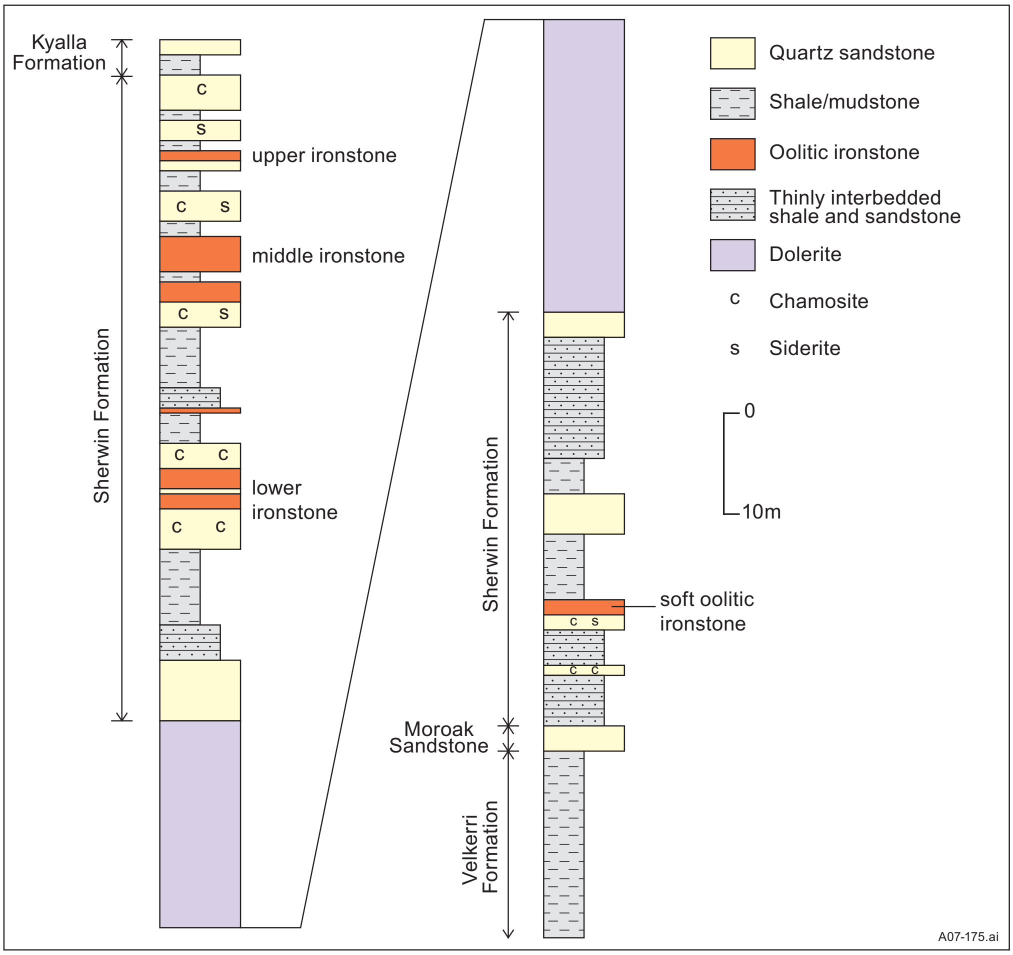


Figure 15.50. Stratigraphic section, Sherwin Creek area, based on drillholes (after Ferenczi 2001).

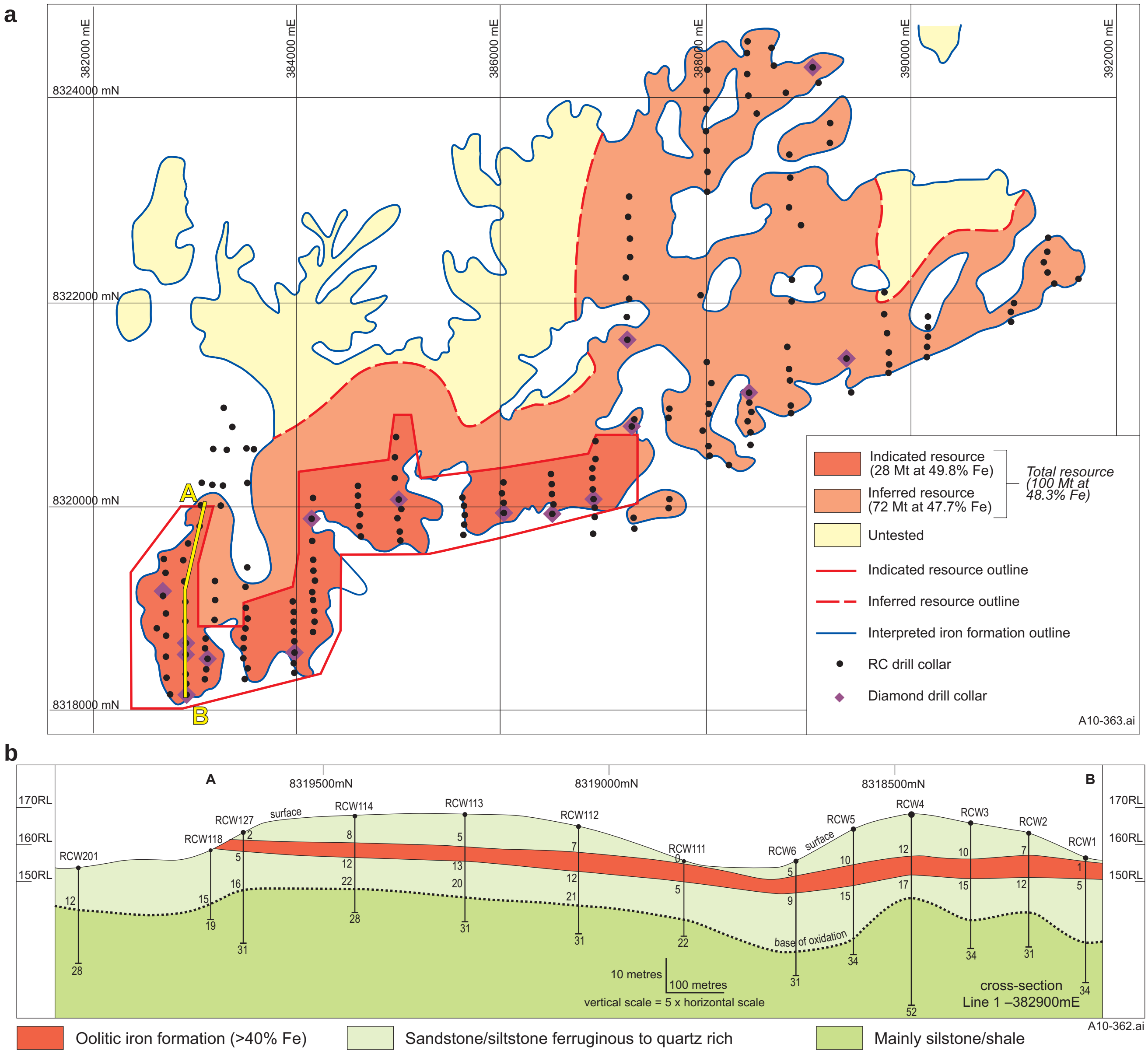


Figure 15.51. Deposit W at Hodgson Downs project area. (**a**) Plan and (**b**) cross-section along north–south-oriented drill line 1 through western end of deposit (after Sherwin Iron Ltd, ASX Announcement, 19 October 2010).

