1:250 000 GEOLOGICAL MAP SERIES
EXPLANATORY NOTES

MILINGIMBI SD 53-2

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ABSTRACT

MILINGIMBI* is situated in the northwest of the Arnhem Land Aboriginal Reserve. The map sheet extends from the northern coast and coastal plains, inland to low undulating country and spectacular escarpment plateau.

MILINGIMBI lies at the northern extent of the McArthur Basin and includes parts of the Pine Creek Inlier in the northwest and the Arafura Basin in the north and east.

The oldest rocks exposed are part of the Pine Creek Inlier, comprising Palaeoproterozoic (Orosirian) granite and gneiss of the Nimbuwah Complex. The Pine Creek Inlier was affected by a major tectonic event, the 1870-1850 Ma Barramundi Orogeny, which involved multiple fold generations, regional metamorphism and emplacement of the Nimbuwah Complex intrusives. These units form the basement to the Palaeoproterozoic to Mesoproterozoic McArthur Basin succession.

The oldest unit of the McArthur Basin is the Katherine River Group, which consists of fluviatile, shallow-marine, and minor aeolian units as well as volcanics. The extensive sheet-like sill of the Oenpelli Dolerite intruded at ~1688 Ma. Deposition of the Mount Rigg Group in a post-rift basin extended across the Arnhem Shelf and Walker Trough to the east.


Undeformed, shallow-marine sediments of the Neoproterozoic to Middle Cambrian Arafura Basin unconformably overlie the McArthur Basin.

A thin cover of Cretaceous shallow-marine sandstone and mudstone mantles the older rocks. Cainozoic alluvium, coastal deposits, laterite and soil cover a large proportion of MILINGIMBI.

Exploration for uranium, bauxite and diamonds has been unsuccessful in locating economic prospects.

* Names of 1:250 000 scale mapsheets in this report are shown in capital letters, e.g. BLUE MUD BAY.
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INTRODUCTION

These second edition explanatory notes and geological map present results of geological investigations on this 1:250 000 scale map sheet. The area is bounded by latitudes 12°00'S and 13°00'S and longitudes 133°30'E and 135°00'E (Figure 1). The Northern Territory Geological Survey (NTGS) and the Australian Geological Survey Organisation (AGSO, formerly BMR, Bureau of Mineral Resources) under the National Geoscience Mapping Accord (NGMA) remapped MILINGIMBI as part of the McArthur Basin program.

Field mapping was undertaken during the dry seasons of 1994-1996. The field base for mapping was colour aerial ‘Arnhem Highway’ 1:50 000 scale photography, flown by the NT Government in 1982. Aerial magnetic and radiometric surveys (500 m line spacing, 100 m terrain clearance) were obtained in 1990 and 1992.

Location, habitation and access

MILINGIMBI is located in the northwest of the Arnhem Land Aboriginal Reserve where a permit is required for entry. The main Aboriginal communities are Mamingrida, Ramingining and Milingimbi. These centres service numerous outstations.

A main sealed road transects northern MILINGIMBI, connecting the main communities of Mamingrida and Ramingining. A ferry service operates to the township of Milingimbi on Milingimbi Island. South of Ramingining a secondary sealed road connects to the Central Arnhem Road. Minor roads provide access to outstations. Access during the dry season is good, but roads are impassable during the wet season. Aircraft and barges provide year-round access to communities and outstations. Considerable tracts of land in southern MILINGIMBI are only accessible by helicopter.

Climate and vegetation

The climate is monsoonal with a distinct ‘dry season’ and ‘wet season’. The mean monthly rainfall ranges from 1.7 mm in the driest month to 282.6 mm in the wettest, with most rain between November and April. The mean daily minimum and maximum temperatures are 18.6°C and 28.5°C in July and 25.2°C and 33.3°C in November (Bureau of Meteorology 1997).

Vegetation is identified as monsoonal, and varying geology and landscape provide a range of habitats. The sandstone plateau habitat is dominated by Eucalyptus woodland and scrubland characterised by Acacia, Phylloides and Grevillea. Isolated monsoon rainforests of diverse flora are preserved along perennially moist gorges. A mixed open forest of Eucalyptus miniata and Eucalyptus tetrodonta dominates the lowlands, with a varied understory of Cycas, small trees, shrubs, annual grasses and herbs. Flood plains, permanent swamps and major watercourses are characterised by paperbark (Melaleuca spp.) stands. Pandanus typically forms belts along fresh watercourses. Coastal areas provide an intertidal mosaic of mangrove stands, low shrubs,
herbaceous plants and grassy plains. Fire is a frequent phenomenon and plays a key role in the development of vegetation.

**Physiography**

The three major physiographic subdivisions of MILINGIMBI (Figure 2) are the Arnhem Plateau, the Arafura Fall and the Coastal Plain (Plumb and Roberts 1992).

The Arnhem Plateau covers southwestern MILINGIMBI and is dominated by subhorizontal Palaeoproterozoic sandstone and volcanics. The flat-lying plateau is dissected by watercourses that in places form spectacular gorges and waterfalls. A near-vertical escarpment, rising in places to 200 m above sea level delineates the northwestern margin of the plateau. To the east the plateau merges gradually with adjacent lowlands.

The Arafura Fall covers the northeast quarter, the northwest and southeast corners of MILINGIMBI. The gently undulating country descends from the plateau and comprises Cainozoic sands and laterite. The underlying rock types influence the topography.

The Coastal Plain comprises areas of low elevation along the coast and extends inland along the major rivers. Coastal sand dunes (both present day and ancient) and tidal flats are present.

Drainage along the major watercourses, the Goomadeer, Liverpool, Mann, Cadell and Blyth Rivers is northward, towards the Arafura Sea. The upper reaches of these rivers flow across the Arnhem Plateau, whereas the lower reaches are tidal and form meandering rivers flowing over alluvial plains. The Goyder River in ARNHEM BAY-GOVE forms an extensive coastal plain (Muckaminnie Plains), part of which occurs in easternmost MILINGIMBI.

