



# Geology and mineral resources of the Northern Territory

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## Chapter 40: Money Shoal Basin

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# Chapter 40: MONEY SHOAL BASIN

M Ahmad and TJ Munson

## INTRODUCTION

The mostly offshore Jurassic to Cenozoic Money Shoal Basin extends northward from the onshore Northern Territory into Indonesian waters (**Figure 40.1**) and covers an area of about 230 000 km<sup>2</sup>. It is a tilted passive margin basin with no specific depocentre, and contains formations that are generally monoclinally and relatively undeformed. The Money Shoal Basin sedimentary succession unconformably overlies the Neoproterozoic to Permian Arafura Basin and Proterozoic rocks of the Pine Creek Orogen and McArthur Basin. It is up to 4500 m thick in the northwest of the basin, but thins rapidly eastward to less than 500 m (**Figure 40.2**). The base of the succession ranges in age from Middle Jurassic in the west to Late Cretaceous in the east. It therefore forms a time-transgressive sediment wedge that onlaps the Arafura Basin from the west. Sediments were mostly deposited in marine environments, but there were occasional deltaic and fluvial incursions.

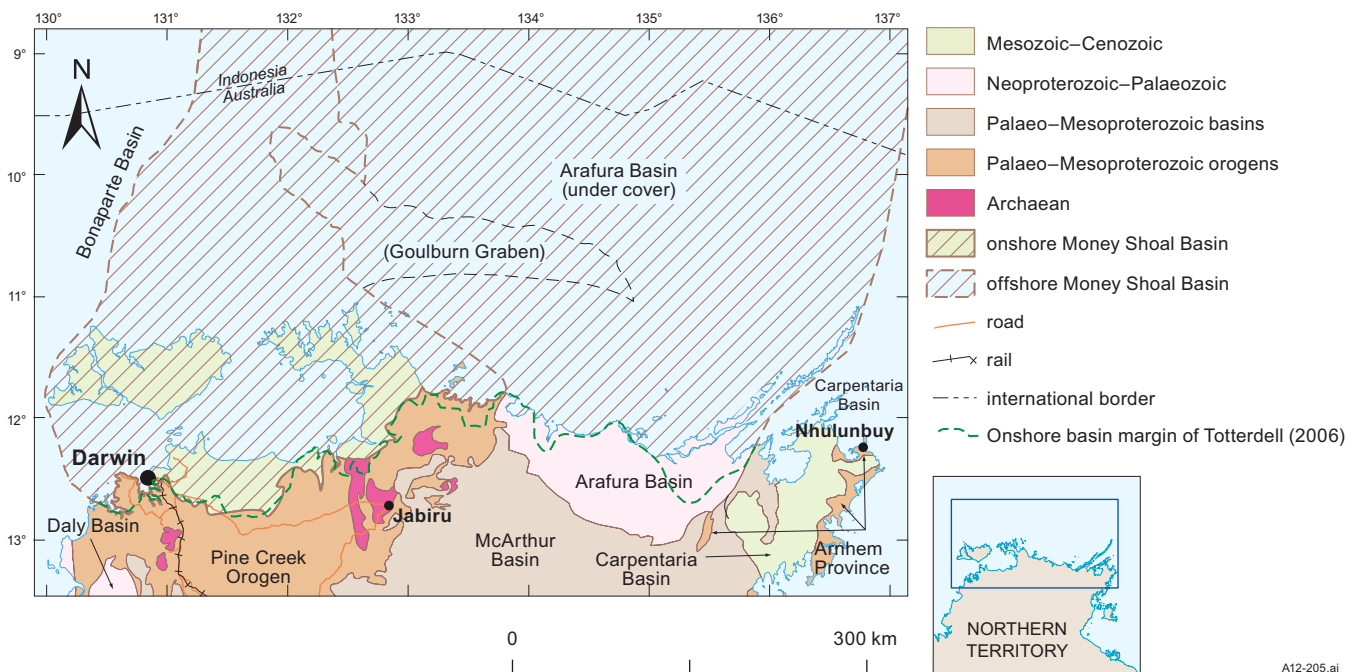
The Money Shoal Basin is bounded to the west by the Lynedoch Bank Fault System, which separates it from the Calder and Malita grabens of the Bonaparte Basin. To the east, the basin is bounded by a Mesozoic hinge (the ill-defined Wessel Rise), which separates it from the contiguous offshore Carpentaria Basin. The southern basin boundary to the south of Darwin is erosional, but at the time of maximum transgression (Aptian to early Albian), when much of northern Australia was inundated under a shallow sea (see Frakes *et al* 1987), the Money Shoal Basin was probably continuous with the onshore Carpentaria Basin, and small scattered erosional outliers of Money Shoal Basin rocks occur over Pine Creek Orogen basement

to the south of the main outcrop tract at least as far as southern DARWIN. Southeast of Darwin, outcrop tracts of the Money Shoal and Carpentaria basins are separated by Proterozoic rocks of the informally named Kombolgie palaeohigh (see **Carpentaria Basin**). Little is known about the northern portion of the basin, which extends beyond the Australia–Indonesia seabed boundary.

The offshore succession of the Money Shoal Basin is relatively well known from petroleum wells in the Goulburn Graben and is correlated with that of the Bonaparte Basin to the west. However, the Money Shoal Basin succession is thinner and less complete than that of the Bonaparte Basin, because it represents the proximal onlap edge of the Mesozoic to Cenozoic succession (Struckmeyer 2006b). It has been divided into four packages; in ascending stratigraphic order, these are the Early–Middle Jurassic Troughton Group equivalent, which is represented by only its youngest unit, the Plover Formation equivalent; the Late Jurassic–Early Cretaceous Flamingo Group equivalent; the late Early–Late Cretaceous Bathurst Island Group; and the Cenozoic Woodbine Group equivalent (Struckmeyer 2006b, **Figure 40.3**). Offshore units are only briefly described below, as a full description of the offshore succession is beyond the scope of this volume.

Onshore exposures of the Money Shoal Basin are scattered across the northern NT and offshore islands from BATHURST ISLAND<sup>1</sup> to westernmost JUNCTION BAY and extend southward into northern ALLIGATOR RIVER and southern DARWIN (**Figure 40.4**). Three discrete successions, separated

<sup>1</sup> Names of 1:250 000 mapsheets are in large capital letters, eg DARWIN.

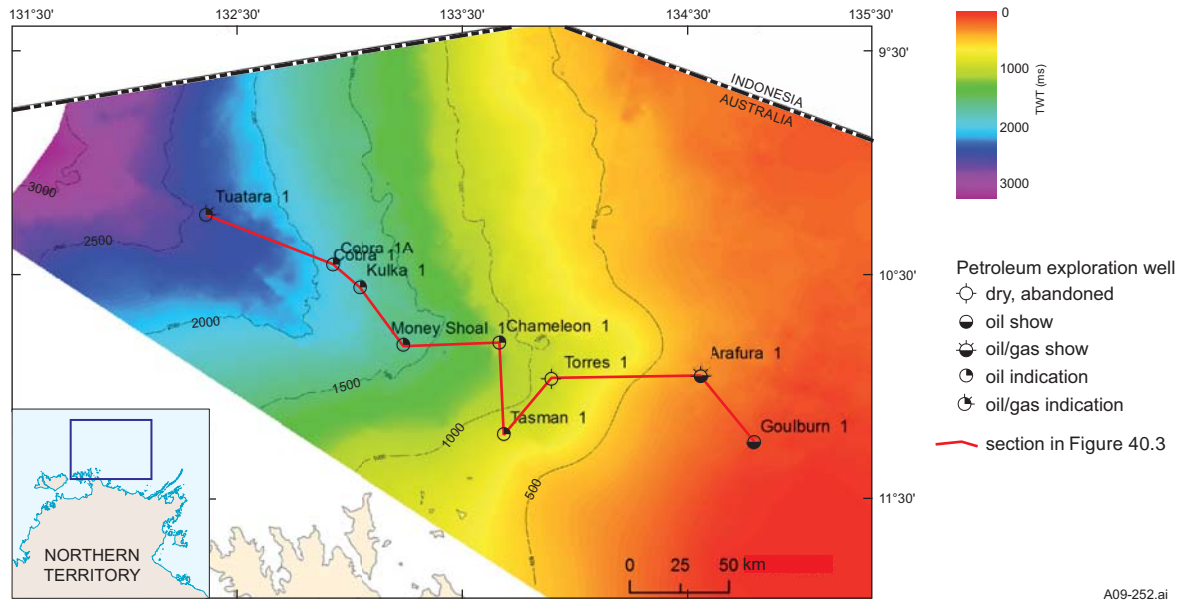


**Figure 40.1.** Regional geological setting of Money Shoal Basin. NT geological regions slightly modified from NTGS 1:2.5M geological regions GIS dataset. Southern margin of basin in geological regions map reflects areas dominated by outcrop of Money Shoal Basin (north) and Pine Creek Orogen (south); small outliers of Money Shoal Basin rocks occur south of this boundary. Arbitrary position of erosional southern margin of basin as interpreted by Totterdell (2006, figure 4) shown by dashed green line. Offshore margins of basin after Petroconsultants (1989) and Totterdell (2006).