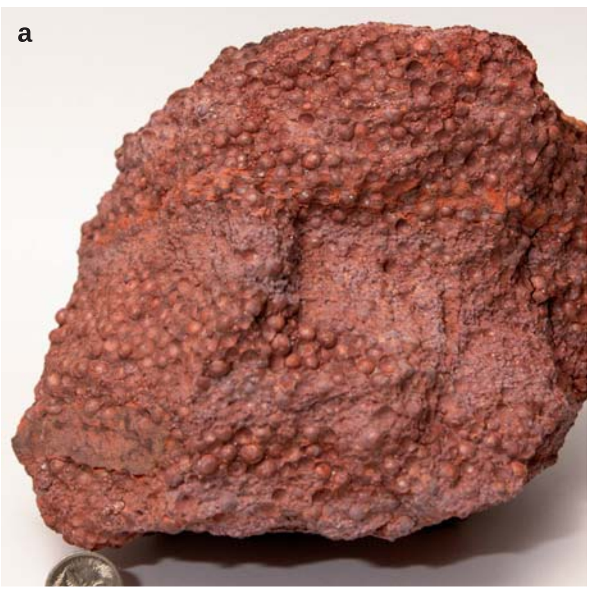


Figure 15.52. Iron ore samples from Roper Bar area (precise location unknown, A Wygralak collection). (**a**) Cemented pisolitic ore. (**b**) Cemented oolitic ore.

interbedded with medium- to very coarse-grained ferruginous (chamosite-siderite at depth) sandstone, sandy mudstone and shale. Massive ironstone beds are typically 1–4 m thick, but range up to 8 m, and are often exposed near the tops of cliff faces (**Figure 15.53**) and around the sides of mesas. A soft, ochreous oolitic ironstone bed near the base is of relatively higher grade and contains less silica. The ore comprises closely packed ooids (0.5–5 mm in diameter) of soft red haematite and goethite, and varying amounts of well rounded quartz grains. Below a depth of 20 m, the ore consists predominantly of haematite and greenalite ooids within haematitic cement.

Other occurrences
Several iron occurrences are known from the basal part of the Mallapunyah Formation in the Tawallah Pocket area. The largest reported occurrence is at the Tawallah Range prospect, where two haematite-rich lodes contain some 12 Mt of iron ore averaging 37–40% Fe (Johnston 1974).

Manganese

Small manganese occurrences, hosted in chert and dolostone assigned to the Karns Dolostone of the Nathan Group, are known from the southeastern McArthur Basin (**Figure 15.28**). These include *Masterton No2, Robinson River No1, Robinson River No2, Camp No1, Manganese 1, Manganese 2* and *Photo (*Ahmad and Wygralak 1989, Ferenczi 2001).

The largest of these occurrences is Masterton No2 (also known as Calvert Hills Mn prospect No1), which is located about 14 km to the northeast of Calvert Hills homestead. Historically, this prospect was described as manganese 'reefs' meaning surface crusts and small pods, some of which were associated with fault-controlled joint-coatings that extend at least sporadically over a length of 1400 m, above and within the Karns Dolostone. The prospect was mapped and sampled by Enterprise Exploration Ltd (Murray 1953) and a sample from one of the outcrops assayed 63.32% Mn, 7.37% SiO_2, 1.57% Fe, 0.43% P and 0.51% Al_2O_3. Shannon (1971) carried out additional sampling, which confirmed the existence of material containing 41–51% Mn. Subsequent RC drilling (3 successful holes totaling 160 m) has indicated that the manganese mineralisation appears to be surficial and is limited to an average thickness of 2–4 m, in lenses up to 160 m long and averaging 10 m wide (Goulevitch 1990). Based on the limited data from these holes, an estimated, recoverable non-JORC compliant resource of 40 000 to 50 000 t grading 50% manganese was calculated. Genesis Resources Ltd, who are currently exploring the area, have reported that fourteen highly selective surface magnocrete samples ranged from 15.65% to 53.1% Mn with relatively low Fe and P.

Figure 15.53. Bench-forming massive oolitic ironstone bed exposed in Mountain Creek project area (photo courtesy of Graham Bubner, Western Desert Resources Ltd).

Phosphate

Massive to flaggy phosphate beds with grades in the range 5–24% and stromatolitic phosphorite uniformly around 29–34% occur in the basal unconformity-bound Karns Dolostone the in the Selby area. Phosphate occurrences are also known from the underlying unit. The region was explored in the 1980s by ANZECO and an Arnhem Land Mining JV who followed up radiometric anomalies associated with the phosphate. Several flaggy uraniferous phosphate beds up to 2 m thick were located. At the *Camp* prospect, a distinctive white pelloidal to massive phosphatic unit outcrops as lenses within the much more extensive flaggy units. A phosphatic breccia is present locally. Values of up to 20% phosphate are associated with significant uranium grades. The *Eastern* prospect encompasses an exposed area of white phosphatic sandstone, with virtually no soil or vegetation cover. Analysis of this material returned phosphate values generally in the range 2.3% to 14.6% P_20_5 with a maximum of 19% P_20_5. The outcropping unit covers an area of about 11 ha. The unit is lensoidal, with a length of some 800 m and a width of 150 m, and is terminated in the east by a 3 m-wide shear zone (Davies 1981). Drilling showed that economic phosphate grades did not persist in the subsurface (Cardno 1983).

Argold Holdings re-evaluated the prospects in the early 1990s. They said that the most significant phosphate (Eastern) occurs as 1–2 m-thick bands of semi-massive and disseminated apatite, overlain by sandstone and shale carrying disseminated phosphate. They assigned the phosphate-bearing sandstone to the Masterton Sandstone, which underlies the Karns Dolostone, and confirmed that other occurrences in the Karns Dolostone (Camp) were stromatolitic (Girschik 1992).

During 2007, Legend International Holdings Inc explored Selby Camp and Eastern (Legend International Holdings, Toronto Stock Exchange Announcement, 27 July 2007). Surface sampling and drilling were undertaken but the results have not yet been publicly released.

Diamonds

A number of diamondiferous deposits are known from the McArthur Basin area, including the significant Merlin and E.Mu deposits. These diamond occurrences are not part of the McArthur Basin succession *senso stricto* and they are geologically younger, but are included here for the sake of completeness and because they are geographically within the McArthur Basin area.

The Australian Diamond Exploration Joint Venture (ADEJV) commenced diamond exploration in the southern McArthur Basin in 1982 and in 1986, the Coanjula microdiamond occurrence was discovered (Lee *et al* 1994). CRA Exploration also explored in the McArthur Basin, where they discovered the E.Mu pipes in 1984 (Atkinson *et al* 1990). Stockdale Prospecting discovered the Packsaddle 1 and Blackjack kimberlite dykes (Fried 1990).

In 1989, RM Biddlecombe, who held an EL covering two unresolved diamond indicator mineral anomalies in the McArthur Basin area, entered into an exploration agreement with ADEJV to undertake an extensive exploration program. This resulted in the discovery of a significant diamondiferous kimberlite pipe, at Excalibur in 1993 (**Figure 15.54**). Subsequently, 12 kimberlite pipes and 2 sandstone breccia pipes were discovered in the area and these are collectively known as the Merlin pipes (Lee *et al* 1998). The locations of the twelve kimberlite pipes and the E.Mu pipes are given in **Figure 15.54** and their dimensions are provided in **Table 15.12**.