**Previous geoscientific investigations**

Previous geoscientific investigations in MILINGIMBI are summarised in Table 1.
Table 1 Summary of previous geoscientific investigations in MILINGIMBI

<table>
<thead>
<tr>
<th>DATE</th>
<th>COMMENTS</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1867</td>
<td>Cadell journeyed inland from near the mouth of the Liverpool River to the Arnhem Land Plateau, describing ‘pinnacled sandstone rocks’ extending “south and southwest as far as the eye could see”: Near the Tomkinson River in northern central MILINGIMBI, Cadell documented exposures of granite.</td>
<td>Cadell 1867</td>
</tr>
<tr>
<td>1884</td>
<td>D. Lindsay explored Arnhem Land from the Muckeninnic Plains to east of the Liverpool River, then upstream. He recorded ‘sandstone, slate, conglomerate and dolerite’ along the Liverpool River.</td>
<td>Lindsay 1884</td>
</tr>
<tr>
<td>1908</td>
<td>H.Y.L. Brown, the first geologist to travel the Arnhem Land coast, documented sandstone, grit, conglomerate and shale.</td>
<td>Brown 1908</td>
</tr>
<tr>
<td>1911</td>
<td>S.G. Love journeyed from Muckeninnic Plains to the Goomadee River, northwest MILINGIMBI, recording granites in the central and northwest of the map sheet and sandstone everywhere else.</td>
<td>Love 1911</td>
</tr>
<tr>
<td>1915</td>
<td>C.J. Gray examined exposed granite in northwest MILINGIMBI.</td>
<td>Gray 1915</td>
</tr>
<tr>
<td>1959</td>
<td>BMR conducted a gravity survey along the northern coast of Arnhem Land; no geological observations were made.</td>
<td>Williams and Waterlander 1959</td>
</tr>
<tr>
<td>1962</td>
<td>BMR produced a photogeological map of MILINGIMBI.</td>
<td>Ruker 1962</td>
</tr>
<tr>
<td>1965</td>
<td>Publication of the 1st edition MILINGIMBI geological map and explanatory notes by BMR, part of their Arnhem Land mapping project.</td>
<td>Rix 1965</td>
</tr>
<tr>
<td>1969-1973</td>
<td>Exploration companies actively exploring for uranium mineralisation over the Alligator Rivers Region, including northwest MILINGIMBI.</td>
<td>Whitehead 1971, Maynard 1971, Purdie 1972a,b</td>
</tr>
<tr>
<td>1971-1972</td>
<td>BMR field mapping of the Alligator Rivers Uranium Field, including northwest MILINGIMBI.</td>
<td>Needham and others 1975</td>
</tr>
<tr>
<td>1990, 1992</td>
<td>Airborne magnetic and radiometric surveys over MILINGIMBI sponsored by NTGS.</td>
<td>This report</td>
</tr>
<tr>
<td>1992</td>
<td>Publication of Geology of Arnhem Land, Northern Territory by BMR, a summary of field data collected in the 1960s.</td>
<td>Plumb and Roberts 1992</td>
</tr>
<tr>
<td>1994-1996</td>
<td>Field work in MILINGIMBI by NGMA (NTGS, AGSO) party.</td>
<td>This report</td>
</tr>
</tbody>
</table>

Terminology, map datum and definitions

The terminology used for rock types follows the scheme used for ARNHENM BAY-GOVE (Rawlings and others 1997). Siliciclastic sedimentary rocks are identified in the field by grain size and probable composition (e.g., medium-grained lithic sandstone). Further classification is by petrological studies and using Folk’s (1974) terminology (e.g., sublitharenite).

Intraclastic, carbonate rock terminology is based on grain size and composition. Dolomitite is composed of mud-sized dolomite grains, dolarenite of sand-sized dolomite grains, and dolorudite of dolomite grains larger than 2 mm. The addition of ‘siliciclastic ’ refers to small (5-25%) quantities of sand- and mud-sized siliciclastic (mainly quartz) components (e.g., siliciclastic dolomitite). The siliciclastic component can be specifically referred to by grain size range as ‘muddy’ or ‘sandy’ (e.g., muddy dolomitite). Dolostone is a general term for a rock composed mainly of the mineral dolomite.

Definitions and classifications of volcanic rock follows the IUGS (Le Maitre 1989) QAPF scheme. The compositional/textural terms basalt and dolerite are used in a non-genetic sense and do not imply an extrusive or intrusive origin. The terms flow, dyke and sill are used to infer origins. ‘Supersequence’ refers to widespread depositional packages with distinctive geometry, sedimentary facies and igneous associations. The Proterozoic geological timescale proposed by the IUGS (Plumb 1991) has been adopted.
The map datum used is AGD66 and the Australian MapGrid (AMG) zone is 53. A grid reference shown, for example, as MG123456 is equivalent to AMG 412300 E and 8645600 N, and can be found on the 1:250 000 map by referring to the letter codes for different 10 km square areas.

**REGIONAL GEOLOGICAL SETTING**

MILINGIMBI lies at the northern extent of the McArthur Basin and includes parts of the Pine Creek Inlier in the northwest and the Arafura Basin in the north and east. The geological setting with respect to adjacent map sheets is depicted in Figure 3. The major tectonic elements of the McArthur Basin are shown in Figure 4.

The oldest component, the Pine Creek Inlier, forms the geological ‘basement’ (Plumb 1979). The geology of the Pine Creek Inlier (previously Pine Creek Geosyncline) is covered in detail by Stuart-Smith and others (1993), Needham and De Ross (1990), Needham (1988), Needham and others (1988), and Needham and Stuart-Smith (1980). The inlier includes folded turbidites, metasedimentary rocks, anatetic granite and a younger granite batholith. The inferred depositional setting is an extensive intracratonic basin, fed from Archaean hinterlands within and at the margin of the North Australian Craton.

Metamorphism and deformation of the sedimentary succession took place during the 1870–1850 Ma Barramundi Orogeny (Page and Williams 1988). The orogeny involved multiple fold generations, metamorphism and emplacement of I- and S-type granites.
The McArthur Basin ‘platform cover’ onlaps and overlies the ‘basement’ units (Plumb 1979). The basin extends from the north coast of Arnhem Land into Queensland in the southeast. It is bounded by older Palaeoproterozoic ‘basement’ units of the Pine Creek Inlier in the northwest, the Murphy Inlier in the southeast and the Arnhem Inlier in the northeast. Otherwise the McArthur Basin extends beneath Neoproterozoic and Phanerozoic cover.