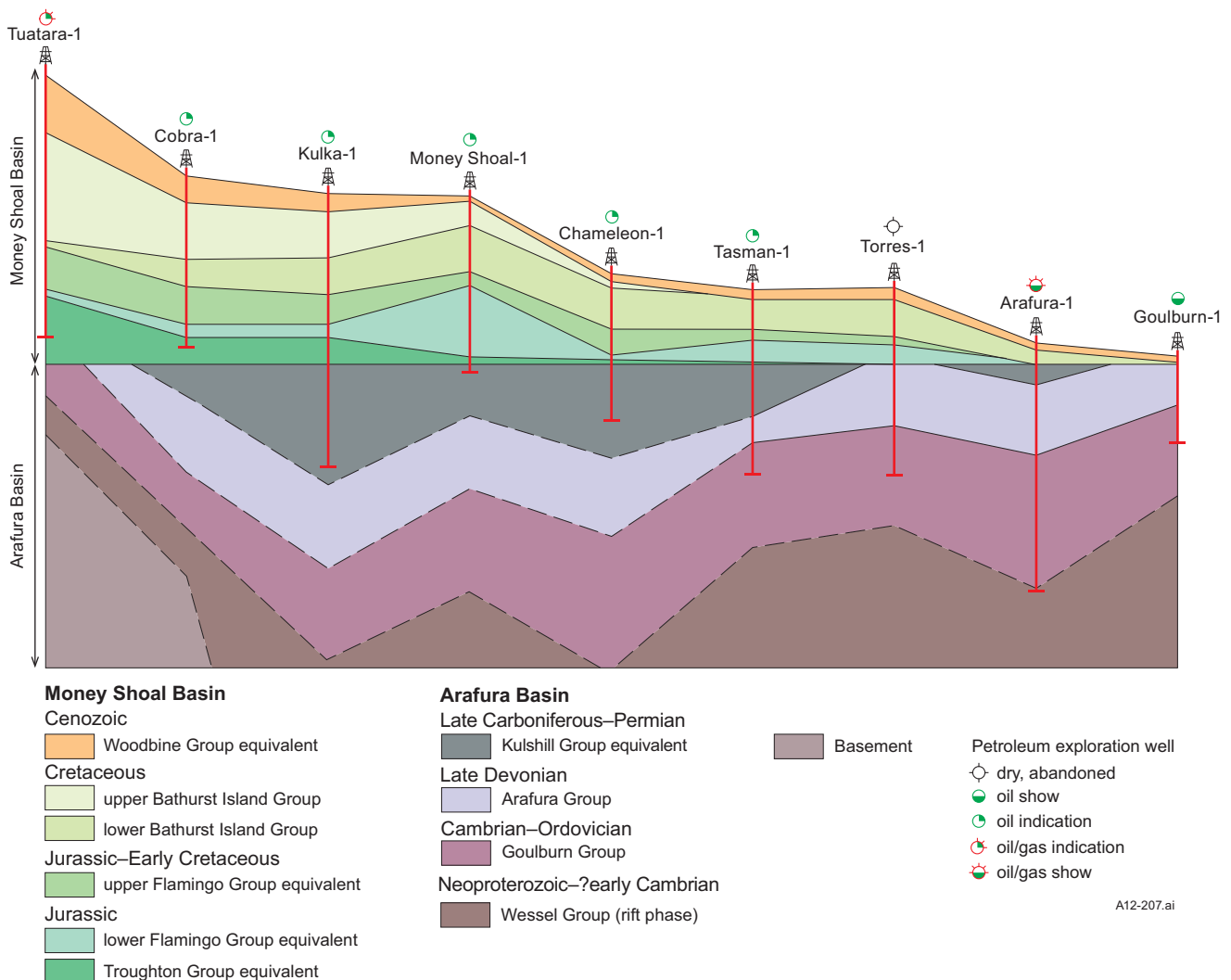
## Money Shoal Basin

by unconformities are represented; in ascending stratigraphic order, these are the Plover Formation equivalent (?Troughton Group equivalent); the Bathurst Island Group, represented by the Darwin, Marligur and Wangarlu formations, and

Moonkinu Sandstone; and the ungrouped Eocene Van Diemen Sandstone (Hughes 1978, Petroconsultants 1989). Flamingo Group equivalent and Woodbine Group equivalent rocks, as presently defined, have not been recognized in onshore areas.



**Figure 40.2.** Northern and eastern portions of offshore Money Shoal Basin in Australian waters, showing total sediment thickness (milliseconds two-way time) and location of drillholes (after Totterdell 2006: figure 25).



**Figure 40.3.** Stratigraphic drillhole correlation flattened on Triassic unconformity (modified from Earl 2006, Struckmeyer 2006b, figure 30). Location of section shown in Figure 40.2.

A summary of the stratigraphic succession of the Money Shoal Basin is in **Table 40.1**.

Significant studies of the Money Shoal Basin and in particular, the onshore succession, include Noakes (1949), Hughes and Senior (1974), Senior and Smart (1976), Hughes (1978), Pietsch and Stuart-Smith (1987), Mory (1988, 1991), Petroconsultants (1989), McLennan *et al* (1990), Henderson (1990, 1998), Doyle (2001), Ferenczi (2001), Stilwell and Henderson (2002), papers in Struckmeyer (2006a) and Geoscience Australia (2007, 2012).

**LATE EARLY–LATE MIDDLE JURASSIC**

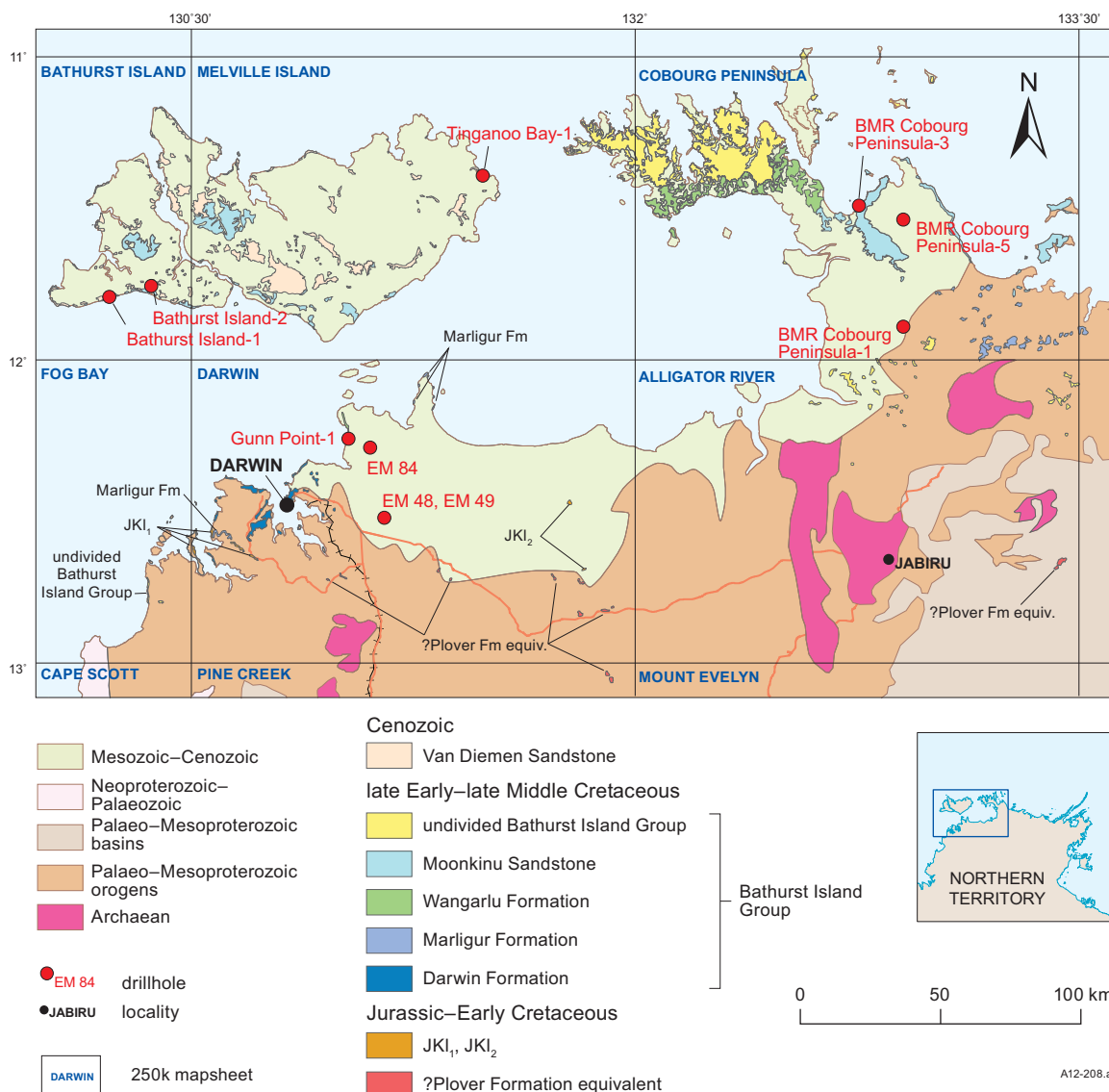
**Troughton Group equivalent**

The Middle Triassic to Middle Jurassic Troughton Group (Gunn 1988) was defined in the Bonaparte Basin, where it comprises, in ascending stratigraphic order, the Cape Londonderry, Malita and Plover formations. An equivalent of the Plover Formation extends into the offshore Money Shoal Basin to the east, where it unconformably overlies Palaeozoic rocks of the Arafura Basin and is unconformably overlain by Middle Jurassic to Early Cretaceous Flamingo Group

equivalent strata. Equivalents of the underlying formations of the Troughton Group are absent in this basin. Rocks that are tentatively assigned to the Plover Formation are also exposed in onshore areas of the Money Shoal Basin in central and southern DARWIN in the northern NT, although it is possible that these may instead be part of the younger Flamingo Group equivalent. These exposures are unconformable on Proterozoic rocks of the Pine Creek Orogen and are unconformably overlain by Cretaceous Bathurst Island Group rocks.

**Plover Fm equivalent**

A unit equivalent to the Plover Formation (Gunn 1988) of the Bonaparte Basin has been intersected in drillholes in offshore areas of the western Money Shoal Basin (**Figure 40.3**) and is also possibly present in onshore areas in central and southern DARWIN, where it forms small scattered outliers on Proterozoic rocks of the Pine Creek Orogen (**Figure 40.4**). Onshore exposures have been previously described as ‘Petrel Formation’ (eg Pietsch and Stuart-Smith 1987, Doyle 2001, Ferenczi and Sweet 2005), but this name was abandoned by Mory (1991), as the former ‘Petrel Formation’ incorporated successions on either side of the regional late Middle Jurassic (Callovian) unconformity;



**Figure 40.4.** Simplified geology of onshore Money Shoal Basin, derived from GA 1:1M geology and NTGS 1:2.5M geological regions GIS datasets.