Lee *et al* (1998), Reddicliffe (1999) and Mendelawitz (1997) described the petrography of the kimberlites (**Figure 15.55**). At Excalibur, the dominant minerals are serpentine, iron oxides, silica, calcite/Mg calcite, phlogopite, spinel and chlorite. Fresh olivine is rarely present. Two generations of pseudomorphed olivine are present; a population of anhedral to subhedral, subangular to well rounded grains up to 15 mm in size, and a second population of smaller (less than 1 mm in size) subhedral to euhedral phenocrysts. Two generations of mica are present; earlier clear cores have been overgrown by late-stage mica which poikilitically encloses fine spinel grains, similar to those in the groundmass. Groundmass minerals include mica, spinel, apatite, serpentine and carbonate minerals. Xenoliths include carbonate, quartzic and laminated fine-grained sedimentary rocks, as well as igneous rocks such as granites and glimmerite. Mendelawitz (1997) considered the E.Mu pipes to be more altered and to contain high levels of carbonate minerals, serpentine and silica.

All Merlin pipes are diamondiferous, whereas diamonds are rare in the E.Mu pipes. Mendelawitz (1997) showed that there is no relationship between diamond grade and kimberlite mineralogy, but there is a clear relationship with the chrome spinel chemistry, which suggest that the Merlin kimberlites have come from a relatively deeper source than those at E.Mu. Diamond grades vary from trace amounts in the E.Mu pipes (see below) to 100 ct/100 t in the Ywain pipe, based on a cut-off size of >1.2 mm. There is a preponderance of diamonds in the size range >0.1–1.2 mm. The quality of commercial diamonds varies from industrial to high-value gemstones larger then 10 ct (Reddicliffe 1999).

Phlogopite from the Excalibur pipe has been dated by R-Sr method at 367 ± 4 Ma. The age of phlogopite from one of the E.Mu pipes has been determined by K-Ar methods at 360 ± 4 Ma (Atkinson *et al* 1990). These data suggest that the pipes were intruded during the Carboniferous.

Merlin pipes

The Merlin field (Reddicliffe 1999) is located about 50 km southeast of the McArthur River base metals deposit. The kimberlite pipes (**Figure 15.56**) intrude the Neoproterozoic Bukalara Sandstone, which unconformably overlies McArthur Group sedimentary rocks. On a regional scale, the pipes lie close to the intersection of the Emu and Calvert faults, at the edge of the Batten Fault Zone. On a local scale, many of the pipes are aligned along fractures that trend towards 015°. These fractures have been found to contain indicator minerals and possibly acted as conduits for the kimberlite pipes (Reddicliffe 1999). Concentric fracturing and marginal sandstone breccias have been observed around the pipes.

Following the valuation of diamonds obtained in bulk samples and a subsequent feasibility study, Ashton Mining NL commenced production from the Merlin field in January 1999. Initial mining took place from eight pits. During 2000, mining concentrated on the southern cluster of pipes, with ore coming from the Excalibur, Sacramore, Launfal and Launfal North pipes. During 2000, a study of underground mining options was undertaken, but mining did not go ahead. In December 2000, Rio Tinto acquired Ashton Mining NL, but in early 2003, they suspended mining and commenced decommissioning of the Merlin operation, due to low grade recovery. However, subsequent studies by Taylor and Glass (2008) revealed that ca 20% of Merlin diamonds do not have an X-ray fluorescence response, as is typical of most diamonds worldwide. X-ray fluorescence machines are routinely used to recover diamonds during production and the earlier grades were low because of a failure to detect the non-fluorescing diamonds. Total production during this earlier phase of mining, from 31 December 1999–June 2003, was 450 000 ct and in January 2003, reserves/resources were estimated to be 11.7 Mt averaging 0.2 ct/t. In 2004, North Australian Diamonds Ltd (NADL) acquired the Merlin leases from Rio Tinto and by 2006, the mine had produced a further 11 811 ct of diamonds. In 2010, NADL released a total JORC-compliant resource for the Merlin Field at 30 Mt averaging 24 ct/100 t for a contained 7.2 Mct of diamonds (NADL 2010). In late 2010, NADL were conducting pre-production trials and feasibility studies prior to recommencing commercial mining operations.

The largest diamond ever found in Australia, the 104.73 ct Jungiila Bunajina diamond, was recovered from the Merlin mine in 2002.

E.Mu pipes

The E.Mu pipes are much larger in size and have a clearer topographical expression than the Merlin Field pipes, which have no topographical expression and a poor magnetic response. All pipes are steep sided, generally cylindrical in shape and maintain their surface diameter to depths exceeding 100 m. Eight of the pipes are filled with bedded bioturbated sandstone or a combination of mudstone and sandstone to depths of up to 42 m (Lee *et al* 1998). Fossil evidence, based on the presence of the deep-water ammonite *Australiceras* indicates a Cretaceous age for the fill. These sedimentary rocks are devoid of kimberlite indicator minerals or diamonds, indicating that the kimberlite ejecta was eroded and removed prior to deposition of the sediments. Reddicliffe (1999) suggested that Cretaceous-