The McArthur Basin is a succession of essentially unmetamorphosed sedimentary and lesser volcanic rocks, deposited largely in shallow marginal marine and lacustrine settings. The most comprehensive studies of the southern basin are provided by Jackson and others (1987), Pietsch and others (1991) and Haines and others (1993), whilst the northern part, enclosed within Arnhem Land is discussed in Plumb and Roberts (1992), Rawlings and others (1997) and Haines and others (1999). Recent amendments to regional basin stratigraphy are given in Pietsch and others (1994). Interpreted correlations between the McArthur Basin and other Proterozoic basins of northern Australia are summarised in Plumb and others (1990).

The McArthur Basin is subdivided into 5 main depositional packages or supersequences (Rawlings and others 1997). The major stratigraphic subdivisions of the McArthur Basin represented on MILINGIMBI are supersequence 1 (Katherine River Group) and younger supersequence 4 (Mt Rigg Group).

The oldest (1815-1710 Ma) package, supersequence 1, includes the Donydi and Spencer Creek groups in the north, and the Groota Eylandt, Tawallah and Katherine River Groups in the eastern, southern and western parts respectively. It is a regionally extensive ‘platform’ of shallow-marine to fluvial sandstone, lesser volcanics and lutite up to 6 km thick. The package exhibits a complex regional tectonostratigraphy, containing numerous hiatuses and erosional unconformities. Rawlings and others (1997) describe in detail four informal subdivisions (1A to 1D) of the supersequence. Typically, the lower two-thirds of the package is a monotonous sandstone-flood basalt succession, which thins towards and onlaps, the ‘basement’ inliers and basin-bounding ridges (e.g., Arnhem Shelf, Murphy Inlier). The upper third comprises a more diverse package of sandstone, basalt, ryholite, dolostone and siliciclastic lutite.

Supersequence 2 (1700-1685 Ma) is the 5 km thick Parsons Range Group, composed almost entirely of shallow marine to fluvial sandstone with minor lutite and carbonate. This supersequence has only been recognised in the northern basin. In the southern basin this interval is represented by an unconformity corresponding to a period of uplift and erosion.

Supersequence 3 (1660-1620 Ma) includes the Balma and Hабgood Groups in the northern McArthur Basin and the McArthur Group in the south (Haines 1994). They are distinctive 5 km thick deposits of stromatolitic and evaporitic dolostone and fine-grained siliciclastic sedimentary rocks with minor coarser-grained sandstone and tuffaceous lutite.

Supersequence 4 (1615-1575 Ma) includes the Nathan and Mount Rigg Groups in both the southern and northern McArthur Basin. It is a succession of mainly dolomitic rocks similar to the underlying basin phase, and was deposited in a shallow water marginal marine or continental sabkha setting.

Supersequence 5, the youngest package of the McArthur Basin, is the widespread Roper Group, a cyclic deposit of fine- and coarse-grained siliciclastic rocks deposited mainly in shallow marine environments. The Roper Group has a minimum age of 1430 Ma (Rb-Sr) for diagenetic illite in the McMinn Formation (Kralik 1982). Recent U-Pb zircon dates of 1494 Ma have been obtained for the Mainoru Formation in the lower Roper Group (Page in Abbott and others, 1999). An estimate of the time range is 1500-1450 Ma.

All the McArthur Basin rocks are generally weakly deformed, except for the north-trending Walker Fault Zone and Batten Fault Zone, where they have been affected by numerous compressional and extensional events.

The ‘Post-Nathan Shortening’, related to west-northwest – east-southeast compression during the Nathan-Roper Group hiatus, resulted in north-directed thrusting, northeast- and northwest-trending faults and joint development. The subsequent ‘Post-Roper Extension’ was characterised by east-west extension, accompanied by sill and dyke emplacement. Structurally and stratigraphically controlled mafic sills and dykes preferentially intrude sandstone units of the Katherine River, Donydi, Parsons Range, Mount Rigg and Roper Groups throughout Arnhem Land (e.g. the 1324 Ma Derim Dolerite, Sweet and others 1999). A second, more extensive, deformational event, the ‘Post-Roper Inversion’, followed. This event was characterised by northeast-southwest compression, resulting in reactivation of northeast- and northwest-trending faults and north-directed thrusts.

Late Neoproterozoic to Palaeozoic successions occur in a number of basins and as scattered outliers across central and northern Australia. One such basin, the Arafura Basin, crops out in the north and east on MILINGIMBI where units of the Goulburn Group and Wessel Group were recognized. Deposition was during the late Neoproterozoic and Middle Cambrian and comprises two cycles of shallow marine sandstone, lutite and lesser carbonates. The basin thickens dramatically to the north under the Arafura Sea where it includes sequences of Mesozoic age.

Thin remnants of marine and terrestrial deposits of Cretaceous age occur throughout northern Australia. Cretaceous sediments (muddy sandstone and mudstone) form thin erosional remnants in MILINGIMBI and over much of Arnhem Land.
Figure 4 Major tectonic elements of the McArthur Basin

PINE CREEK INLIER ROCK UNITS

PALAEOPROTEROZOIC (OROSIRIAN)

Nimbuwah Complex (Bxn)

The Nimbuwah Complex is the only component of the Pine Creek Inlier exposed on MILINGIMBI. It is part of a basement complex which covers 2500 km² in the northeast of the Alligator Rivers region (Page and others 1980). First named the Nimbuwah Granite by Dunn (1962), it was later changed by Rix (1965) to Nimbuwah Complex. Needham and others (1973, 1975) defined a type locality. The Nimbuwah Complex was studied in detail by the BMR during 1971-1972 mapping of the Alligator Rivers uranium field (Needham and others 1973, Needham and others 1975, Needham and Stuart-Smith 1978, Smart and others 1974).