## Money Shoal Basin

Unit, thickness, (distribution)	Lithology	Depositional environment	Stratigraphic relationships
<b>Miocene–Recent</b>			
<b>WOODBINE GROUP EQUIVALENT</b>			
<b>undivided Woodbine Group equivalent</b> <1300 m (offshore)	Lower unit of coarse quartzite sandstone with claystone interbeds, minor coal and dolostone; upper unit of calcareous claystone and marl with calcarenite interbeds (drillhole Cobra-1A).	Shallow marine to deltaic. Alternating fluvial and shallow marine at top.	Unconformable on Bathurst Island Group and ?Van Diemen Sandstone.
<b>Eocene</b>			
<b>UNGROUPED</b>			
<b>Van Diemen Sandstone</b> <60 m (offshore and onshore)	Cross-bedded, medium- to coarse-grained quartz sandstone, minor lenses of siltstone and granular conglomerate.	Fluvial.	Unconformable on Bathurst Island Group.
<b>Late Early–Late Cretaceous</b>			
<b>BATHURST ISLAND GROUP</b>			
<b>undivided Bathurst Island Group</b> <2000m (offshore and onshore)	Mostly fine-grained rocks including claystone, marl and siltstone with locally thick interbeds of mostly fine-grained sandstone.	Deltaic to open marine environments, deepening to west.	Unconformable on Flamingo Group equivalent, or Proterozoic rocks of Pine Creek Orogen (in south).
<b>Moonkinu Sandstone</b> ca 400 m (offshore and onshore)	Cross-bedded, fine-grained glauconitic sandstone and quartz sandstone, interbedded with lesser siltstone and mudstone.	High-energy shallow marine.	Conformable on Wangarlu Formation in Money Shoal Basin. Lateral equivalent of middle part of Wangarlu Formation equivalent in Bonaparte Basin.
<b>Wangarlu Formation</b> 287 m (offshore and onshore)	Micaceous mudstone, claystone; variable amounts of glauconitic siltstone, sandstone, marl and limestone.	Shallow marine	Conformable on Darwin Formation.
<b>Marligur Formation</b> 62 m (onshore)	Medium- to coarse-grained, poorly consolidated quartz sandstone, clayey sandstone and sandy claystone.	Marginal marine, paralic.	Unconformable on Proterozoic rocks of Pine Creek Orogen. Equivalent of Darwin Formation.
<b>Darwin Formation</b> <63 m (offshore and onshore)	Claystone and minor silty claystone, sandy claystone, phosphatic nodular claystone, radiolarian siltstone, partially lithified clayey sandstone, clean sandstone and glauconitic sandstone; locally developed basal conglomerate.	Shallow marine, neritic.	Unconformable on Proterozoic rocks of Pine Creek Orogen. Equivalent of Marligur Formation.
<i>Howard Sand member</i> 26 m (onshore)	Deconsolidated, clean to clayey quartz sandstone.	Shallow marine, neritic.	Unconformable on Proterozoic rocks of Pine Creek Orogen.
<b>Late Middle Jurassic–Early Cretaceous</b>			
<b>FLAMINGO GROUP EQUIVALENT</b>			
<b>Undivided Flamingo Group equivalent</b> 1230 m (offshore)	Fine-grained, partly glauconitic quartz sandstone with interbedded mudstone and minor coal.	Fluvial, deltaic and shallow marine, deepening to west.	Unconformable on Plover Formation equivalent. Unconformity divides group into lower and upper successions.
<b>Jurassic–Early Cretaceous</b>			
<b>GROUP UNCERTAIN</b>			
<b>Undivided (JKI<sub>1</sub>)</b> <10 m (onshore)	Conglomerate, conglomeratic sandstone, sandstone and sandy claystone.	Fluvial to paralic.	Unconformable on Proterozoic rocks of Pine Creek Orogen.
<b>Undivided (JKI<sub>2</sub>)</b> <57 m (onshore)	Unconsolidated quartz-rich sand, clayey in part.	Fluvial to paralic.	Unconformable on ?Plover Formation equivalent.
<b>?Plover Formation equivalent</b> <5 m (onshore)	Friable, poorly sorted, commonly limonitic sandstone and minor conglomerate.	Fluvial to shallow marine.	Unconformable on Proterozoic rocks of Pine Creek Orogen.
<b>Late Early–late Middle Jurassic</b>			
<b>TROUGHTON GROUP EQUIVALENT</b>			
<b>Plover Formation equivalent</b> <564 m (offshore)	Fine- to coarse-grained sandstone interbedded with siltstone and claystone, and minor coal.	Fluvial braided river systems; ?marine in upper part, deepening to west.	Unconformable on Palaeozoic rocks of Arafura Basin.

**Table 40.1.** Summary of Mesozoic–Cenozoic stratigraphic succession of the Money Shoal Basin.

the lower interval, which underlies the unconformity, was referred to the Plover Formation, whereas the overlying interval was placed within the Flamingo Group.

In the western Goulburn Graben, the offshore Plover Formation equivalent is up to 564 m thick, but the unit thins rapidly to the north and east and is absent in drillholes of the eastern Goulburn Graben (Struckmeyer 2006b). The formation comprises fine- to coarse-grained sandstone, interbedded with siltstone and claystone, and minor coal. These were deposited in an overall fluvial depositional environment (Struckmeyer 2006b). Barber *et al* (2004) suggested that the depositional setting was a series of braided river systems that fed into a wide, northeast–southwest-trending marine shelf, with the Goulburn Graben being the focus of one of these rivers. Lowe-Young *et al* (2004) interpreted an increasing marine influence in the upper Plover Formation in the Evans Shoal area, which is just to the west of the Money Shoal Basin in the northeastern Bonaparte Basin. The base of the offshore Plover Formation equivalent is dated as late Early Jurassic (Pliensbachian) in age, whereas the age of the top of the unit is constrained by the regional Callovian unconformity.

All onshore fluvial and marine rocks of Mesozoic age in the Katherine–Darwin region were originally included within the former ‘Mullaman Beds’ (Skwarko 1966, equivalent to ‘Mullaman Group’ of Noakes 1949). This term was abandoned by Hughes (1978), who divided the Mesozoic succession into a lower unit equivalent to the former ‘Petrel Formation’ and an upper unit, the Darwin Formation of the Bathurst Island Group. This nomenclature was followed by Pietsch and Stuart-Smith (1987) during mapping of the Second Edition DARWIN mapsheet. Onshore exposures of the former ‘Petrel Formation’ consist of friable, poorly sorted, commonly limonitic sandstone and minor conglomerate. In the Berry Springs–Rum Jungle area (central-western DARWIN), these rocks form numerous small isolated outcrops less than 4 m in thickness. Further to the east, in central and southern DARWIN, exposures consist of rubble at the edges of floodplains and remnant mesa-like caps, at least 3 m thick, over Pine Creek Orogen metasedimentary rocks. No fossils have been found in these rocks and Pietsch and Stuart-Smith (1987) tentatively assigned an age of Late Jurassic to Neocomian<sup>2</sup> to them. However, the age of these rocks could range from Early Jurassic to Early Cretaceous and without a more precise age control, they could be representatives of either the Plover Formation equivalent or the overlying Flamingo Group equivalent, as these units contain broadly similar rock types that were deposited in similar environments.

Pietsch and Stuart-Smith (1987) also mapped two unnamed units (JKI<sub>1</sub> and JKI<sub>2</sub>) as ‘undivided sediments’ in the Bynoe Harbour–Indian Island and Mary River areas, respectively (Figure 40.4). The age and stratigraphic positions of these units are also uncertain and they may belong either to the Bathurst Island Group or to underlying strata (Pietsch and Stuart-Smith 1987). Unit JKI<sub>1</sub> consists of an up to 10 m-thick succession of conglomerate, conglomeratic sandstone, sandstone and sandy claystone,

deposited under fluvial to paralic conditions. Unit JKI<sub>2</sub> is an unconsolidated quartz-rich sand, clayey in part, which overlies limonitic sandstone and conglomerate that Pietsch and Stuart-Smith (1987) identified as ‘Petrel Formation’.

## LATE MIDDLE JURASSIC–EARLY CRETACEOUS

### *Flamingo Group equivalent*

A Callovian (late Middle Jurassic) to Hauterivian (Early Cretaceous) succession, intersected in offshore drillholes of the Money Shoal Basin (Figure 40.3), is equivalent to the Flamingo Group (Gunn 1988) of the Bonaparte Basin (Struckmeyer 2006b). The succession was previously called the ‘Money Shoal Group’ by Petroconsultants (1989), but this name has been abandoned. Flamingo Group equivalent strata have not been recognised in onshore areas of the NT, although the group may be represented by poorly dated rocks in central and southern DARWIN that are currently tentatively assigned to the Plover Formation equivalent (see above). The group is unconformable on Troughton Group equivalent rocks and is unconformably overlain by the Bathurst Island Group. These unconformities are of regional extent and are dated as Callovian and Aptian (late Early Cretaceous), respectively. The group is separated into lower and upper successions by a mid-Tithonian (late Late Jurassic) unconformity (Struckmeyer 2006b).

The Flamingo Group equivalent consists of fine-grained, partly glauconitic quartz sandstone with interbedded mudstone and minor coal, and was deposited in fluvial, deltaic and shallow marine environments (Struckmeyer 2006b). The marine influence increases towards the west, and in the Bonaparte Basin, the group consists mostly of a condensed succession of mudstone deposited in an open marine setting. Towards the east, the group becomes increasingly sand-prone. Like the underlying Plover Formation equivalent, the group is thickest in the western Goulburn Graben region (1230 m in drillhole Money Shoal-1), but it thins rapidly to the north and east and is absent in wells of the eastern Goulburn Graben. The lower part of the group was deposited in a fluvial-deltaic setting, whereas the unconformably overlying upper succession represents prograding marine deltaic deposits (Struckmeyer 2006b).

Struckmeyer (2006b) identified an clastic unit of Hauterivian (Early Cretaceous) age at the top of the offshore Flamingo Group equivalent as ‘Darwin Formation equivalent’, and correlated it with the similarly aged (Valanginian–Barremian) Echuca Shoals Formation, which forms the base of the Bathurst Island Group in the Bonaparte Basin, and with the Darwin Formation, which forms the base of this group in the southern Money Shoal Basin. However, the Darwin Formation in the southern part of the basin is younger (Aptian) in age (Burger in Hughes 1978) and is therefore not a correlative of this unit.

## LATE EARLY–LATE CRETACEOUS

### *Bathurst Island Group*

The Bathurst Island Group (Mory 1988) was originally defined as the ‘Bathurst Island Formation’ (Hughes and

<sup>2</sup> European Early Cretaceous epoch containing the Berriasian to Hauterivian ICS stages.

## Money Shoal Basin

Senior 1974, Hughes 1978) in the Money Shoal Basin, but the unit extends westward across the Bonaparte Basin, and elements of the group are also known from the adjoining Browse Basin further to the west. The group is mainly located offshore on the northern and northwestern Australian continental shelf, but it extends onshore in the northern NT on BATHURST ISLAND, MELVILLE ISLAND, COBOURG PENINSULA, westernmost JUNCTION BAY, northern ALLIGATOR RIVER and DARWIN (**Figure 40.4**). The offshore Bathurst Island Group is up to 2 km thick in the western Money Shoal Basin and thickens to the west into the Calder Graben of the Bonaparte Basin. However, the group thins markedly eastwards to be less than 100 m thick to the east of Goulburn-1 (Struckmeyer 2006b, **Figure 40.3**, see also **Arafura Basin: figure 35.4**). The succession thins



**Figure 40.5.** Darwin Formation. (a) Flat-lying claystone of Darwin Formation unconformably overlying moderately dipping Proterozoic Burrell Creek Formation (Pine Creek Orogen). Note regolith profile (ferruginous duricrust, mottled zone) developed at top of section (road cutting in Tiger Brennan Drive, east of Darwin city, DARWIN, 52L 708000mE 8624000mN). (b) Basal conglomerate of Darwin Formation above scoured unconformity surface on near-vertical Burrell Creek Formation. Clasts in lower, normally graded conglomerate bed are dominantly of vein quartz; upper polymictic conglomerate bed contains clasts of vein quartz and Burrell Creek Formation (road cutting in Tiger Brennan Drive, Darwin city, DARWIN, 52L 700800mE 8621600mN).

rapidly to the south towards the margins of the Money Shoal Basin and is 569 m thick in drillhole Tingano Bay-1 in northeastern Melville Island, 289 m in BMR Cobourg Peninsula-3, and 83 m in Gunn Point-1, which is its maximum thickness in the Darwin region (Kemezys 1968, Hughes 1973, 1978). In the Money Shoal Basin, the Bathurst Island Group is dominated by mostly fine-grained rocks including claystone, marl and siltstone, with locally thick interbeds of mostly fine-grained sandstone (Struckmeyer 2006b). These form a series of stacked, thick prograding units deposited in deltaic to open marine environments that deepened to the west. The onshore succession is divided into the Darwin, Marligur, Wangarlu formations and Moonkinu Sandstone (Hughes 1978, Pietsch and Stuart-Smith 1987), which were deposited in shallow marine, lacustrine and near-shore fluvial environments (Doyle 2001).