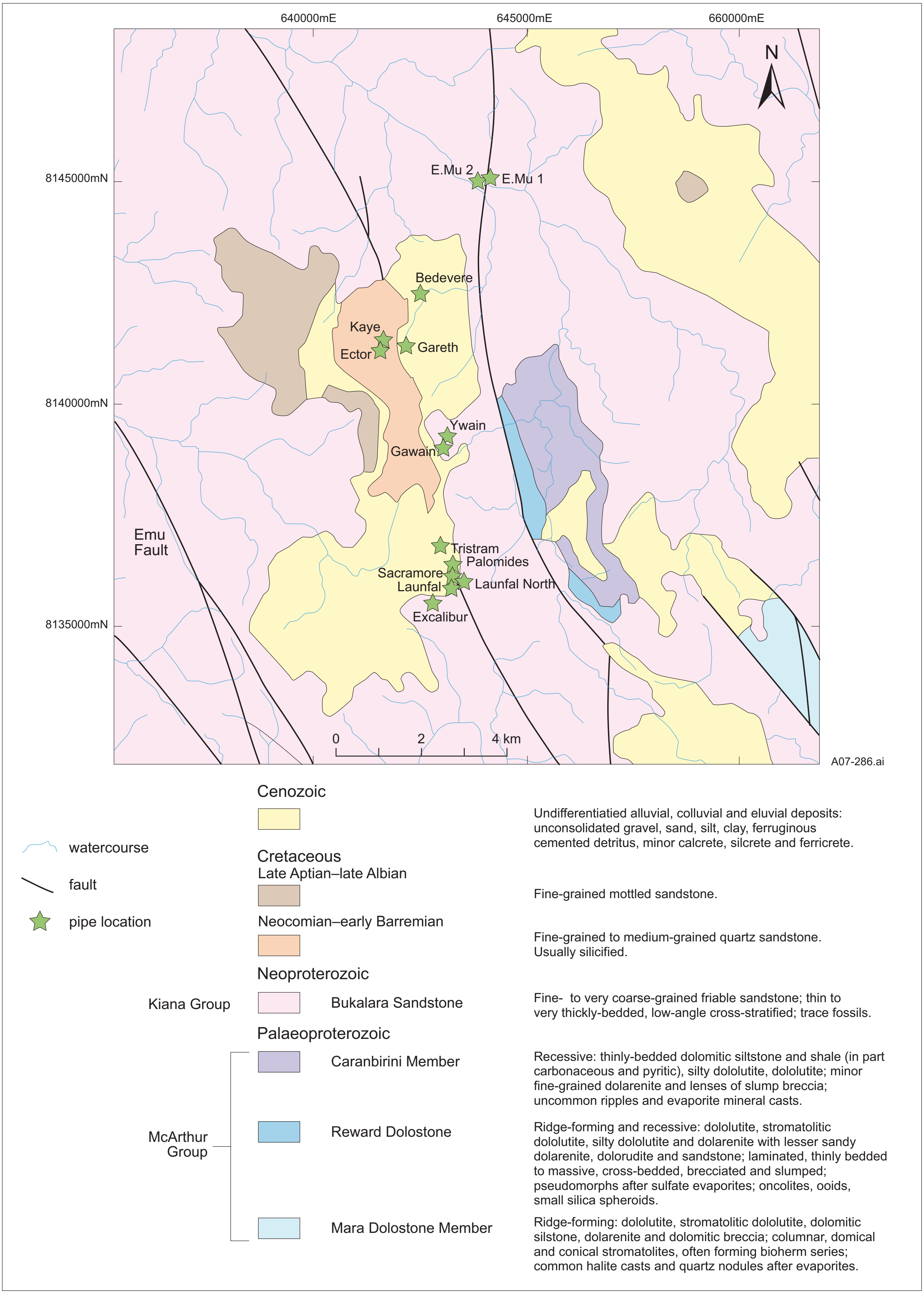


Figure 15.54. Local geology of Merlin diamond field (after Reddicliffe 1999).

Cluster	Pipe	Diametre (m)	Area (ha)	Cluster area (ha)
1	E.Mu 1	250	4.5	6.3
	E.Mu 2	100	1.8	
2	Bedevere	40	0.13	2.81
	Ector	125	1.2	
	Kay	125	1.2	
	Gareth	60	0.28	
3	Ywain	25	0.05	0.25
	Gawain	50	0.2	
4	Excalibur	60	0.28	1.37
	Launfal	50	0.2	
	Launfal North	30	0.07	
	Palomides	60	0.28	
	Sacramore	60	0.28	
	Tristram	50	0.2	
	Breccia Pipe 1	20	0.03	
	Breccia Pipe 2	20	0.03	

Table 15.12. Dimensions of Merlin and E.Mu Kimberlite pipes after Reddicliffe (1999).

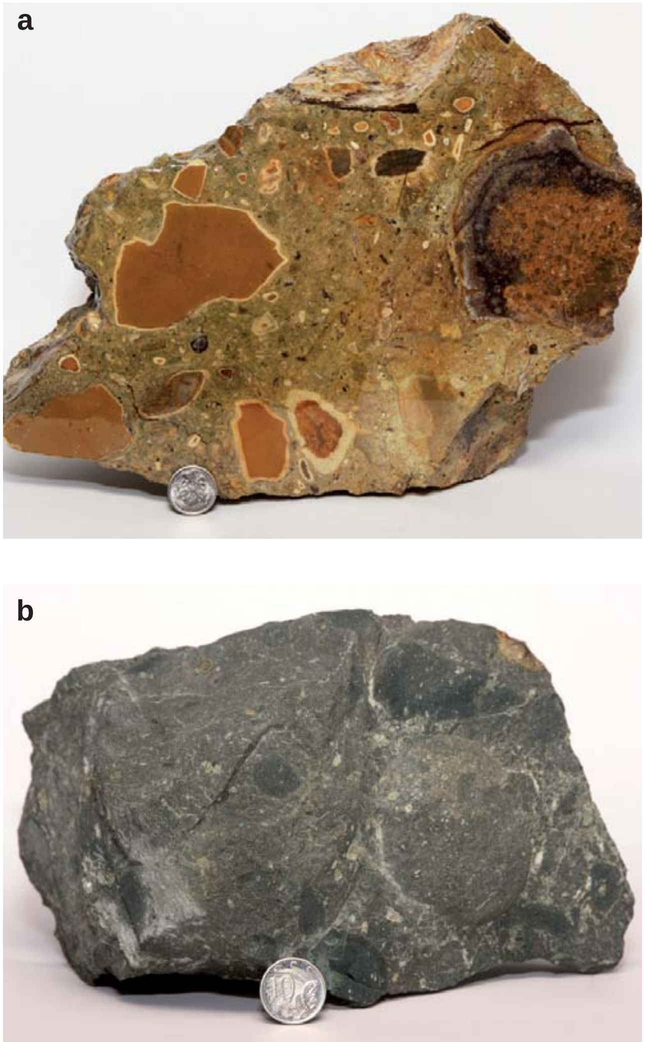


Figure 15.55. (**a**) Polished slab of weathered Merlin kimberlite, showing alteration haloes around a diverse range of rock fragments and megacrystic matrix (NTGS collection). (**b**) Unweathered olivine-rich megacrystic Merlin kimberlite, showing large spherical ?lapilli (A Wygralak collection).

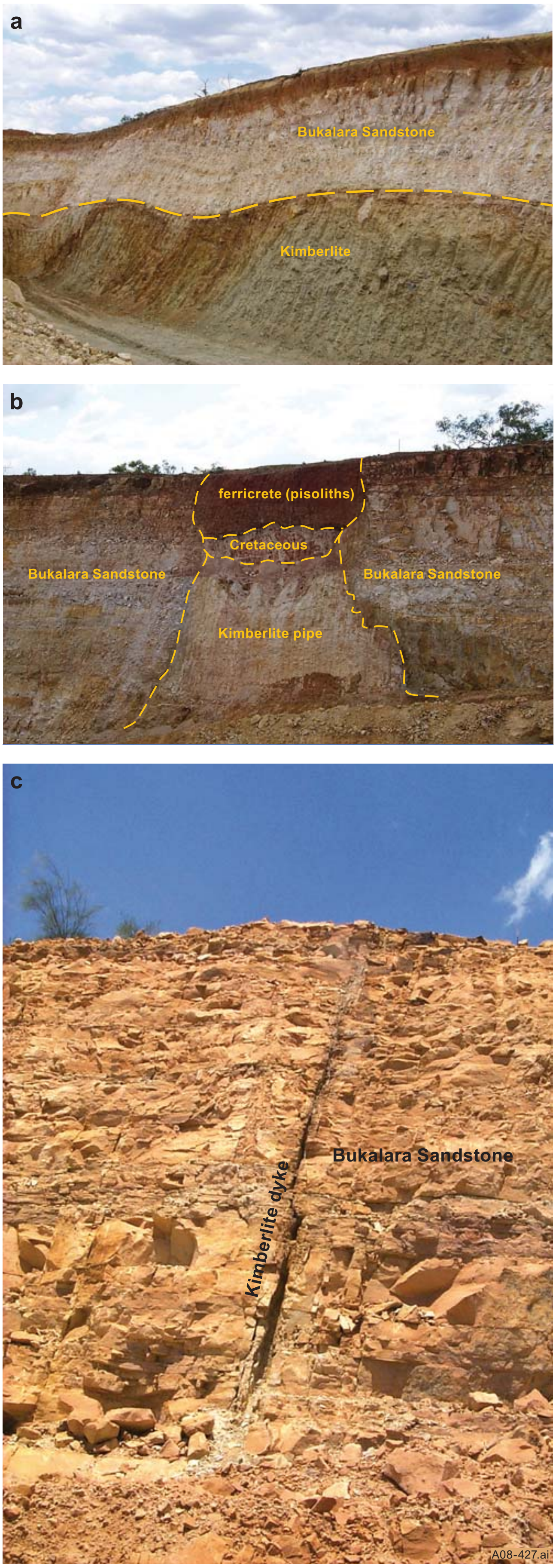


Figure 15.56. Merlin kimberlite pipes. (**a**) Bukalara Sandstone overlying Octa Kimberlite pipe. (**b**) Ywain kimberlite pipe intruding Bukalara Sandstone and cap of Cretaceous strata. (**c**) Kimberlite dyke intruding Bukalara Sandstone, Excalibur pit.