The Nimbuwah Complex on MILINGIMBI comprises massive to foliated granite, gneissic granite and migmatic
gneiss. Outcrop of this complex is poor. Scattered exposures occur in the centre and northwest of MILINGIMBI, forming isolated small hills and slopes that are commonly capped by Kombolgie Subgroup (Plate 1). The contacts between granitic units vary from sharp to an “intermixing” zone, and in places strong deformation has resulted in interlayering of units. Narrow granitic veins cut the complex.

Migmatitic gneiss is grey to white, medium- to coarse-grained, and characterised by anastomosing compositional partitioning. The granitic gneiss is medium-grained, foliated to banded with thin, alternating pale and dark layers.

Two main granite types were observed. Medium- to coarse-grained, white-grey to pink-grey equigranular granite varies from massive to localised zones where a weak to strong foliation is developed. Medium- to coarse-grained porphyritic granite is massive with a localised weak alignment of K-feldspar phenocrysts (Plate 2). K-feldspar (identified as microcline, Needham 1988) ranges from 1-4 cm in length and up to 1 cm in width and occurs in a fine- to medium-grained granitic groundmass.

In addition, younger, post-tectonic granites intrude the complex. These are massive, pink to grey, medium-grained equigranular biotite granites, which form isolated hills.

Granite of the Nimbuwah Complex range from monzogranite to tonalite and have anhedral to subhedral crystals. Recrystallisation is indicated by cosertal textures and minor subgrain development. The main minerals are quartz, plagioclase, K-feldspar and biotite. The more mafic phases contain hornblende, pyroxene and minor myrmekite. Secondary chlorite replaces ferromagnesian minerals and sericite replaces plagioclase. Accessory minerals include zircon, apatite and sphene (Needham 1988).

The Nimbuwah Complex is assigned an Orosirian age. A U-Pb zircon date of 1866±8 Ma for granite is thought to indicate an igneous age (Page and others 1980).

The Nimbuwah Complex has been interpreted as a structurally complex migmatite dome in which an anatectic granite core grades outward through banded gneiss, porphyroblastic granite and migmatite, lit-par-lit gneiss, a transitional zone and finally greenschist-facies rocks of the Pine Creek Inlier (Ferguson and others 1980, Needham 1982). The metamorphic facies ranges from middle- to upper-amphibolite in the migmatite zone to lower-amphibolite in the outer transitional zone.

Isotopic data indicates the Nimbuwah Complex was not formed from re-worked earlier gneisses such as the Nanambu Complex, nor is it anatectic melt from Palaeoproterozoic sediments (Page and others 1980). The Nimbuwah Complex has an I-type granite origin whereas other complexes in the Pine Creek Inlier have S- and I-type granites (Ferguson and others 1980). The granitic core initially intruded Palaeoproterozoic supracrustals and was later metamorphosed in the 1870-1850 Ma Barramundi Orogeny.

MCARTHUR BASIN STRATIGRAPHY

The stratigraphic units of the McArthur Basin in MILINGIMBI are shown on Table 2.

PALAEOPROTEROZOIC (STATHERIAN)

KATHERINE RIVER GROUP

The Katherine River Group crops out extensively in the Katherine-Darwin region and Arnhem Land (Noakes 1949, Walpole 1958, Ruker 1959). It is lithostratigraphically equivalent to the Tawallah Group of the southern McArthur Basin (Pietsch and others 1994). Walpole (1958) recognised two formations, the Edith River Volcanics and the Kombolgie Formation. Subsequently Ruker (1959) and Randel (1963) subdivided the Katherine River Group into several units. Walpole and others (1968) revised the units, which formed the basis for establishing the Plumb and Roberts (1992) defining reference. Further work has now defined three sandstone formations in the former Kombolgie Formation and revised the name to the Kombolgie Subgroup.
Kombolgie Subgroup

The Kombolgie Subgroup (revised name, see APPENDIX 1) was previously known as the Kombolgie Formation (Dunn 1962, Walpole and others 1968) and McKay Sandstone (Roberts and Plumb 1965). The existence of distinct and mappable volcanic units, developed on major erosional and weathering surfaces, enable the former Kombolgie Formation to be divided into the Mamadawerre Sandstone (Ehe), Gumarrimbang Sandstone (Ehr), and Marlgowa Sandstone (Ehl). The former Nungbalgarri Volcanic Member has been raised to formation status, and the McKay Sandstone, thought to be partly equivalent to the upper Marlgowa Sandstone, has been included in the subgroup.

The Kombolgie Subgroup is a thick siliciclastic unit that forms the base of the Katherine River Group. It forms the spectacular escarpment country of the Arnhem Land Plateau (Plate 3). The basal formation is the Mamadawerre Sandstone, overlain by the Nungbalgarri Volcanics, the Gumarrimbang Sandstone, the Giliuth Volcanic Member (a thin discontinuous layer at the top of the Gumarrimbang Sandstone) and the Marlgowa Sandstone. Schematic reference sections through parts of the sandstone formations of the Kombolgie Subgroup are shown in Figure 5.

The Kombolgie Subgroup is assigned a Palaeoproterozoic (Statherian) age, constrained by the underlying Orosirian Nimbuwal Complex affected by the 1870-1850 Ma Barramundi Orogeny, and the younger Oenpelli Dolerite (1688±13 Ma), which intrudes the subgroup.

Sandstone formations of the Kombolgie Subgroup are mainly mineralogically and texturally mature, quartz arenites. The depositional setting of the Kombolgie Subgroup has been interpreted as braided-stream fluvial (Ojakangas 1979, Needham 1982), and for the most part may represent braided streams deposits (Reineck and Singh 1980).

Mamadawerre Sandstone (Ehe)

The Mamadawerre Sandstone (new name, see APPENDIX 1), crops out extensively along the western margin of the Arnhem Land escarpment in the northwest of MILINGIMBI and unconformably overlies the Nimbuwal Complex. The formation thickness ranges from 133-176 m estimated from drill holes (KLD 001, 005-008, 021) in western MILINGIMBI (Rippert 1992). A measured section (M95/01) estimated to lie a few metres above the Nimbuwal Complex, has a thickness of 75 m before faulting disrupts the sequence (Figure 5a).