The Bathurst Island Group was deposited in the Early–Late Cretaceous during an overall transgressive–regressive cycle that reached its peak during the Aptian to early Albian, when much of the northern part of Australia was inundated (Frakes *et al* 1987, Henderson 1998). The base of the group is diachronous; in the Bonaparte Basin it is Valanginian (Early Cretaceous, Geoscience Australia 2011), whereas in the eastern Money Shoal Basin, it is slightly younger (Late Aptian, Struckmeyer 2006b). The top of the group is Maastrichtian (Late Cretaceous) and is unconformable beneath the Cenozoic Van Diemen Sandstone or Woodbine Group equivalent.

### *Darwin Formation*

The Darwin Formation (Mory 1988, ‘Port Darwin Beds’ of Jensen 1914) and its lateral equivalent, the Marligur Formation, comprise the basal units of the Bathurst Island Group in the Money Shoal Basin. These units are equivalent to the upper part of the former ‘Mullaman Beds’, a name that was previously used to describe all onshore Mesozoic outcrops of the Northern Territory (Skwarko 1966, Hughes 1978). The Darwin Formation and its equivalent are widespread through the western Money Shoal and Bonaparte basins and extend onshore in places along the northern and western coasts of the NT. In the offshore Bonaparte Basin, the equivalent unit has been named the ‘Darwin Radiolarite’ (Geoscience Australia 2011). Struckmeyer (2006b) correlated a clastic unit at the top of the Flamingo Group equivalent in the offshore Money Shoal Basin with the Darwin Formation, but this unit is older (Hauterivian as opposed to Aptian) and is therefore not an age correlative (see above).

The Darwin Formation is exposed in the Darwin region (DARWIN, **Figure 40.4**) and has been intersected in drillholes in Bathurst and Melville islands, the Cobourg Peninsula and in the offshore area. In the Darwin area, it is flat-lying and unconformably overlies the Proterozoic Burrell Creek Formation of the Pine Creek Orogen with a marked unconformity, which is well exposed at the bases of sea cliffs around Darwin city and in several road cuttings (**Figure 40.5a**). Elsewhere, the formation unconformably overlies other Pine Creek Orogen units, including the Wildman Siltstone and Koolpinyah Dolostone. A basal 0.1–4 m-thick polymictic conglomerate, which is visible in cliff exposures around Darwin (**Figure 40.5b**), lies on

the unconformity surface locally (Doyle 2001). The Darwin Formation and its equivalent form a relatively thin layer across the southern portion of the Money Shoal Basin and eastern Bonaparte Basin. The succession is 30 m thick in drillhole Petrel-1 to the west of Darwin (see **Bonaparte Basin: figure 36.2**) and 42 m thick in Tinganoo Bay-1 in northeastern Melville Island (Hughes 1978). In the Darwin region, the formation rarely exceeds 20 m, but a maximum thickness of 63 m was intersected in drillholes EM 48 and 49 (Doyle 2001).

The onshore Darwin Formation dominated by claystone and minor silty claystone. Other rock types include sandy claystone, phosphatic nodular claystone, radiolarian siltstone, partially lithified clayey sandstone, clean sandstone, glauconitic sandstone and a locally developed basal conglomerate (Hughes 1978, Pietsch and Stuart-Smith 1987, Doyle 2001). In the Darwin area, the formation is capped by a lateritic duricrust. According to Pietsch and Stuart-Smith (1987) and Henderson (1998), drillhole intersections show that the unit grades laterally into and interfingers with the equivalent coarser-grained Marligur Formation to the east. However, Doyle (2001) noted that the facies relationships between these formations are not clear and that the Darwin Formation varies lithologically from east to west and from north to south and is not always fine-grained, as suggested by Hughes (1978). The formation contains trace-fossil beds (burrows) and has yielded macrofossils (belemnites, ammonites, marine reptiles) and microplankton (Hughes 1978, Murray (1985, 1987), Pietsch and Stuart-Smith 1987, Henderson 1998, Doyle 2001, Kear 2002). Palynological studies indicate a late Aptian age for outcrop and subsurface samples of the formation (Burger in Hughes 1978, Henderson 1998, Kear 2002), but the top may range into the Albian, if the unit is genuinely conformable beneath the middle Albian–Cenomanian Wangarlu Formation (see below). The environment of deposition has been interpreted as relatively low-energy shallow marine/paralic (Pietsch and Stuart-Smith 1987, Henderson 1998).

The Darwin Formation includes the informally named *Howard Sand member* (Doyle 2001), which consists of deconsolidated, clean to clayey, medium- to coarse-grained quartz sandstone lenses occurring above the Proterozoic unconformity. This unit is widespread in the subsurface in the Darwin rural area and is of variable thickness from 2–3 m up to a maximum of 26 m. A typical section from the western side of the Howard River contains basement siltstone, unconformably overlain by deconsolidated sand of the Howard Sand member, overlain by silicified claystone containing ammonites. A typical section from east of the Howard River consists of a basal interval of quartz and chert fragments in brown clay above the unconformity with the Koolpinyah Dolostone, overlain by the Howard Sand member, overlain by claystone and sandy claystone (Doyle 2001).

#### *Marligur Formation*

The Marligur Formation (Mory 1988, 'Marligur Member' of Hughes and Senior 1974) outcrops in southeastern COBOURG PENINSULA, westernmost JUNCTION BAY, and northernmost DARWIN (**Figure 40.4**). Pietsch and Stuart-Smith (1987) also mapped small areas of the formation

in western DARWIN, but it is unclear whether or not these are genuinely of this unit. The Marligur Formation has also been intersected widely in drillholes in the Koolpinyah and Woolner station areas in the northern part of DARWIN, but it is not recognised in offshore areas. Exposures are generally poor, deeply weathered and only a few metres in thickness. In many areas, extensive lateritisation and deep chemical weathering have resulted in the development of a surficial ferricrete and an underlying multicoloured mottled zone over the unit. At Cape Hotham at the mouth of the Adelaide River (DARWIN), the formation is exposed in low cliffs up to 3 m high and as coastal pavements.

The Marligur Formation comprises medium- to coarse-grained, poorly consolidated quartz sandstone, clayey sandstone and sandy claystone, and was deposited under marginal marine/paralic conditions (Pietsch and Stuart-Smith 1987). It is unconformable on Proterozoic basement rocks and a thin quartzic conglomerate bed, known only from rubble, is present at the base of the formation above the contact (Henderson 1998). Drillhole intersections show that the unit grades laterally into and interfingers with the finer-grained Darwin Formation to the west (Pietsch and Stuart-Smith 1987, Henderson 1998), although Doyle (2001) noted that the facies relationships between these units are not clear (see above). Burger in Hughes (1978) indicated a broad Neocomian to Aptian age for the formation from palynological studies of samples from drillhole BMR Cobourg Peninsula-1, but it is generally regarded as being the same age (late Aptian) as the Darwin Formation (Henderson 1998). The maximum thickness of the unit is a drillhole intersection of 62 m in BMR Cobourg Peninsula-5.

#### *Wangarlu Formation*

The Wangarlu Formation (Mory 1988, 'Wangarlu Mudstone Member' of Hughes and Senior 1974) of the western Money Shoal Basin and its equivalent in the Bonaparte Basin are widely distributed in offshore areas of these basins. The formation extends onshore in the northern NT, where it is exposed in western COBOURG PENINSULA and northern DARWIN (**Figure 40.4**), and it has also been intersected in drillholes in BATHURST ISLAND and MELVILLE ISLAND, as well as on the mainland. Strata equivalent to the formation reach a maximum thickness of over 2000 m in the Malita Graben of the offshore Bonaparte Basin to the northwest of Bathurst Island, and are 756 m thick in drillhole Petrel-1 in the Petrel Sub-basin to the west of Darwin (see **Bonaparte Basin: figure 36.2**). In the southern Money Shoal Basin, the Wangarlu Formation is 287 m thick in Bathurst Island-2 and 212 m thick in BMR Cobourg Peninsular-3 (Hughes 1978), but the unit thins towards the southern margin of the basin to be only 32 m thick in drillholes near Gunn Point in DARWIN (Pietsch and Stuart-Smith 1987).

The Wangarlu Formation is dominated by micaceous mudstone with variable amounts of glauconitic siltstone, sandstone, marl and limestone (Mory 1988, 1991). Pyrite, which oxidises to leave sulfurous encrustations, dark grey pyritic nodules, calcareous concretions and carbonaceous material are relatively common in the onshore succession (Hughes 1978). Widespread exposures in western COBOURG PENINSULA are soft and shrink on drying

## Money Shoal Basin

to form crumbly blocks (Hughes 1978), indicating the presence of swelling clay minerals (smectites, **Figure 40.6**). Pietsch and Stuart-Smith (1987) described the succession in northern DARWIN as consisting of weathered kaolinitic claystone, which is exposed sporadically along the cliff line facing Shoal Bay and as small, sporadic wave-cut ledges and escarpments along the north coast. A 20–30 m-deep laterite profile capped by ferricrete is commonly developed over these outcrops (Henderson 1990, Doyle 2001). The Wangarlu Formation is a marine unit which contains neritic to bathyal, as well as reworked fluvial microfaunas (Rexilius, 1987, 1988). Much of the shale in the formation is probably prodeltaic in origin (Mory 1988, 1991). Doyle (2001) interpreted relatively slow rates of marine sedimentation during deposition of the unit.

In the offshore Bonaparte Basin, the Wangarlu Formation equivalent has been given a broad Albian to Maastrichtian age (Berger in Hughes 1978, Mory 1991, Geoscience Australia 2011), but the formation spans a shorter time interval (Albian–Cenomanian) in the Money Shoal Basin. A relatively diverse ammonite fauna, recovered from the lower and middle parts of the formation at Cox Peninsula and Shoal Bay (DARWIN), has been dated as late Albian (Whitehouse 1928, Henderson 1990, 1998), and dinoflagellates from near the base of the formation at Gunn Point are no older than middle Albian (Dettmann in Henderson 1998). The age of the top of the formation in the southern Money Shoal Basin is constrained by the conformably overlying Cenomanian Moonkinu Sandstone, which is a lateral equivalent of and may interfinger with the middle part of the Wangarlu Formation equivalent in the Bonaparte Basin (Mory 1991, Henderson 1998). Palynological age determinations of drillhole samples of the Wangarlu Formation from MELVILLE ISLAND and COBOURG PENINSULA have yielded a wholly Cenomanian age for the unit in this area (Burger in Hughes 1978).

The contact between the Darwin and Wangarlu formations has generally been interpreted as conformable (eg Mory 1991, Pietsch and Stuart-Smith 1987), and Doyle (2001) reported it as being conformable and gradational over 3–4 m in northern DARWIN. However, the apparent absence of an early Albian section in the southern Money Shoal Basin suggests either that a disconformity spanning this time interval occurs between the Darwin/Marligur and



**Figure 40.6.** Wangarlu Formation. Fresh smectite (montmorillonitic) clay from drillhole EM84 in northern DARWIN (after Doyle 2001: figure 73).

Wangarlu formations (Burger in Hughes 1978, Henderson 1998), or alternatively, a highly condensed early Albian section might be present at the top of the Darwin Formation (Henderson 1998).