aged sedimentary rocks subsided into the pipes after the cessation of intrusive activity. This is supported by the sagged nature of the infill sediments, upturned edges with associated slickensides, and the presence of a non-kimberlitic basal conglomerate. The E.Mu pipes do not contain sandstone or mudstone, and are covered with a thin veneer of soil and sand.

The grade of the E.Mu pipes is very low. Fifty-nine tonnes of material from the E.Mu 1 pipe gave three macrodiamonds and 29 microdiamonds. The largest stone was 0.0085 ct while ten tonnes of material from the E.Mu 2 pipe yielded 33 macrodiamonds and 22 microdiamonds (Atkinson *et al* 1990, Smith *et al* 1990).

ABN021

The ABN021 pipe is in Abner Range, about 40 km southwest of the McArthur River base metals deposit (**Figure 15.28**). In January 2005, Gravity Diamonds Limited (Gravity) announced the discovery of the kimberlite pipe, after drilling an anomaly identified in a Falcon® airborne gravity gradiometry survey in an area where Ashton Mining Ltd had previously reported microdiamonds. The steeply dipping pipe is covered by lithified sediments 5–10 m thick and is weathered to at least 150 m subsurface (Gravity Diamonds Limited, ASX Announcement, 28 November 2005). It is estimated to cover an area of about 1.3 hectares and is associated with a separate satellite lobe of 0.3 hectares, both of which are diamond-bearing (**Figure 15.57**). Several macrodiamonds, the largest being 0.147 ct, and numerous microdiamonds have been recovered from drilling programs, but an economic diamond deposit is yet to be demonstrated. Almost all the ABN021 diamonds are whole, unresorbed, colourless stones with no or minimal inclusions. Bulk testing of ABN021 was carried out by Gravity in 2006, but the results remain confidential. In November 2006, Gravity were acquired by Mwana Africa PLC, an African-focused diamond explorer/producer. The area around ABN021 remains prospective for diamonds and contains a number of EM, gravity and magnetic anomalies that constitute attractive targets for diamondiferous kimberlites.

Packsaddle and Blackjack

The sub-economic Packsaddle 1 and Blackjack 1 kimberlite dykes were discovered in the Roper River district (**Figure 15.28**) in 1989 after extensive stream and loam sampling, magnetic surveys and follow-up drilling by Stockdale Prospecting (Fried 1990).

Packsaddle 1 is located about 12.5 km to the west-northwest of the abandoned Roper Valley homestead. Closely spaced (100 m) grid sampling of loam immediately west of a magnetic anomaly produced abundant kimberlitic garnet spinel and a single (0.00235 ct) diamond (Podolsky 1989). A non-outcropping, sub-vertical, north-northwest-trending kimberlite dyke was intersected in five holes during a follow-up RAB/RC drilling program. This dyke is up to 2 m wide and at least 700 m in strike length. About 117 kg of drill material was analysed and 46 diamonds weighing a total of 0.00096 ct were recovered. Petrographic analysis of highly weathered rock chips recovered from the drilling suggests that the Packsaddle 1 dyke can be classified as a phlogopite-olivine parakimberlite (Fried 1990).

Blackjack 1 is located along the western edge of a plateau, about 5.5 km to the west of the abandoned Roper Valley homestead. Numerous kimberlitic chromites and occasional kimberlitic ilmenites were recovered from stream sediment samples. The north-northwest-trending, highly weathered and ferruginised kimberlite dyke is exposed over a 1 km strike length (Fried 1990), within the gently dipping Bukalorkmi Sandstone.

Heavy minerals

The McArthur Basin has potential for heavy mineral deposits occurring within the ilmenite-bearing Derim Derim Dolerite and associated regolith soils. Extensive lateritised outcrops and regolithic soils of the dolerite occur over ca 1300 km^2 of the Roper River region in the vicinity of the Roper Highway in URAPUNGA. The dolerite is 60–70 m thick and has thick chilled margins. It was emplaced as sills at various stratigraphic intervals within the Roper Group and outcrops as low-relief, medium- to coarse-grained, variably altered and weathered rounded boulders, consisting of plagioclase (40%), clinopyroxene (40%), amphibole (7%), ilmenite and magnetite (5%) and clay (7%). Associated, mostly *in situ*, clay-rich or pisolitic regolith soils contain abundant liberated ilmenite and accessory titanomagnetite, magnetite and haematite. The soils are mineralised from the surface to a depth in excess of 2–3 m. Australian Ilmenite Resources Pty Ltd holds extensive tenements over the region for their *Sill 80 project*, and have conducted an exploration program that included the drilling of 6000 auger holes and analysis of more than 20 000 samples. This company has announced a measured resource of over 300 000 t ilmenite, with a further 4 Mt either indicated or inferred. The ilmenite is very low in deleterious minerals such as Cr_2O_3, U and Th, and is suitable for the production of both synthetic rutile and titanium sponge. Work is continuing on the southern tenements, where it is believed that further ilmenite is present in the top 1 m of soils (Ian Johnstone, Australian Ilmenite Resources Pty Ltd, pers comm, 28 October 2009, Australian Ilmenite Resources Pty Ltd website, **www.ilmenite.com.au/projects.html**, accessed October 2010).

Petroleum

The McArthur Basin has long been recognised as having potential for petroleum (eg Muir *et al* 1980) and both oil and gas are known to have flowed from petroleum wells and mineral exploration drillholes. Small oil shows are locally abundant and extensive bitumen/pyrobitumen has been reported from numerous intervals within the succession, from overlying Palaeozoic rocks, and even from breccia pipes that penetrate the succession in the Redbank area (Knutson *et al* 1979, **Figure 15.44**). Thomas (1981) described a mineral exploration drillhole (GR9) which flowed gas to such a rate that it had to be plugged with cement.