The Mamadawerre Sandstone is fine- to coarse-grained, medium- to thick-bedded, white to grey quartz arenite. Trough crossbedding dominates the lower part of the succession, with large-scale trough beds at the base. The middle to upper part of the formation is predominately planar-laminated beds with interbeds of trough and planar crossbedding. Asymmetric and symmetric ripples with straight and curved crests are abundant. Scattered rounded quartz pebbles and thin granule- to pebble-rich bands are common.

At a contact with the Nimbuwal Complex (lat. 12°15’S, long. 133°43’E), the basal beds range from cobble conglomerate with quartz and granite clasts to pebbly or granular sandstone. These units are lenticular and no major conglomerate base was observed.

Isolated outcrops of the Mamadawerre Sandstone form dome structures with gently dipping slopes (e.g. lat. 12°30’04”S, long. 133°32’26”E). The overlying Nungbalgarri Volcanics onlaps the dome structures which may represent palaeohills or regional warping prior to volcanic activity. The Oenpelli Dolerite and dolerite dykes intrude the succession.

Palaeocurrent directions in the Mamadawerre Sandstone were obtained from 10 localities, mostly from planar crossbedding, but also from trough crossbedding and asymmetrical ripple marks. District means were directed to the west and south-southwest in the northernmost outcrop.
<table>
<thead>
<tr>
<th>UNIT, WITH MAP SYMBOL</th>
<th>LITHOLOGY</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
<th>STRATIGRAPHIC RELATIONSHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOUNT RIGG GROUP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dook Creek Formation (Eoo)</td>
<td>Medium-grained quartz arenite, silty sandstone and chert breccia</td>
<td>Shallow marine setting inferred, outcrop poor</td>
<td>Contacts not observed, but upper and lower contacts probably unconformable</td>
</tr>
<tr>
<td>Bone Creek Formation</td>
<td>Medium- to coarse-grained, quartzose sandstone</td>
<td>Shallow marine setting inferred, outcrop poor</td>
<td>Contacts not observed, but lower contact probably unconformable</td>
</tr>
<tr>
<td>KATHERINE RIVER GROUP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gundii Sandstone (Pth)</td>
<td>Medium- to coarse-grained, medium-bedded, lithic and feldspathic sandstone, local pebble to boulder conglomerate; minor mudstones and ferruginous mafic igneous rocks and porphyritic rhyolite</td>
<td>Shallow marine, aeolian dune systems, fluvial, and probable subaerial volcanic activity</td>
<td>Both upper and lower contacts are unconformities</td>
</tr>
<tr>
<td>McCaw Formation (Pha)</td>
<td>Fine-grained, lithic and feldspathic sandstone, medium- to thick-bedded, massive, planar laminated and trough crossbedded. Minor glauconitic horizons and mudstone</td>
<td>Shallow marine shelf</td>
<td>Contacts not observed. Lower contact probably conformable</td>
</tr>
<tr>
<td>Shadforth Sandstone (Pbs)</td>
<td>Medium- to coarse-grained, medium- to thickly bedded, trough and tabular crossbedded, quartz arenite</td>
<td>Fluvial, to probable shallow marine conditions at the top</td>
<td>Lower contact probably unconformable</td>
</tr>
<tr>
<td>Cottee Formation (Phc)</td>
<td>Hemispherical stromatolitic bioherms, interbedded mudstone, dolostone, and fine- to medium-grained sandstone. (Lower part of formation only present)</td>
<td>Shallow marine, often above wave base; bioherms grew in at least 6 m of water</td>
<td>Contacts are not observed. Lower contact conformable on Marlgowa Sandstone and McKay Sandstone</td>
</tr>
<tr>
<td>McKay Sandstone (Phm)</td>
<td>Fine- to medium-grained, thin- to medium-bedded, trough crossbedded, quartz arenite, lithic and ferruginous sandstone</td>
<td>Shallow tidal marine</td>
<td>Lower contact conformable and gradational. Probably laterally equivalent to ferruginous units in the Marlgowa Sandstone</td>
</tr>
<tr>
<td>KOMBOLGIE SUBGROUP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marlgowa Sandstone (Ehi)</td>
<td>Fine-grained to granular, thick- to very thick-bedded, dominantly trough crossbedded, planar crossbedded, white, quartz arenite; fine- to medium-grained, thin- to medium-bedded and trough crossbedded, ferruginous sandstone interbeds</td>
<td>Braided fluvial and shallow tidal marine environments</td>
<td>Probably conformable lower contact</td>
</tr>
<tr>
<td>Gilnuth Volcanic Member (Ehrg)</td>
<td>Laterite and saprolite, possibly after volcanic rocks. Basalt, tuff and siltstone in adjoining regions</td>
<td>Extrusive volcanism</td>
<td>Probably conformable lower contact</td>
</tr>
<tr>
<td>Gumarrirbang Sandstone (Ehr)</td>
<td>Fine- to very coarse-grained, medium- to thick-bedded quartz arenite, dominantly planar laminated, trough crossbedded</td>
<td>Distal braided fluvial system; aeolian environment at the top</td>
<td>Conformable lower contact</td>
</tr>
<tr>
<td>Nungbalgarri Volcanics (Elh)</td>
<td>Vesicular and amygdaloidal basalt</td>
<td>Extrusive volcanism</td>
<td>Conformable lower contact</td>
</tr>
<tr>
<td>Manadawerre Sandstone (Ehe)</td>
<td>Fine- to coarse-grained, medium- to thick-bedded quartz arenite, planar crossbedded, trough crossbedded and minor planar laminated</td>
<td>Distal braided fluvial system; aeolian environment at the top</td>
<td>Unconformably overlies the Nimbuwhak Complex</td>
</tr>
</tbody>
</table>

areas (8 localities), and southerly in the vicinity of the headwaters of the Goomadee River.