### *Moonkinu Sandstone*

The Moonkinu Sandstone (Mory 1988, ‘Moonkinu Member’ of Hughes and Senior 1974, ‘Puffin Formation Equivalent’ of McLennan *et al* 1990) appears to be mostly restricted to the southwestern Money Shoal Basin and probably the eastern Bonaparte Basin. It conformably overlies the Wangarlu Formation, but is also a lateral equivalent of and may interfinger with the middle part of the Wangarlu Formation equivalent of the Bonaparte Basin (Mory 1991, Henderson 1998). The distribution of this formation within the eastern Bonaparte Basin is difficult to determine, as it is difficult to distinguish it from sandstone intervals within the Wangarlu Formation equivalent (Mory 1988, 1990). The extent of the unit to the north and northwest of Bathurst Island and Cobourg Peninsula is also uncertain, although McLennan *et al* (1990) noted that it pinches out to the north. The formation is unconformably overlain by Cenozoic sedimentary rocks of the Van Diemen Sandstone and Woodbine Group equivalent in onshore and offshore areas, respectively.

The Moonkinu Sandstone is exposed in eastern BATHURST ISLAND, southern and western MELVILLE ISLAND and central and eastern COBOURG PENINSULA (**Figure 40.4**), and has been intersected in numerous drillholes in this area. It consists of grey to yellow, cross-bedded fine-grained glauconitic sandstone and quartz sandstone, interbedded with lesser light to dark grey siltstone and mudstone. The abundance of fine sandstone within this unit distinguishes it from the underlying mudstone-dominated Wangarlu Formation. The type section is the cliffs adjacent to Moonkinu Beach on Bathurst Island, where the unit is about 18 m thick, but the succession thickens to a maximum of ca 400 m in drillhole Tingano Bay-1 (Hughes 1978). The Moonkinu Sandstone is sparsely fossiliferous, but scattered molluscan faunas (Wright 1963, Skwarko 1983, Henderson in Hughes 1978, Stilwell and Henderson 2002) place it within the Cenomanian–Turonian. Hughes (1978) interpreted a shallow marine to deltaic setting for the Moonkinu Sandstone, and sedimentary structures in the type section were considered to be indicative of a shoreface environment by Mory (1991). Henderson (1998) noted that sandstone of the Moonkinu Formation is characteristically bioturbated and has sedimentary structures that are consistent with deposition on a shallow shelf. The sandstone of the formation was reinterpreted as sand sheets driven by storm activity onto the shelf, with interbedded mudstone and siltstone intervals representing ambient, fair-weather deposition of suspended load.

## CENOZOIC

### *Ungrouped*

#### *Van Diemen Sandstone*

The Van Diemen Sandstone (Hughes and Senior 1974, Hughes 1978) unconformably overlies the Moonkinu

Sandstone and is widely exposed as sea cliffs, discontinuous low ridges and dissected plateaux on BATHURST ISLAND and MELVILLE ISLAND (**Figure 40.4**). Exposures are strongly weathered and are heavily iron-stained, particularly inland (Hughes 1978). The distribution of the formation in offshore areas of the basin to the north of the islands is uncertain; however, the unconformity at the base of the unit dips gently to the northwest and can be traced for over 200 km on seismic profiles (Jongsma 1974). Onshore, the formation is overlain by Quaternary sand and soil; offshore relationships with the younger Neogene Woodbine Group equivalent are unclear.

The Van Diemen Sandstone comprises white to yellow, cross-bedded, medium- to coarse-grained quartz sandstone, with minor lenses of siltstone and granular conglomerate. The sandstone is friable and poorly sorted, and is composed of sub-angular to rounded quartz, with minor opaque minerals and tourmaline, and little matrix. On southern Bathurst Island, up to 60 m of Van Diemen Sandstone was intersected in auger drillholes (Laws 1967). The formation gradually thickens northward across the islands and, in its type section at Cape Van Diemen, an incomplete section of more than 55 m in thickness is exposed (Hughes and Senior 1974). Plant fossils have been recovered from mudstone within the unit and these are Eocene or possibly younger in age (White in Hughes 1978). A fluvial environment of deposition has been interpreted for the formation (Hughes 1978).

In the Bonaparte Basin, the Woodbine Group contains Paleogene units of equivalent age to the Van Diemen Sandstone, suggesting that the range of the equivalent group in the Money Shoal Basin could be extended into the Paleogene to include this formation.

#### *Woodbine Group equivalent*

Sedimentary rocks equivalent to the Woodbine Group (McLennan *et al* 1990) of the Bonaparte Basin are widespread over much of the offshore Money Shoal Basin, but are not present in onshore areas. The group is generally less than 400 m thick over much of the western portion of the basin, but thickens rapidly to the west towards the Calder Graben of the Bonaparte Basin, where it is a maximum 1300 m thick in Lynedoch-1 (Struckmeyer 2006b). The group thins to less than 100 m in the eastern Goulburn Graben (McLennan *et al* 1990), but seismic evidence suggests that further to the east, the unit may gradually thicken towards the Carpentaria Basin (Struckmeyer 2006b). In the Bonaparte Basin, the Woodbine Group ranges from Paleocene to Holocene, with a hiatus occurring during the Oligocene (Mory 1988, Geoscience Australia 2011), but the base of the equivalent group in the Money Shoal Basin is much younger (early Miocene), and there is a significant hiatus spanning the Paleogene and early Neogene that separates the group from the underlying Bathurst Island Group.

The Woodbine Group equivalent is poorly documented in the Money Shoal Basin and is not subdivided into formations. BHP Petroleum (1993) provided a description of the succession in drillhole Cobra-1A, where it consists of a lower unit of probable early to middle Miocene age, consisting of coarse-grained quartzitic sandstone with

claystone interbeds and minor coal and dolostone, overlain by an upper late Miocene and ?younger unit of calcareous claystone and marl with calcarenite interbeds. Struckmeyer (2006b) interpreted this succession as representing initial deposition in localised, shallow marine to deltaic settings, followed by a more widespread open marine environment in the late Miocene. This is comparable to interpretations of the Woodbine Group in the Bonaparte Basin where a lower sandy succession grades upwards during Miocene time into a widespread shelf carbonate succession that appears to have transgressed the basin's palaeohighs (Petroconsultants 1990).

The Quaternary succession at the top of the Woodbine Group equivalent was laid down during periods of fluctuating climate and sea level that accompanied glacial–interglacial cycles (Nott and Roberts 1996). This resulted in periods of widespread exposure at times of lower sea level that alternated with shallow marine conditions at times of higher sea level. During sea level lowstands, the present river systems also drained across an extensive exposed shelf, transporting sediments to areas which are now submerged (Woodroffe 1993). Exposed areas were subjected to widespread erosion and fluvial processes, and developed calcrete and soil profiles (Rollet *et al* 2009). During sea level highstands, conditions were likely to have been similar to those prevailing on the present-day shelf, with terrigenous sand nearshore, silt and clay on the middle shelf, and a general increase in carbonate content seawards (Jongsma 1974).

#### STRUCTURE AND TECTONICS

Mesozoic strata of the Money Shoal Basin were largely deposited during a period of passive margin subsidence, but were mildly affected by the far-field effects of tectonism occurring on the northwestern Australian margin to the west. In the late Cenozoic, the basin experienced a compressional tectonic phase related to collision between the Australia-India plate and Southeast Asian microplates to the north.

The Late Jurassic was characterised by Oxfordian to Tithonian rifting in the Bonaparte Basin that led to the formation of the Malita and Calder grabens, and the Vulcan Sub-basin (Patillo and Nicholls 1990, Longley *et al* 2002). The effects of this extension were much less pronounced in the Money Shoal Basin, but were expressed as relatively small-scale normal faulting along the boundaries of the Goulburn Graben, particularly along the southern boundary. These faults were probably reactivated Late Carboniferous structures and controlled sedimentation in this area in the Late Jurassic to Early Cretaceous. The Callovian unconformity that underlies the Flamingo Group equivalent was the result of a minor extensional event, which is reflected by an increase in the thickness of the lower Flamingo Group equivalent across a reactivated boundary fault of the Goulburn Graben (Struckmeyer 2006b).

Late Early Cretaceous to Cenozoic strata dip at a low angle to the northwest as a result of slow subsidence and flexuring of the Australian plate. Small listric normal faults occur in Albian claystone of the Bathurst Island Group in the eastern Bonaparte and western Money Shoal basins, and are probably related to differential compaction across

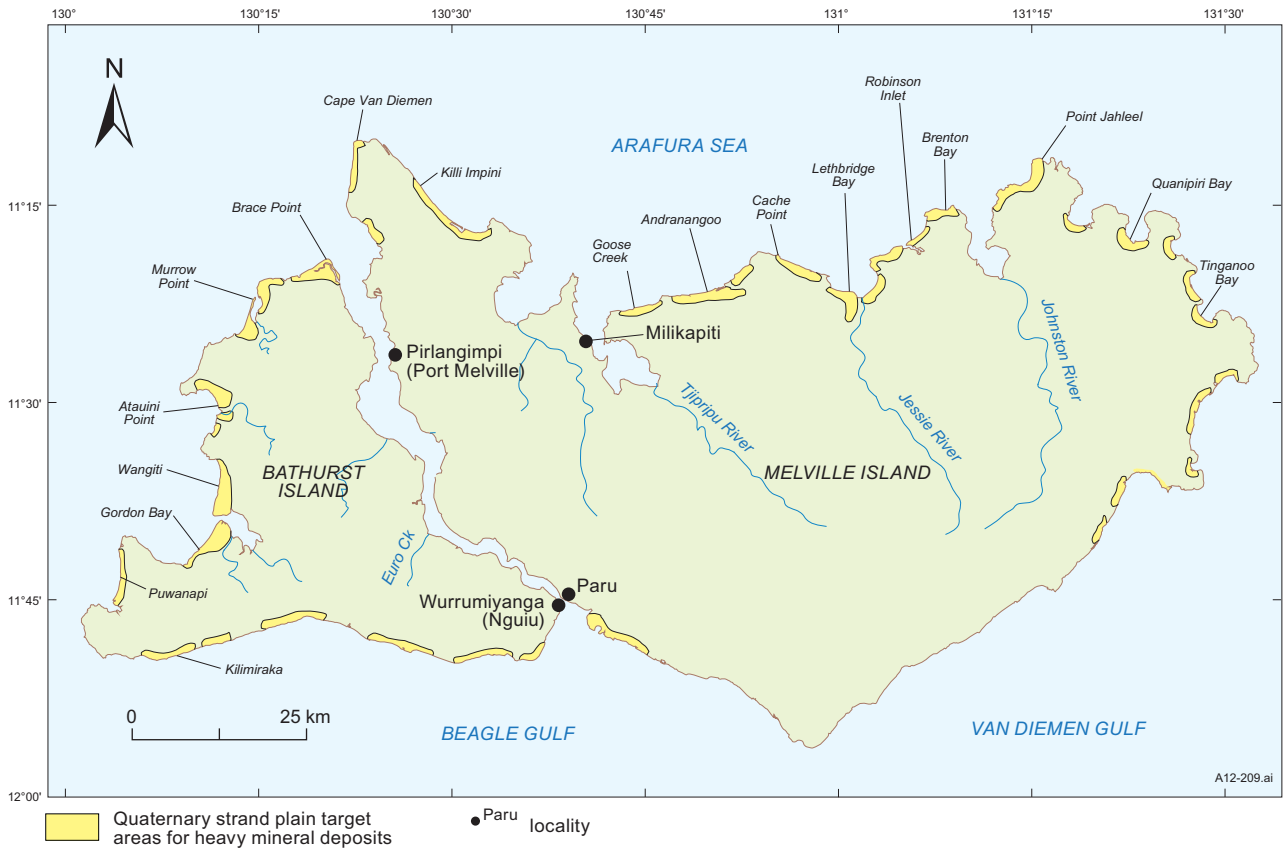
## Money Shoal Basin

graben margins. Most fault displacements apparently die out upwards in the thick Wangarlu Formation (McLennan *et al* 1990). The Woodbine Group equivalent is generally undeformed, although some structures have formed as a result of northern margin collisional processes, related to the subduction of Australia beneath the Eurasia plate in the late Miocene to Holocene. These include occasional steep, normal reactivation faults in the northern part of the basin close to the Indonesian border, a large anticline in the vicinity of drillhole Money Shoal-1, and small inversion and other compressional