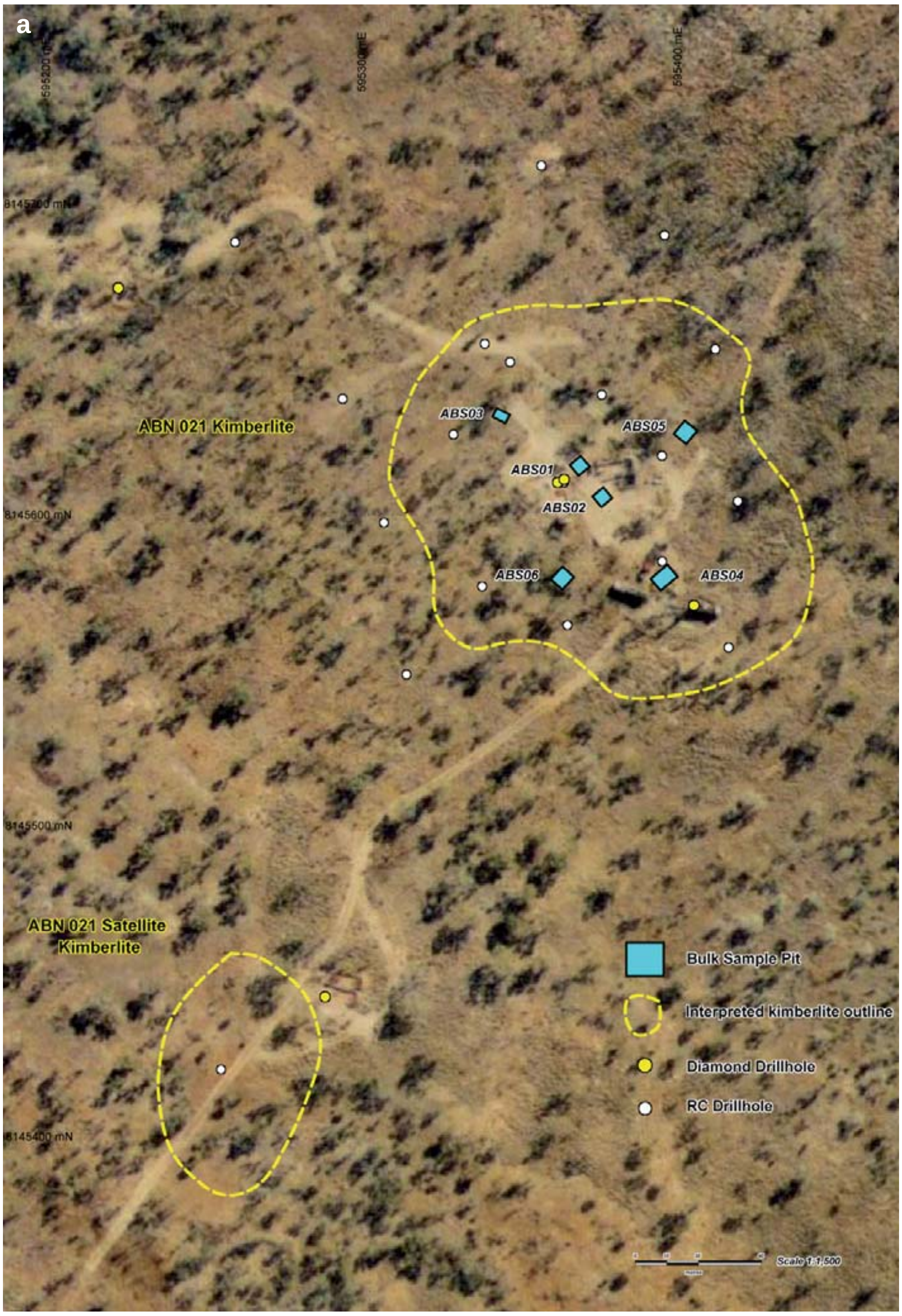


Figure 15.57. ABN021 kimberlite pipes (after Gravity Diamonds Ltd, ASX/AIM Announcement, 29 November 2006). (**a**) Aerial view showing outlines of kimberlite pipes, bulk sampling locations and drillholes. (**b**) Bulk sampling pit. (**c**) Weathered ABN021 kimberlite, showing a range of angular to sub-rounded rock fragments in soft matrix.

Despite the Proterozoic age of the succession, proven source rocks are present and large parts of the McArthur Basin are relatively undisturbed structurally and have not been subjected to significant heat/stress regimes, and hence are regarded as being prospective. The McArthur and Roper groups are recognised as having the most petroleum potential, with most interest focused on the Roper Group within the Beetaloo Sub-basin (eg Lanigan *et al* 1994, Silverman *et al* 2007).

The McArthur Basin has attracted intermittent exploration activity from a number of companies since the 1960s (Lanigan *et al* 1994), with exploration activity peaking between the 1980s and 1990s. Between 1981 and 1984, work by a major joint venture between Amoco Australia Petroleum Company and Kennecott Copper Corporation [then owned by Standard Oil of Ohio (SOHIO)] included field mapping, stratigraphic drilling and geophysical surveys. This was followed by another period of activity from the mid 1980s to the 1990s by CRA Exploration Pty Ltd and Pacific Oil and Gas that included aerial photography, field mapping, ground geophysics and a substantial drilling program. In the mid 2000s, the Beetaloo Sub-basin was subjected to an exploration program by Sweetpea Petroleum Pty Ltd, a fully owned subsidiary of PetroHunter Energy Corporation, that included seismic acquisition and stratigraphic drilling. Falcon Oil & Gas Ltd has subsequently acquired a 75% working interest in the exploration program, and are the current operator. Falcon is targeting large unconventional, as well as conventional hydrocarbon resources within the sub-basin.

Source rocks

Crick *et al* (1988) recognised five potential source rocks in the McArthur Basin, defined as having total organic carbon (TOC) greater than 0.5%. These include intervals within the Barney Creek, Lynott and Yalco formations of the McArthur Group, and the Velkerri and Kyalla formations of the Roper Group. Of these, the Barney Creek and Velkerri formations have the highest TOC values, ranging up to 8% and 12%, respectively (Crick *et al* 1988, Lanigan *et al* 1994, Falcon 2009). Maturation levels in the McArthur Group vary from marginally mature to overmature and hydrocarbon generation is considered to have occurred prior to deposition of the Roper Group (Crick *et al* 1988, Jackson *et al* 1988). Source potential is limited by the variable distribution of source rock facies, intrusions and by early hydrothermal fluid movements, which may have made source rocks overmature at an early stage of burial (Jackson *et al* 1988). Roper Group source rocks vary in maturity from below to above the oil window (Crick *et al* 1988, Summons *et al* 1988, George and Ahmed 2002), with hydrocarbon generation occurring during the late Mesoproterozoic (Dutkiewicz *et al* 2007) and possibly in the early Palaeozoic (Jackson *et al* 1988).

Within the greater McArthur Basin, the Barney Creek Formation is the oldest potential source rock. Thick sections greater than 500 m with good source rock characteristics occur within small fault-bounded sub-basins in the southern Batten Fault Zone, but away from these sub-basins, the formation is much thinner and lacks organic facies. The Caranbirini Member of the Lynott Formation contains organic-rich shale similar to that of the Barney Creek Formation, but limited data indicate that it has a generally lower TOC content (Dorrins and Womer 1983, Jackson *et al* 1988). The Yalco Formation contains thin organic shale intervals that have TOC values of up to 6%, but although there is potential to generate hydrocarbons from mature zones, thick and laterally extensive source beds are not likely to be present (Jackson *et al* 1988). Where they have been sampled in the central and northern Batten Fault Zone and in areas adjacent to major faults, all three formations and their stratigraphic equivalents are late mature to overmature (Crick *et al* 1988, Jackson *et al* 1988), thus downgrading their petroleum potential. Based on studies of oil-bearing fluid inclusions, the most likely source for oils in the Roper Group is the Velkerri Formation, with a possible component from the older Barney Creek Formation of the older McArthur Group (Dutkiewicz *et al* 2007).