Near the western edge of MILINGIMBI (lat. 12°25'32"S, long. 133°36'53"E), large subcircular depressions in a distinctive "honeycomb" pattern (Plate 4) occur on a surface of the Manadawerre Sandstone, apparently at the base of the Nungbalgarri Volcanics. The depressions are the northeastern-most occurrence of an extensive 200 km-long surface bearing such structures in adjacent ALLIGATOR RIVER and MOUNT EVELYN, where the features have been described by Needham (1978) and Nott and Ryan (1996).
The structures are up to 300 m in diameter and 10 m in depth. Sandstone beds dip radially inwards from the rims, except on the southeastern sides, where they dip outwards to the southeast (Plate 5). There are two general bedding trends, northeast and northwest, with dips of 9-28° towards the centres of the depressions. The centres of the depressions have dark sandy soil with some laterite pebbles.

Needham (1978) interpreted the structures as giant load casts formed by the loading of basalt of the Nungbalgarri Volcanics onto water-saturated sand. However, as pointed out by Nott and Ryan (1996), the "hydroplastic deformation" reported by Needham is not convolute bedding, and basalt is not everywhere present overlying the structures. Approximately 15 km northwest of Myra Falls in Alligator River, Nott and Ryan (1996) found the circular structures developed 20 m apart on Gumarrinbang Sandstone surfaces. Near the headwaters of Jim Jim Creek one such surface occurs above the top of Nungbalgarri Volcanics; elsewhere the structures occur at the base of the volcanics, or where volcanics are absent from the succession.

Nott and Ryan (1996) interpreted the depressions as giant laminate current ripples, modified by the effects of sandstone dissolution by tropical meteoric waters. They envisaged these ripples as forming in a Proterozoic braided to anastomosing stream system, draining to the southeast, and subjected to rare, high-magnitude flood events or possibly an increase in stream gradient.

Nott and Ryan (1996) and Needham (1978), however, did not consider an aeolian origin. The structures are primary depositional features, and the evidence marshaled by Nott and Ryan (1996) could equally well fit an origin as a field of aeolian reticulate dunes. Modern examples of such dunes occur in the Great Victoria Desert of Western Australia, and are of similar size. Reticulate dunes form in areas where winds blow from various directions during the year, although if one direction is more common than the others, it can impose directionality on otherwise non-directional structures.

This could explain the southeastern outward dips in the Proterozoic structures. These surfaces are interpreted as regional erosion surfaces on which dune fields developed and on one of which volcanics were erupted. The truncated dolerite dykes of Nott and Ryan (1996, Figure 6) represent unequivocal evidence of one such period of erosion. The emplacement of the intrusions and the volcanics around this time implies tectonic activity, which may have caused the erosional surfaces to form as a result of uplift. The possibility of the structures forming by a fluvial process is not discounted, but an aeolian origin can explain the structures, erosion, and igneous activity as related, instead of relying on an unusual event affecting a fluvial system that coincided with the erosion and igneous events.

The depositional environment for the remainder of the formation is interpreted as distal braided streams (fluvial), based on sedimentary structures and textural and compositional maturity.

**Nungbalgarri Volcanics (Pbn)**

The Nungbalgarri Volcanics is a recessive unit of mainly fine-grained equigranular basalt that forms low undulating hills. The designated reference area (but no type section) lies between the Goomadeer River and Nungbalgarri Creek (lat. 12°16'S, long. 133°47'E) in northwest MILINGIMBI as given by Plum and Roberts (1992). The unit mainly outcrops on the western Arnhem Land Plateau, where it conformably separates the Mamadawerre Sandstone from the Gumarrinbang Sandstone.

Minor exposures occur in central MILINGIMBI, where small isolated outcrops of volcanics (interpreted as the Nungbalgarri Volcanics) occur above a 3 m thick basal pebble-cobble conglomerate of the Mamadawerre Sandstone that rests on the Nimbuwah Complex. The Nungbalgarri Volcanics was not observed further east of here. The underlying conglomerate surface shows plying of grooves/ striations and small pressure ridges, attributed to basal flow scraping the surface (Plate 6). Overlying the Nungbalgarri Volcanics at this location is pebble-cobble conglomerate and
Figure 5 Schematic reference sections through parts of the sandstone formations of the Kombolgie Subgroup. Sections are incomplete due to the lack of outcrop and/or faulting. A partial reference section of the Gumarrinbang Sandstone measured on MOUNT MARUMBA is included for comparison.

(a) Lower part of the Mamadawerre Sandstone (M95/01, from lat. 12°15'49"S, long. 133°43'34"E, to a fault zone at lat. 12°15'34"S, long.133°43'29"E).

(b) Upper part of the Gumarrinbang Sandstone (AB/02, from lat. 13°11'17"S, long. 133°31'02"E, to lat. 13°11'41"S, long. 133°30'45"E).

(c) The base of the Marlgow Sandstone (M95/02 lat. 12°29'52"S, long. 133°47'41"E, to lat. 12°30'03"S, long. 133°47'42"E).
Plate 4  An aerial view of the circular depressions formed on the upper surface of the Mamadawerre Sandstone (GR LG310285). The diameter of depressions is approximately 300 m

Plate 5  Internal bedding features of the circular depressions, Mamadawerre Sandstone (GR LG310285). Barry Pietsch is the human scale

Plate 6  Flow striations on the upper surface of the Mamadawerre Sandstone is attributed to the Nungbulgarri Volcanics (GR MG079132)
coarse-grained sandstone of the Gumarrinbang Sandstone, suggesting a localised erosion surface.

A complete 92.5 m type section of the Nungalgarri Volcanics was measured from the underlying Mamadawerre Sandstone exposed in a creek (M95/05, lat. 12°32’5 S long. 133°36’E) to the Gumarrinbang Sandstone (APPENDIX 1). The thickness of the Nungalgarri Volcanics in the reference area of Plumb and Roberts (1992) is 60 m. From drillholes in western MILINGIMBI a thickness of 86 to 128 m is recorded (KLD 005-008, 019; Rippert 1992).

The Nungalgarri Volcanics in central MILINGIMBI is characterised by strong anastomosing subhorizontal foliation/banding (Plate 7). This fabric may be generated by shearing and stretching during flow of the basal portion of the unit. Quartz ‘phenocrysts’ (?relic quartz pebbles) wrapped by the fabric suggest fragments of the Mamadawerre Sandstone was incorporated in the base of the Nungalgarri Volcanics.