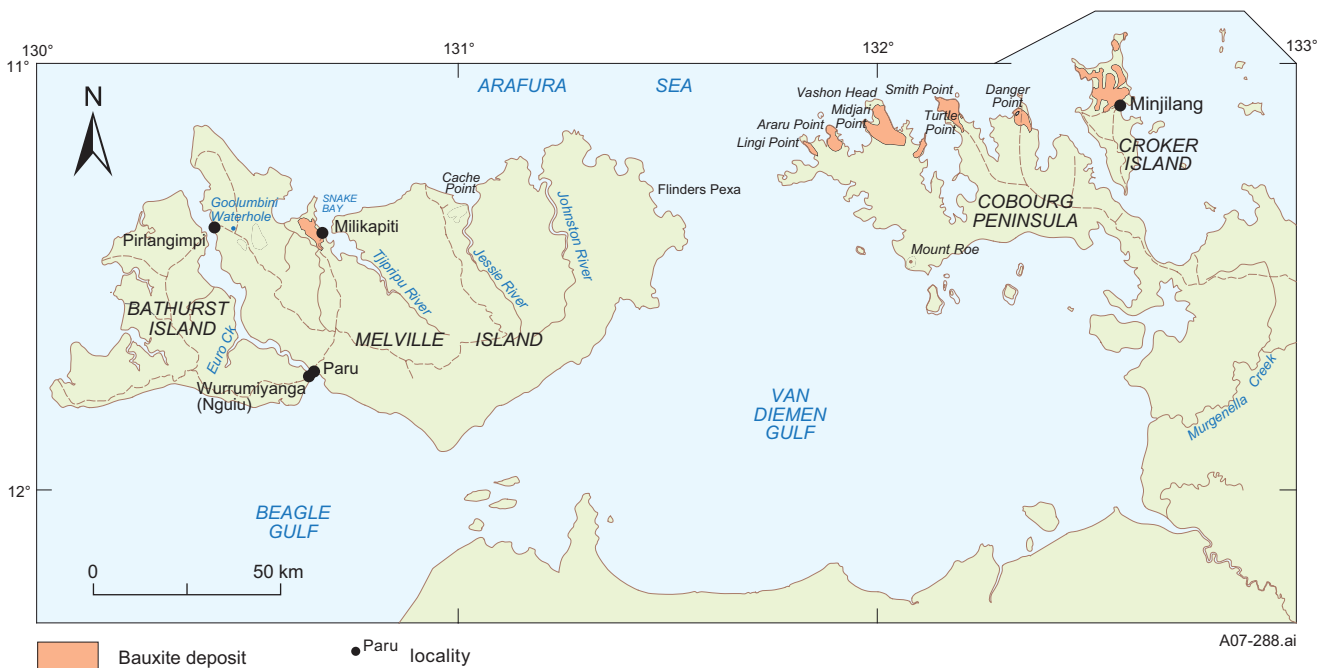
features that have developed along major graben-bounding faults (McLennan *et al* 1990, Struckmeyer 2006b).

## MINERAL RESOURCES

The Money Shoal Basin is prospective for a number of mineral commodities including mineral sands (**Figure 40.7**), bauxite (**Figure 40.8**) and extractive minerals. Mineral sands deposits have been discovered at numerous locations on the beaches of Melville and Bathurst islands and some of



**Figure 40.7.** Heavy mineral sands occurrences of the Money Shoal Basin (redrawn and slightly modified from Matilda Zircon 2009).



**Figure 40.8.** Bauxite occurrences of the Money Shoal Basin (after Ferenczi 2001).

these have been intermittently mined since 2006. Bauxite profiles have been recorded at several locations on the Cobourg Peninsula, and on Croker and Melville islands, but these are yet to be exploited. Extractive minerals, including sand and porcellanite, are quarried in the Darwin region for a variety of industrial and ornamental uses. The offshore Money Shoal Basin is also very prospective for petroleum, although no commercial discoveries have yet been made.

### Heavy mineral sands

Ilmenite-, leucoxene-, zircon- and rutile-bearing heavy mineral sands are present along the Quaternary coastal plains of Melville and Bathurst islands. Heavy mineral sand accumulations are present within both the Pleistocene and Holocene strands. The most economically significant of these are Pleistocene-aged littoral quartzic sands associated with the palaeo-shoreline. The immediate provenance of the heavy mineral sands is the Cenozoic Van Diemen Sandstone, which contains thin laminae of identical heavy minerals. The Pleistocene and Holocene deposits have been subjected to two cycles of erosion and deposition, being originally derived from Palaeoproterozoic igneous and metamorphic rocks of the Pine Creek Orogen. Carbon dating of the underlying shelly coquina at the Lethbridge deposit on Melville Island has yielded a date of 2000 years (Matilda Zircon 2010a).

Early investigations to assess the concentrations of mineral sands on Melville Island included Mackay (1956), Murphy (1970), Hughes (1978), and McGoldrick (1995). These investigations included shallow auger drilling to the water table and indicated the presence of heavy mineral sand as zones and layers of black sand near the high-water mark, associated with depressions in the dunes behind. No heavy mineral grades were reported in these early studies and the rutile content was stated as too low to be of interest at that time; however, a modal analysis of 80 samples from a number of localities (Hughes 1978) indicated a prevalence of zircon over rutile and ilmenite. Zircon, rutile, tourmaline and kyanite are the main heavy minerals with zircon forming up to 70% of the heavy mineral fraction. Since 2003, Matilda Minerals Ltd (now Matilda Zircon Ltd) has conducted an extensive exploration program for heavy mineral sands along the coastlines of Melville and Bathurst islands and has identified a number of potentially economic deposits.

The more significant heavy mineral accumulations in the Tiwi Islands are shown in **Figure 40.7**. In 2006, total resources were given at 6.98 Mt averaging 4.4% heavy minerals, mainly zircon, rutile and leucoxene (**Figure 40.9a**). These resources were established at the *Andranangoo* (3.52 Mt), *Lethbridge* (1.57 Mt) and *Puwanapi* (1.89 Mt) deposits (Matilda Minerals 2006). Production commenced in late 2006 and was suspended in September 2008 after producing a total of 46 000 t of zircon concentrate grading 50% zircon (Matilda Zircon 2009). In 2010, Matilda mined the small *Lethbridge West* deposit. Mining produced 11 400 t of high-grade concentrate (**Figure 40.9b**), containing approximately 70% combined zircon and rutile, from 134 500 t of ore. This was loaded onto bulk carriers by barge in Lethbridge Bay

(**Figure 40.9c**) and shipped to China for processing (Matilda Zircon 2009, 2010b). Mining commenced at the *Lethbridge South* deposit, 4 km southeast of Lethbridge West, in March 2012. This deposit contains JORC compliant reserves of 1.16 Mt at 2.47% heavy minerals (Matilda Zircon 2011a) and is described in Hughes (1978) and in various reports by Matilda Zircon (2006, 2009, 2010a, b, 2011a, 2012). In 2011, Matilda announced a maiden Inferred Resource for the large *Kilimiraka* deposit on the south coast of Bathurst Island near Cape Fourcroy that comprises 56.2 Mt grading 1.6% heavy minerals for 893 700 t of heavy minerals, including over 92 000 t zircon, 57 000 t rutile, 127 000 t leucoxene and 368 000 t ilmenite. This deposit is much larger than the Lethbridge deposits and has the potential to underpin an 8–10-year mining operation (Matilda Zircon 2011b).



**Figure 40.9.** Lethbridge heavy mineral sands mining operations (after Matilda Zircon 2011c). (a) Heavy mineral sand concentrate. (b) Lethbridge West processing plant with concentrate stockpile. (c) Conveyor loading heavy mineral sands concentrate onto a barge at Jessie River, Lethbridge Bay, Melville Island.

**Bauxite**

Lateritic bauxite deposits in the Money Shoal Basin include occurrences on the Cobourg Peninsula, Croker Island and Melville Island (Figure 40.8). Those in the Cobourg Peninsula–Croker Island area have developed over undivided Bathurst Island Group, whereas those on Melville Island are developed over the Cenozoic Van Diemen Sandstone. The bauxitic laterite in the Cobourg Peninsula–Croker Island area is up to 4 m thick and averages about 2 m. It forms a gently north-sloping land surface that is best exposed along the northern coastlines (Hughes 1978).

Brown (1908) first reported the presence of pisolitic laterite that assayed 47.32% Al<sub>2</sub>O<sub>3</sub> at Mount Roe on the southern flank of the Cobourg Peninsula. This was followed-up by Owen (1949) who established the presence of 0.6–1.4 m-thick pisolitic bauxite at the locality visited by Brown. Rio Tinto Exploration Pty Ltd conducted some reconnaissance work on bauxite deposits on Croker Island (Matheson 1957) that were later drill-tested by Reynolds Metals Company (Kidd 1961). Australian Mining and Smelting Company Ltd (Patterson 1958) investigated bauxites in the Snake Bay area on Melville Island and United Uranium NL conducted geochemical sampling of bauxite occurrences on the Cobourg Peninsula (Larsen 1965). Swiss Aluminum Mining Australia Pty Ltd conducted geochemical sampling at Cache Point on western Melville Island and prospects on the Cobourg Peninsula (Swiss

Aluminum 1969, 1970a, b). These bauxite occurrences were described by Ferenczi (2001).

A close correlation exists between the distribution of bauxite and thorium anomalies detected by airborne radiometric surveys (Hughes 1978). Thorium concentrations in 13 samples collected from the Cobourg Peninsula ranged from 6–54 ppm and averaged 35 ppm (Hughes 1978). Of the 12 known occurrences of bauxite in the Money Shoal Basin, drilling has been conducted at three deposits to define resources: Vashon Head, Croker Island and Araru Point.