In the Beetaloo Sub-basin (**Figures 15.1**, **15.23**, **15.58**), the Roper Group reaches a thickness of about 3000 m in the main depocentre, which is an approximately oval, broad gentle depression. Source-rock successions are in the oil window over large areas of the sub-basin and are probably gas mature in the main depocentre (Ambrose and Silverman 2006). The oldest source rocks (Velkerri Formation) have an age of about 1.43 Ga (Lanigan *et al* 1994) and are up to 1150 m thick. Three organic-rich mudstones in the medial part of the formation are tens of metres thick and can be correlated over much of the drilled area of the basin. These source rock intervals have TOC values between 1 and 3%, with maximum recorded values of 8–12% (Jackson and Raiswell 1991, Warren *et al* 1998, Falcon 2009). A second major source-rock interval is represented by the stratigraphically higher Kyalla Formation. This unit reaches a maximum thickness of about 730 m and is believed to be restricted to the heart of the Beetaloo Sub-basin. TOCs are generally less than 2%, but range up to about 9% (Jackson *et al* 1988). Oil and gas shows are common within both the Velkerri and Kyalla formations, with numerous reports of strong odours, and gas and oil 'bleeds' (Silverman *et al* 2007).

Reservoirs

In the greater McArthur Basin, fair to good conventional reservoirs occur in the McArthur and Nathan groups, including both vuggy carbonate and porous clastic rocks (Jackson *et al* 1988). Dorrins and Womer (1983) considered the best potential reservoirs to include carbonate rocks of the Teena Dolostone exhibiting secondary vuggy porosity, and coarse breccia intervals within the Barney Creek Formation that have locally high primary and secondary porosity. In drillhole GR9 in the southern Batten Fault Zone, Thomas (1981) reported over 400 m of 'dolomitic bituminous Barney Creek Formation', including a 10 m interval of 'bedded and partly brecciated, porous bituminous dolomite'. The underlying Coxco Dolostone Member was described as being 'very porous and fractured, often containing bitumen clots in open fractures'. This hole flowed gas. Other potential reservoirs in the greater McArthur Basin include the Stretton Sandstone, which has locally good primary intergranular porosity, the Yalco and Looking Glass formations, which are characterised by intervals of dolostone with secondary vuggy porosity (Jackson *et al* 1988) and possibly the Wollogorang Formation from the underlying Tawallah Group, the lower part of which commonly contains bitumen nodules in fine-grained carbonate rocks (Jackson *et al* 1987, **Figure 15.14**). The distribution of all these potential reservoir rocks is highly variable and complex, increasing the difficulties and risks of exploration. Dorrins and Womer (1983) considered that unbreached oil-saturated reservoirs may have inhibited the formation of late-stage dolomite in pore spaces, thus preserving enhanced reservoir conditions.

At least seven good potential reservoir units have been identified in the Beetaloo Sub-basin (Falcon 2009). These occur within the succession from the Bessie Creek Sandstone to the Bukalara Sandstone (**Figure 15.58**). A ca 1280 Ma dolerite sill, which separates the Bessie Creek Sandstone and the Velkerri Formation in some drillholes, locally contains abundant inclusions of migrated oil (Dutkiewicz *et al* 2004) and may be another possible reservoir. The principle potential sandstone reservoirs are the Bessie Creek, Moroak, 'Jamison' and Bukalara sandstones, and thin sandstone intervals within the Velkerri Formation, Kyalla Formation and 'Hayfield mudstone' also have some reservoir potential where cumulative

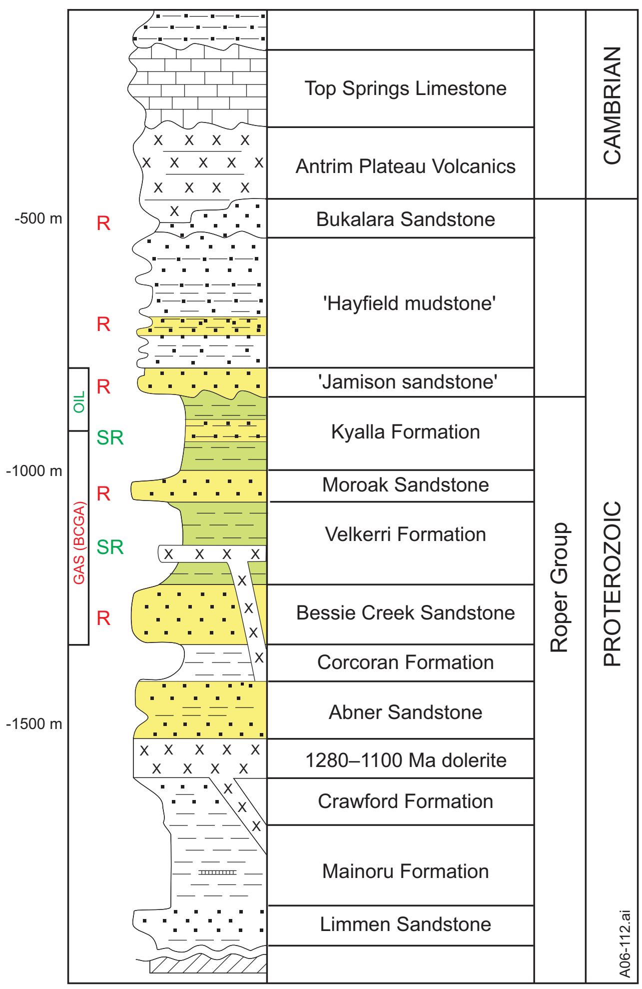


Figure 15.58. Stratigraphic column showing Roper Group and overlying Neoproterozoic to Cambrian units. R = conventional reservoir; SR = source rock and unconventional reservoir; BCGA = basin-centred gas accumulation (after Silverman *et al* 2007, Falcon 2009).

thicknesses are significant. The sandstone units are all quartz rich and texturally mature, and have grainsizes that vary considerably over short intervals. They would originally have had good to excellent conventional reservoir properties, but diagenesis, compaction and pressure solution have reduced primary porosities and secondary porosity is relatively minor (Lanigan *et al* 1994). Under conditions of low permeability, there is also significant potential for unconventional reservoirs, such as tight-gas sandstones, heavy oil, gas shale and other types of basin-centred gas accumulations. Intervals with significant potential for unconventional hydrocarbon reservoirs (Falcon 2009) include the Bessie Creek Sandstone, Velkerri Formation shale, Moroak Sandstone and lower Kyalla Formation shale (all for basin-centred gas), and the upper Kyalla Formation shale (unconventional oil).

The Bessie Creek Sandstone forms a viable reservoir target immediately below the Velkerri Formation, which might have acted as both source rock and seal. This sandstone is over 400 m thick and exhibits variable porosity, ranging from poor to good. The presence of pore-filling bitumen in some intervals in drillholes in the greater McArthur Basin indicates that the sandstone retained good porosity, prior to and during the generation and migration of hydrocarbons, and that it received a good hydrocarbon charge (Silverman *et al* 2007). However, the unit is probably at depths of up to 3000 m over much of the Beetaloo Sub-basin, thereby reducing its attractiveness as a target, except where it reaches shallower depths near the sub-basin's margins. The Moroak Sandstone occurs between two significant source units, the Velkerri Formation (below) and the Kyalla Formation (above); the latter unit also has potential to act as a regional seal. This sandstone is up to 300 m thick and occurs at average depths of 1500–1700 m across most of the sub-basin, but is truncated or absent towards the sub-basin's margins. The Moroak Sandstone also occurs in wells to the north in the greater McArthur Basin, where oil shows have been reported, demonstrating that it has received a hydrocarbon charge (Silverman *et al* 2007). The 'Jamison sandstone' is unconformable on Kyalla Formation source rocks and is conformably succeeded by the 'Hayfield mudstone', which has potential as a regional seal. It is between 75 and 160 m thick in the Beetaloo Sub-basin and mostly occurs at depths of 500–900 m, but is within 200 m of the surface near the sub-basin's margins (Lanigan *et al* 1994, Falcon 2009). In Jamison-1, DSTs recovered gas-cut water and small flows of gas and oil (Silverman *et al* 2007), demonstrating that this interval constitutes an economic target.