Individual flows have a massive non-vesicular base and vesicular and/or amygdaloidal (commonly infilled with celadonite) upper margin. One drill hole (KLD019) encountered four flows in a 91 m section ranging in thickness of 10 to 53 m (Rippert 1992). The type section contains a 10 m zone of columnar jointing, as well as narrow zones of horizontal “cleavage” that forms disc platelets.

In thin section, the Nungalgarri Volcanics is hiatal, with fine-grained bladed plagioclase, clinopyroxene, minor quartz, and abundant bladed opaques including magnetite, hematite and pyrite (Needham 1988). In the samples examined, Needham (1988) described clinopyroxene up to 3 mm, however in the current study clinopyroxene was <1 mm and replaced by carbonate. The microcrystalline matrix is altered to chlorite, sercite and carbonate.

The occurrence of flow grooves/striations on the surface of the underlying sediments and the lack of hyaloclastites indicate the flows were extrusive, subaerial basalt. Needham and Stuart-Smith (1978) observed pillow structures, which suggests a localised submarine extrusion. The lack of volcanics further east implies the volcanics onlapped the basement high but did not flow over it.

A Rb-Sr total rock age of 1648±29 Ma is given for a sample taken from near Gudjebbinj (Page and others 1980, AGSO 1997). However, this age is reset by alteration, as the contained plagioclase is albite (L. Wyborn, pers. comm.). The Nungalgarri Volcanics is assigned Statherian age based on age constraints on equivalent units and the formation’s position in the Katherine River Group. The Hickerton Rhyolite on Groote Eylandt occurs below the Bartalumba Basalt (equivalent to the Nungalgarri Volcanics; Pietsch and others 1997) and has a U-Pb age of 1814±8 Ma. The West Branch Volcanics, at the top of the Katherine River Group, has SHRIMP U-Pb ages of 1712-1705 Ma (Kruse and others 1994). Therefore the age of the Nungalgarri Volcanics is constrained between 1814 and 1712 Ma.

**Gumarrinbang Sandstone (Bhr)**

The Gumarrinbang Sandstone (new name, see APPENDIX 1) outcrops in southwestern and western MILINGIMBI and is about 125 m thick. A measured section in MOUNT MARUMBA shows 60 m of stratigraphy at the top of the unit (Figure 5). The Gumarrinbang Sandstone conformably overlies the Nungalgarri Volcanics and is conformably overlain by the Marlgowa Sandstone. In central MILINGIMBI the Gumarrinbang Sandstone overies the Nimbuluw Complex and the underlying Mamadawerre Sandstone is absent. The Gilruth Volcanic Member is the upper most unit of the Gumarrinbang Sandstone.

The Gumarrinbang Sandstone is mainly fine- to medium-grained, medium- to thick-beded, pink-grey to white quartz arenite. Coarse-grained to pebbly bands are common and there are minor pebble conglomerates. The basal bed in central MILINGIMBI is pebble-cobble conglomerate, with clasts of quartz, minor sandstone and rare granite. Internal stratification is dominantly planar.

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*Plate 7* Basal portion of the Nungalgarri Volcanics characterised by strong anastomosing “flow” foliation (GR MC073124). Pen is 12 cm.
lamination. Planar crossbedding (some with scoured bases) and massive bedding are common. Minor large-scale, low-angle trough crossbeds were also observed. Graded beds with granular bases fine upward to fine- to medium-grained quartz arenite. Ripples are asymmetric with 3-4 cm wavelengths and straight crests, asymmetric with wavy and bifurcated crests and 6-8 cm wavelengths, or symmetric with straight and curved crests and wavelengths of 4-7 cm.

The palaeodrainage directions, obtained from crossbeds at 12 localities scattered over the region, were fairly consistently to the south. The strong westerly direction noted in several northern outcrops of the Mamadawerre Sandstone was not evident here. This is perhaps because the two units occur in different areas, as there is no difference in the palaeocurrent directions where the two formations occur close together in the headwaters of the Goomadeer River.

Similar to the Mamadawerre Sandstone, the Gumarrinbang Sandstone was deposited in a distal braided stream environment.

**Gilruth Volcanic Member (2hrg)**

Smart and others (1974) first documented the Gilruth Volcanic Member as a lateritised surface observed at the headwaters of the Goomadeer River and South Alligator River area. Needham and Stuart-Smith (1978) defined the Gilruth Volcanic Member and described it as a thin 5 m thick band of tuffaceous siltstone, tuff, banded jasper and amygdaoidal and vesicular basalt. The type locality is in ALLIGATOR RIVER, lat. 12°52'S and long. 133°18' E. The member is assigned to the top of the Gumarrinbang Sandstone.

No outcrop was observed on MILINGIMBI, however the recessive unit forms a distinct narrow zone, clearly visible on airphotos, of reddish laterite and saprolite rubble on a topographic bench of Gumarrinbang Sandstone. The Gilruth Volcanic Member corresponds to a distinct, narrow, high uranium and thorium pattern on the radiometric image and therefore is an excellent marker unit, traceable across MILINGIMBI.

The member is conformable within the succession, separating the underlying Gumarrinbang Sandstone from the overlying Marlowa Sandstone. It is assumed to be a subaerial volcanic flow and tuff sequence.

South of the headwaters of the Goomadeer River, the Gilruth Volcanic Member preserves northeast-trending linear dunes on the sandstone substrate. The base of the member, or its correlational level, is a regional surface interpreted as a sequence boundary. A pattern of rectilinear dune structures (Plate 8) is developed over part of this surface, extending almost 100 km in MILINGIMBI and adjacent ALLIGATOR RIVER, and locally further south in MOUNT EVELYN (Needham 1978). Where dune structures were examined in detail in southwest MILINGIMBI, there was no trace of possible overlying volcanics. The structures have a strongly consistent 035-045° orientation in MILINGIMBI, but elsewhere range to 060° - a very small variation in orientation over a vast area. Wavelengths are about 70-80 m and the heights of the crests above the troughs vary from 2.1-3.5 m. The areas between ridges are occupied by sandy soil.