**Vashon Head and Midjari Point**

At *Vashon Head* on the Cobourg Peninsula, a 1–4.5 m-thick bauxite deposit that averages 3 m in thickness extends over an area of about 48 km<sup>2</sup> (Figure 40.10). The pisolitic bauxite layer overlies a ferruginous nodular laterite that has developed over a shale bed in the undivided Bathurst Island Group (Weber 1969). The deposit has been explored by United Uranium NL by rock chip sampling, auger drilling and pit excavation. This work has outlined inferred resources of 9.7 Mt averaging 46.2% Al<sub>2</sub>O<sub>3</sub> and 16.1% SiO<sub>2</sub> at an average thickness of 3 m, and 5.8 Mt averaging 36.7% Al<sub>2</sub>O<sub>3</sub> and 20.2% SiO<sub>2</sub> at an average thickness of 1.7 m. Most of the silica appears to be reactive ie, it is present in silicate minerals such as clay (usually kaolinite). Fe<sub>2</sub>O<sub>3</sub> content is about 14% and TiO<sub>2</sub> content is about 3% (Larsen 1965, Weber 1969, Ferenczi 2001). The bauxite resource at Vashon Head appears to be of sub-metallurgical-grade, but no ore characterisation work has been conducted and if the clay minerals are loosely bound in the bauxite material, then crushing and washing may reduce the reactive silica content and improve the potential of this deposit as a source of metal-grade bauxite (Ferenczi 2001).

The *Midjari Point* prospect is located just to the south of Vashon Head. A measured section of the bauxite profile at this locality is shown in Figure 40.11. Gibbsite is the principal mineral within the bauxite layers and is commonly in the form of pisoliths that generally vary from 2–8 mm in size. Kaolinite, haematite and minor quartz form the remaining minerals. The pisoliths occur with reworked framework grains of quartz, feldspar, calcite, tourmaline, opaque minerals, broken pisoliths and rock fragments, and are set in a matrix composed of very fine quartz and kaolinite (Hughes 1978). Pisolith nuclei consist of older pisoliths, laterite fragments, or very fine quartz grains. Ferruginous nodules and detrital clasts from underlying beds are commonly scattered through the loose pisolitic layer.

**Croker Island**

Bauxite is present only in the northern part of Croker Island. It averages about 1.5 m in thickness and occupies an area of about 80 km<sup>2</sup> (Kidd 1961). Pisolitic bauxite overlies a hard, red-brown tubular laterite with a sharp contact. Pisoliths are 3–8 mm in diameter. The tubular laterite grades down into a mottled clay zone that in turn overlies grey weathered shale of the Bathurst Island Group. This deposit was explored by Reynolds Metals Company by

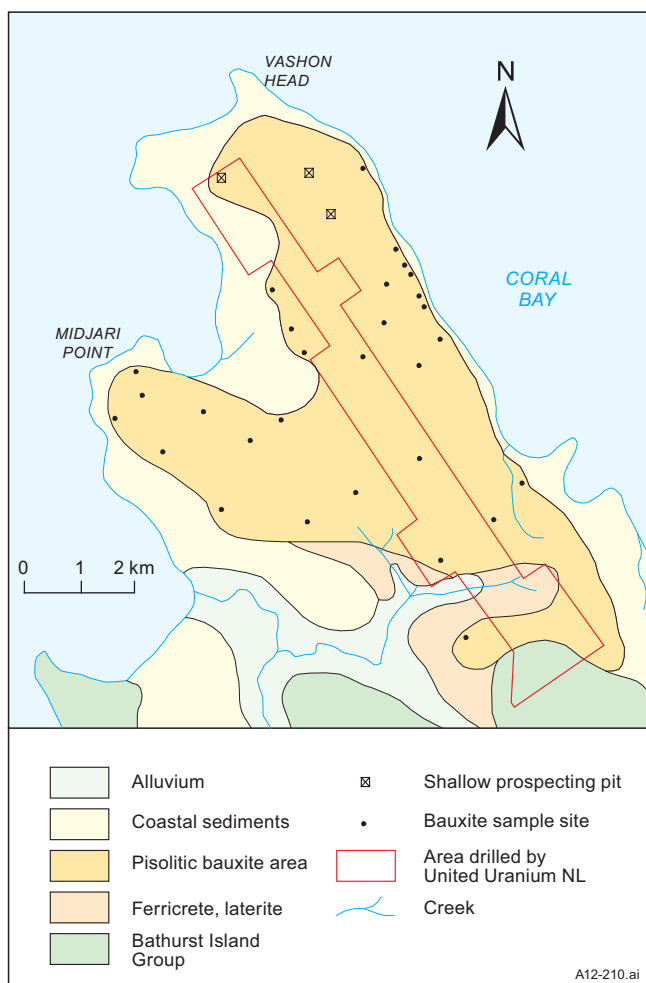


Figure 40.10. Vashon Head bauxite deposit, Cobourg Peninsula (after Ferenczi 2001, modified from Weber 1969).

drilling, which outlined an inferred resource of 660 000 t averaging 30%+ Av. $Al_2O_3$  (Kidd 1961). Six grab samples subsequently obtained by United Uranium NL averaged 35.3%  $Al_2O_3$ , 31.2%  $SiO_2$ , 25.6% Re. $SiO_2$ , 15.4%  $Fe_2O_3$  and 1.85%  $TiO_2$  (Larsen 1965). The high levels of reactive silica in the Croker Island deposit reduces the potential for commercial exploitation (Ferenczi 2001).

**Araru Point**

A 0.5–2.4 m-thick pisolitic bauxite deposit has been outlined over an area of 13 km<sup>2</sup> at Araru Point on the Cobourg Peninsula. United Uranium NL explored this deposit by surface sampling and drilling, and identified a resource of 2.4 Mt averaging 35–40%  $Al_2O_3$  and 20%+  $SiO_2$  (Larsen 1964, Weber 1969). Additional surface sampling was conducted by Swiss Aluminum Mining Australia Ltd and 12 samples from this work averaged 42.3%  $Al_2O_3$ , 18.1%  $SiO_2$ , 16.1%  $Fe_2O_3$  and 3.2%  $TiO_2$  (Swiss Aluminum 1970a, b). Low tonnages and  $Al_2O_3$  content, and high levels of reactive silica reduce the commercial viability of this deposit as a source of metallurgical-grade bauxite (Ferenczi 2001).

**Other occurrences**

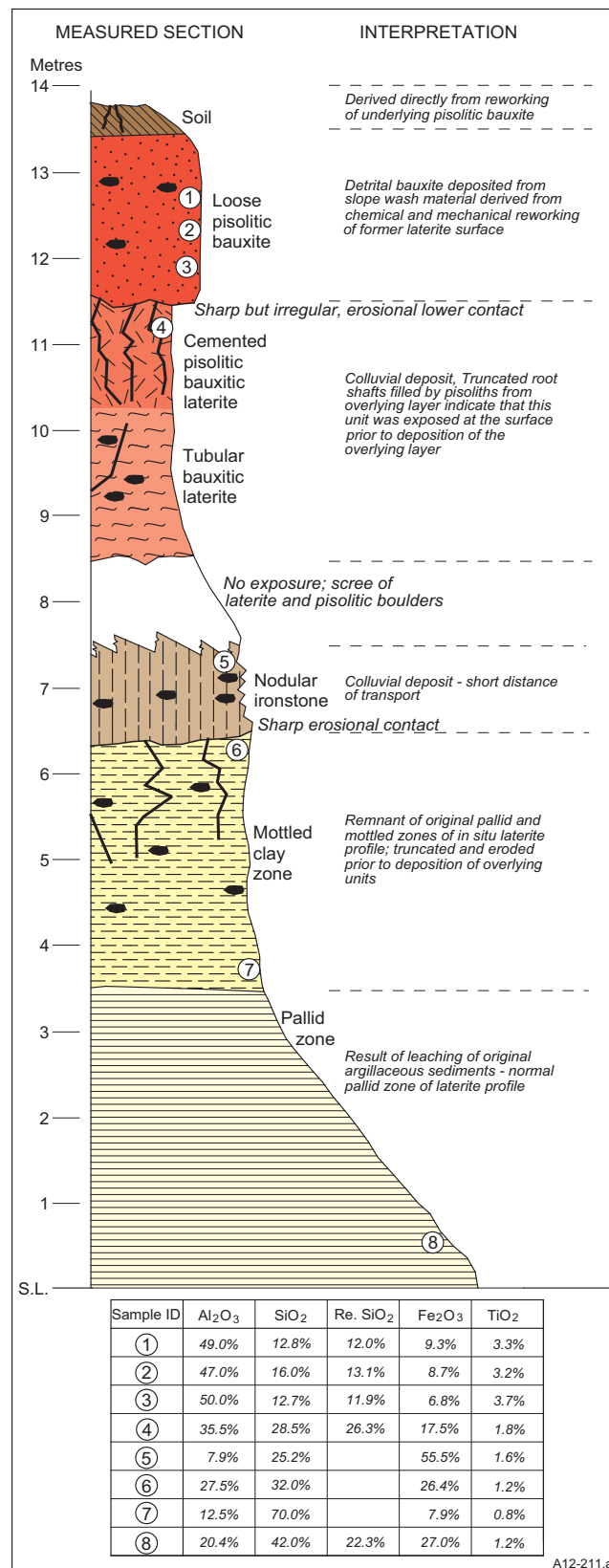
Bauxite has been reported from a number of other locations on the Cobourg Peninsula and Melville and Bathurst islands (Swiss Aluminum, 1969, 1970a, b, Hughes 1978, Ferenczi 2001, **Figure 40.8**). At *Smith Point* on the Cobourg Peninsula, tabular bauxite has been reported along the narrow headland separating Port Essington and Port Bremer (Hughes 1978). It covers an area of about 20 km<sup>2</sup> and varies in thickness from 0.5–2 m. At *Turtle Point*, along the western shore of Port Essington, a bauxite profile is estimated to be about 2 m thick (Hughes 1978) and at *Danger Point* in the northeastern Cobourg Peninsula, the presence of an iron-enriched bauxite profile was noted by Larson (1965). On Melville Island, bauxite has been reported at *Milikapiti Hill* and *Piper Head*. At the former occurrence, bauxite is known to extend over an area of 15 km<sup>2</sup> and the maximum thickness of the pisolitic layer is about 6 m (Hughes 1978).

**Extractive minerals**

**Sand**

Doyle (2001) provided details of investigations, including geological mapping and extensive drilling, for extractive materials in the Darwin region and identified several prospective areas. The Howard Sand member of the Darwin Formation supplies large amounts of coarse and fine washed sand for used in the construction industry. The *Boral Sand Pit* (**Figure 40.12**) near Howard Springs is operated by Boral Industries and produces 60 000–80 000 t/yr of coarse washed sand and up to 120 000 t/yr of fine washed sand. Dredging extends to 20–25 m below the surface and there is still a substantial resource that could be accessed by extending the western and northern sides of the excavation (Doyle 2001). *AN47*, which is located to the south of the Howard Springs Forestry Reserve and owned by All Earth

Industries, is extracting sand by bucket excavation from the Howard Sand member to about 6 m depth (**Figure 40.13**). This operation produces about 7000 m<sup>3</sup> per year of coarse washed sand for concrete aggregate. A number of other sand prospects have been located and drilled by Doyle (2001) and the total sand resource in the Darwin region is estimated to be about 10 Mt, most of it in the Howard Sand member.