Migration and thermal maturity

Burial history and diagenetic studies (eg Powell *et al* 1987) are suggestive of the early generation and migration of hydrocarbons in the McArthur Basin. Crick *et al* (1988) presented geochemical and petrological evidence that early migration occurred within the Barney Creek Formation prior to deposition of the Roper Group. Detailed work on solid bitumen and oil inclusions in the Roper Group, as summarised in Dutkiewicz *et al* (2007), indicate that there was extensive oil migration during the late Mesoproterozoic. Textural relationships, microthermometry and geochemical data suggest that the group experienced multiple episodes of oil and brine migration, involving hydrocarbons of different molecular compositions. The earliest of these took place during burial, when diagenetic quartz cement was just starting to form. Oil migration during a later stage of burial is indicated by solid bitumen occurring within secondary porosity and as coatings on minerals. Fracture bitumen in a vein within a 1280 Ma dolerite sill shows that oil also migrated during cooling of the sill (George *et al* 1994). The most significant oil migration episode during the Proterozoic is interpreted to have probably occurred following extensive compaction, cementation, and contact metamorphism associated with the dolerite intrusion and vein infilling of the dolerite, probably before significant uplift, during structural inversion between 1300–1000 Ma (Dutkiewicz *et al* 2007).

There is also some evidence of later hydrocarbon migration while the Roper Group was buried beneath Palaeozoic cover (see Jackson *et al* 1988, RobSearch 1992, Ambrose and Silverman 2006). Wade (1924) reported the occurrence of 'bitumen glance in (presumably Cambrian) basalt overlying sandstone' in the McArthur Basin area, and primary bitumen has recently been discovered in an interval of sedimentary rocks within the Cambrian Antrim Plateau Volcanics (Kalkarindji Province) in the Sturt Plateau area to the southwest of Mataranka (Matthews 2008). The most likely source for this bitumen is underlying strata of the Roper Group.

Maturation levels in McArthur Group sedimentary rocks were studied by Crick *et al* (1988), who reported that they vary from marginally mature to overmature, with abrupt changes over short distances associated with faults. In the central and northern Batten Fault Zone, there is evidence that elevated heat flow was associated with major faults and adjacent sub-basins; some of this has been associated with base metals mineralisation (see above). In these areas, the Barney Creek Formation is late mature to overmature for oil generation, but away from major faults, maturity levels tend to be lower, in the mature zone. In the southern Batten Fault Zone, in the Glyde region, the Barney Creek Formation is marginally mature to mature for oil generation.

Jackson *et al* (1988) determined that the younger Roper Group was probably buried to a maximum depth of 2.5 km, shortly after deposition, and that the maximum burial temperature experienced by the Velkerri Formation was about 75ºC. However, higher burial temperatures of at least 80ºC were indicated by George and Ahmed (2002) and even higher palaeotemperatures of >105ºC were suggested by Duddy *et al* (2004), before Mesozoic cooling commenced. This suggests that either thermal maturity varies considerably laterally within the basin and/or maximum burial temperatures have previously been underestimated and that the Velkerri Formation has reached the oil window and above. Ambrose and Silverman (2006) reported that source rocks are in the oil window over large areas of the sub-basin, but are probably gas-mature in the main depocentre of the Beetaloo Sub-basin and noted that the centre of the basin has probably passed through the gas window.

Prospectivity

The main caveat for successful exploration in the greater McArthur Basin and Beetaloo Sub-basin is the preservation of hydrocarbons over hundreds of millions of years. Any economic accumulations of Proterozoic petroleum would have been derived from some of the oldest-known viable source rocks. Although generally uncommon, there are a number of areas of the world that contain economic Proterozoic hydrocarbons, including Oman, the Siberian Platform in Russia and the Sichuan Basin in China (see Walter 1992, Schopf and Klein 1992). Oil and gas generation appears to have occurred in these basins at multiple times in the late Proterozoic and Phanerozoic, and hydrocarbons are hosted in reservoirs at various stratigraphic levels ranging from the Neoproterozoic to Mesozoic. Sub-economic gas has also been discovered in Neoproterozoic sandstone in the Amadeus Basin in central Australia (Dingo Field). However, all of these accumulations were derived from younger Neoproterozoic-aged successions, rather than from Palaeo- to Mesoproterozoic rocks, as in the McArthur Basin.

In the case of the McArthur Basin, a late oil charge (or remigration) is more likely to survive, particularly with regards to seal integrity, destruction of petroleum in pore spaces by biodegradation, and/or water-washing and fault reactivation (see Duddy *et al* 2004). Although a major episode of migration probably occurred in the Late Mesoproterozoic (Dutkiewicz *et al* 2007), the occurrence of bitumen within the overlying Cambrian Antrim Plateau Volcanics (see above) indicates that hydrocarbons have been actively generated and expelled or remigrated, probably from Roper Group source rocks, at relatively young Palaeozoic or possibly even younger ages. Palaeozoic oil/gas pools in the younger Daly and Georgina basins to the west and southwest of the McArthur Basin might have a reasonably good chance of survival, although the successions in these basins are relatively thin and unstructured, reducing their petroleum potential.

Powell *et al* (1987) and Jackson *et al* (1988) listed four types of possible conventional traps that may be applicable to the Beetaloo Sub-basin and greater McArthur Basin. These included:

(1) structural and diagenetic traps in the Bessie Creek Sandstone within the Beetaloo Sub-basin, mainly sourced from the Velkerri Formation.
(2) small structural traps, diagenetic traps and pinchouts relating to lapping of facies onto the 'Urapunga Tectonic Ridge' in the Roper River region. However, reinterpretation of the former 'Urapunga Tectonic Ridge' as a major fault zone (see **Introduction** above) negates these previous pinch-out models.
(3) small structural and diagenetic traps in McArthur Group carbonate rocks in the Batten Fault Zone, sourced from the Barney Creek Formation.
(4) various types of traps in Palaeozoic strata to the south and west of the McArthur Basin, formed under conditions of late migration or remigration.

In addition, there is some possibility that suitable reservoir/seal pairs within McArthur Basin strata may occur offshore under Cretaceous strata of the western Carpentaria

Basin and these could be prospective for hydrocarbons, like their onshore equivalents.

In the above scenarios, diagenetic traps (Wilson 1977) refer to the early migration of hydrocarbons into a reservoir before significant cementation has taken place; the accumulation then inhibits further cementation. The possibility of this type of trap could indicate that current permeability/porosity data may not be an accurate refection of the true characteristics of unbreached reservoirs (Jackson *et al* 1988).

As potential reservoirs in the Beetaloo Sub-basin often have relatively low permeability, current petroleum exploration is focused on unconventional (basin-centred gas and oil shale; see above), as well as on conventional hydrocarbons.

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