**Figure 40.11.** Bauxite profile at Midjari Point, Cobourg Peninsula (after Ferenczi 2001, modified from Hughes 1978).

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### Porcellanite

Porcellanite is a local term for silicified mottled claystone that occurs in the siliceous zone beneath lateritic duricrust of the Darwin Formation in the Darwin area, where it is exposed in coastal cliffs. The upper 2–4 m of the porcellanite profile is made up of a brittle, high-strength rock with a silica content approaching that of silcrete. The underlying altered and porous siltstone is much weaker and deforms plastically under loading. The geotechnical properties of the Darwin porcellanite have been described by McQueen (1957) and more recently by McNally *et al* (2000). Porcellanite has been used in many of the historical buildings of Darwin (**Figure 40.14**) and was obtained from the now-abandoned Larrakeyah Quarry, located at Doctors Gully at the northern end of Darwin city. Another quarry was developed during the Second World War on the present site of the Stuart Park Primary School. Porcellanite was crushed and used as exposed aggregate in concrete bunkers and gun turrets at East Point and Casuarina Beach (Doyle 2001). The currently operating Koolpinyah Porcellanite Quarry at Shoal Bay Peninsula (**Figure 40.15**) has been excavated down to about 3 m depth, below which the material becomes softer. The porcellanite from this quarry is hand worked by stonemasons for building stone; other material is washed and rounded and is used as an ornamental landscape stone.

### Petroleum

The history of petroleum exploration in the Arafura and Money Shoal basins is discussed in **Arafura Basin**. A number of exploration programs involving drilling and seismic acquisition have been conducted in these stacked

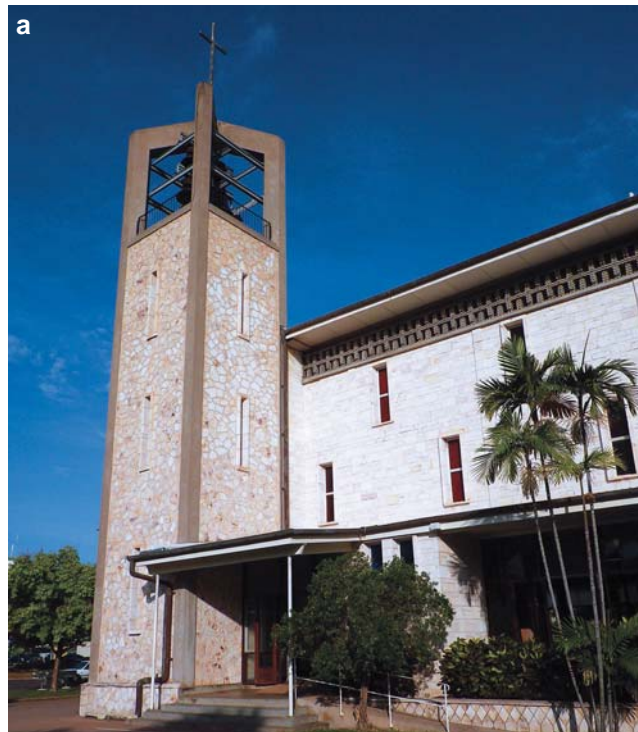


**Figure 40.12.** Dredge in operation at Boral sand pit in Howard Sand member (photograph from Doyle 2001).



**Figure 40.13.** One of the open pits at AN47 quarry. Excavation is down to water table (photograph from Doyle 2001).

basins, particularly since the 1960s, but so far, no commercial hydrocarbon accumulations have been discovered. Despite this, the Money Shoal Basin remains underexplored and is prospective for petroleum. Nine offshore petroleum exploration wells have been drilled in the basin, all in the region of the underlying Goulburn Graben. Direct evidence of hydrocarbon generation and expulsion is provided by



**Figure 40.14.** (a) Porcellanite block work in St Mary's Cathedral, Darwin. (b) Detail of block work in bell tower of St Mary's Cathedral.

oil shows/indications and gas indications in the majority of wells drilled, at various levels in the Palaeozoic and Mesozoic successions.

**Source rocks and thermal maturity**

Potential source rock intervals occur at a number of levels in the stacked McArthur, Arafura and Money Shoal basins (Figure 40.16) and those from the pre-Mesozoic successions are discussed in McArthur Basin and Arafura Basin. In the Money Shoal Basin, potential source rocks containing oil-prone Type II/III kerogen occur throughout the Mesozoic section. The Jurassic Plover Fm equivalent has Total Organic Carbon (TOC) values in the range 0.5–8%, and some intervals within the overlying Jurassic–Early Cretaceous Flamingo Group equivalent have TOC values up to 4.9%, indicating fair to very good source potential for these units (Struckmeyer and Earl 2006). Both successions are generally immature for oil generation over much of the basin, particularly in the east, but maturity increases to the northwest and in the deepest parts of the basin, such as the western Goulburn Graben and areas further to the north, they are likely to be mature for oil and possibly gas generation (McLennan *et al* 1990, Higgins 2009). The Cretaceous Bathurst Island Group has TOC values in the range 0.5–2.7%, indicating that some intervals have fair to good source potential. Over most of the Money Shoal Basin, these rocks are immature for hydrocarbon generation, but they may be buried deep enough to reach oil maturity in the westernmost Goulburn Graben and adjacent areas of the Bonaparte Basin (Struckmeyer and Earl 2006).

**Reservoirs and seals**

The upper Plover Formation provides the reservoir for gas accumulations in the eastern Bonaparte Basin and equivalent rocks in the Money Shoal Basin have variable porosities in the range 5–27% (Earl 2006), indicating that there is potential for favourable reservoirs in the basin. Seals could be provided by claystone-rich intervals in the lower Flamingo Group equivalent, and

by the Bathurst Island Group in the eastern part of the basin (Figure 40.16). Flamingo Group rocks host major hydrocarbon accumulations in the Bonaparte and Browse basins, and equivalent rocks in the Money Shoal Basin are likely to have similar reservoir potential (Struckmeyer and Earl 2006). Earl (2006) reported that samples of this group from drillhole Tasman-1 have good to excellent reservoir properties, with an average porosity of 18.5% and a maximum of 32%. Interbedded mudstone intervals could provide intraformational seals and fine-grained rocks of the Bathurst Island Group could provide a regional seal. The reservoir properties of sandstone intervals within the Bathurst Island Group have not been properly assessed, but samples from drillhole Tuatara-1 have yielded porosities of 13–33 %, with an average of 20% (Earl 2006).

**Prospectivity**

An assessment of the prospectivity of the Money Shoal Basin by Higgins (2009) concluded that the underexplored northern portion of the basin was most likely to contain hydrocarbon accumulations, particularly towards the western margins, where up to 4.5 km of preserved section is thick enough to have enabled the generation of hydrocarbons from *in situ* Jurassic source rocks. The portion of the basin overlying the Goulburn Graben has been tested by nine exploration drillholes that



Figure 40.15. Koolpinyah Porcellanite Quarry. Depth of pit is about 3 m (Shoal Bay Peninsula Road, DARWIN, 52L 719400mE 8627600mN, after Doyle 2001: figure 67).

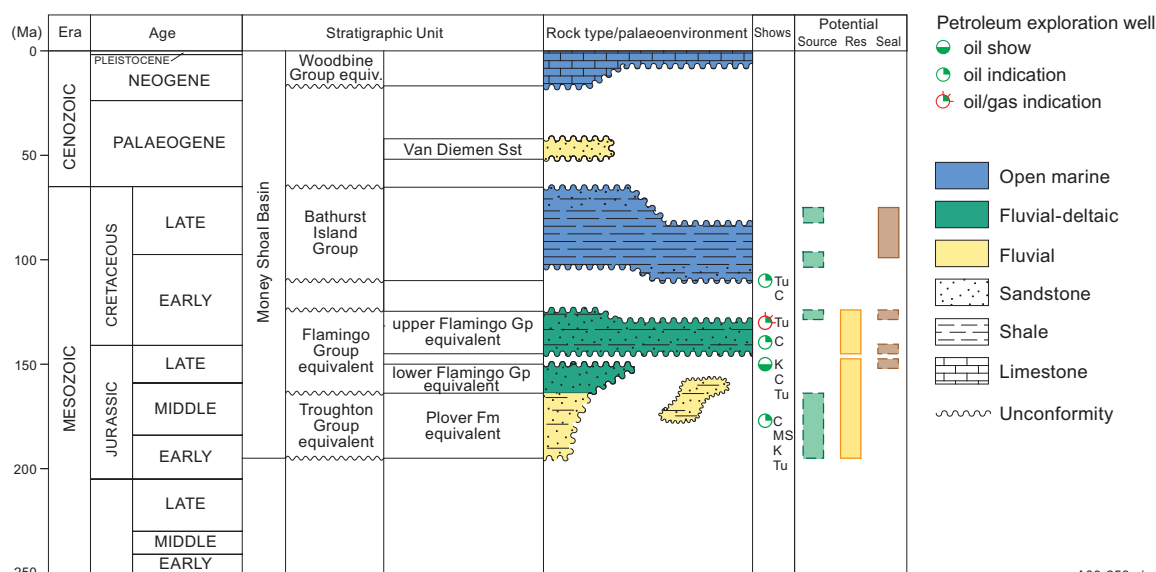


Figure 40.16. Stratigraphic succession and petroleum systems elements for the Money Shoal Basin (modified from Struckmeyer 2006b: figure 26). Abbreviations: C = Cobra-1, 1A; K = Kulka-1; MS = Money Shoal-1; Tu = Tuatara-1; Fm = Formation; Gp = Group.

have demonstrated the presence of good-quality reservoirs and seals in the basin succession, and of hydrocarbons in the region; however, these have failed to locate any commercial hydrocarbon accumulations. The southern portion of the basin contains less than 3 km of sedimentary rocks and has received little exploration interest. Due to the thinness of the succession, *in situ* sourcing of hydrocarbons is unlikely and long-range migration from neighbouring source kitchens in the Bonaparte and Arafura basins would be necessary to charge potential traps (Higgins 2009).

The Money Shoal Basin has a variety of potential stratigraphic and combined stratigraphic/structural plays for hydrocarbons sourced from underlying Palaeozoic sedimentary rocks and from mature Mesozoic source rocks in the western and northwestern parts of the basin. Onlap plays associated with the underlying Triassic unconformity occur within increasingly younger strata to the east, and provide numerous potential targets within Middle Jurassic fluvial sandstone reservoirs and/or Late Jurassic to Early Cretaceous fluvial-deltaic clastic reservoirs, in lowstand, transgressive and highstand settings (Struckmeyer 2006c). Other plays include broad anticlines draped over the Palaeozoic succession and tilted fault blocks above the margins of the Goulburn Graben (McLennan *et al* 1990). Good potential plays are also associated with a large Late Jurassic (Tithonian) channel system, at least 225 km long and an average of 10 km wide, that follows the major bounding faults of the Goulburn Graben (BHP Petroleum 1993, Miyazaki and McNeil 1998, Barber *et al* 2004). This system provides numerous potential stratigraphic and structural traps within channel fills and associated erosional features, which remain untested. Middle–Late Cretaceous prograding shelf and contiguous slope and basin deposits also provide numerous potential plays, particularly within lowstand wedge deposits such as slope fans, channel-levee systems and basin floor fans (Struckmeyer 2006c).

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