Outcrops of the crests display interfering sets of crossbedding, commonly dipping away from the crest at various angles up to 31°, similar in style to that found in modern seif dunes by McKee and Tibbitts (1964). The crossbedding has a bimodal distribution, with a bias towards northeast. One ridge crest consists of antiformal bedding, concordant with the outer surface, and shows a smooth dip reversal at the axis (Plate 9). The typical rock type is medium-grained, well-sorted, quartz arenite.

The environment that formed the straight dunes is unclear. A fluvial interpretation is considered unlikely - the proposed origin is seif dunes advancing across an equilibrum surface. The ridges display the features of seif dunes, which commonly occur over very large areas with consistent orientations. Crossbedding suggests an average paleowind direction.

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**Plate 8 Aerial view of linear dunes on the upper surface of the Gumarrinbang Sandstone (GR LF453918). Wavelengths of the dunes are about 60 m.**
towards the northeast. Preservation of self dunes in the geological record is unusual (Selley 1985), and provides paleogeographic data for the period. The presence of the Gilruth Volcanic Member on the same surface in adjacent map areas suggests that the igneous activity and formation of the erosion surface were possibly related to the same tectonic event.

**Marlgowa Sandstone (Phl)**

The Marlgowa Sandstone (new name, see APPENDIX 1), crops out in southern, central and southwestern MILINGIMBI. It conformably overlies the Gilruth Volcanic Member of the Gumarrimbang Sandstone.

The Marlgowa Sandstone consists of medium- to very coarse-grained, with some coarse-grained to pebbly bands, thick- to very thick-beded, white-grey quartz arenite. Internal stratification is predominately trough crossbedding, however planar crossbeds are also common, and there is minor massive and convolute bedding. Asymmetrical ripples have wavy crests with wavelengths of 2-3 cm.

**Ferruginous sandstone (Phlf)** interbeds occur at different levels. These units are fine- to medium-grained, thin- to medium-beded and dominated by trough crossbedding. Biotite flakes and mafic minerals are more abundant than in non-ferruginous quartz arenites.

Sections were measured through the Marlgowa Sandstone at different localities and stratigraphic levels (Figure 5). A section (M95/02) measuring 107.7 m, from the base of the formation, is an incomplete section. A measured section (M95/03) in ferruginous sandstone is most likely located in the middle of the formation, and section M95/04 is possibly located in the uppermost part of the unit (see APPENDIX 1 for locations). In MILINGIMBI the estimated total thickness is 360 m.

Palaeocurrents in non-ferruginous sandstone were directed southerly over the region and ranged from southeasterly to southwesterly between areas. Measurements, mostly from crossbedding, were obtained from 15 localities. The pattern is essentially a persistence of that in the Gumarrimbang Sandstone. The depositional environment remained braided fluvial for the most part. In contrast to the planar-beded facies of the Marlgowa equivalent in the McKay Dome in MOUNT MARUMBA, which is interpreted as a distal sandy floodplain subject to sheet flooding (Sweet and others 1999), section M95/02 consists of stacked braided migrating channels.

A change in depositional conditions occurred in the ferruginous sandstone facies. Twenty localities provided palaeocurrent data from planar and trough cross bedding. Some outcrops displayed a strong northeast-southwest bipolar distribution, and many others had palaeocurrents in one of these directions. Genuine herringbone cross bedding was found at GR LF81999. These alternating directions indicate tidal influence rather than a simple fluvial regime, and imply that relative sea level was rising, prior to the open marine conditions of the later Cottee Formation.

**McKay Sandstone (Phm)**

The McKay Sandstone forms a northeast trending unit that extends from MOUNT MARUMBA into southern MILINGIMBI. The unit is defined in MOUNT MARUMBA in the McKay Hills (lat. 13°12'S, long. 133°58'E; Plumb and Roberts 1992, Sweet and others 1999). The McKay Sandstone is similar to the ferruginous facies of the upper Marlgowa Sandstone.

In MOUNT MARUMBA the McKay Sandstone conformably overlies the Marlgowa Sandstone with an apparently transitional contact, commonly recognised by the contact of distinct white and red sandstones. However, because the ferruginous units are not continuous and contacts are obscured by poor exposure and structural complications, the relationship between the two units in MILINGIMBI is uncertain.
The upper contact of the McKay Sandstone with the Cottee Formation was not observed in MILINGIMBI due to poor outcrop.

The McKay Sandstone is fine- to medium-grained, white-grey, resistant, quartz arenite interbedded with red-brown to purple, recessive, ferruginous sandstone with a clay matrix. Ferruginisation can be uniform and pervasive, or mottled and irregular. Coarse-grained to pebbly bands and lags, and intraclastic molds are present in places. The sandstone is mainly thin- to medium-bedded, although in places thick-bedded. Low-angle, trough crossbedding is dominant, although horizontal, planar lamination is also present. Ripples vary from asymmetrical and sinuous-crested with 3-7 cm wavelengths to symmetrical with branching crests and 3-5 cm wavelengths.

The depositional environment appears to be shallow tidal marine, similar to that of the Marlgora Sandstone ferruginous facies. The change in the Marlgora/McKay interval, from exclusively white sandstone to ferruginous sandstone interbeds, coincides with a change in depositional regime from fluvial to tidal and may imply a causal relation. Marine conditions may have formed glauconite, as in parts of the McKay Sandstone in KATHERINE (Kruse and others 1994), which weathers to yield ferruginous cement.

**Cottee Formation (Pbc)**

The Cottee Formation is a poorly exposed recessive unit and is restricted to a few areas in southern MILINGIMBI. The general reference area is the McKay Hills (lat. 13°12′30″S, long. 133°58′E; Plumb and Roberts 1992). In MILINGIMBI the Cottee Formation is characterised by large hemispherical bioherms, carbonate, sandstone and mudstone. The basal contact, although not exposed, appears to be a sharp change from higher energy McKay Sandstone and Marlgora Sandstone to low energy mudstone, sandstone and dolostone.

In MOUNT MARUMBA, the Cottee Formation was subdivided into three lithologically distinct units (Sweet and others 1999). Only the lowest of these is preserved in MILINGIMBI and consists of basal, recessive, maroon mudstone interbedded with thinly-bedded dolostone and fine- to medium-grained sandstone. The sandstone includes dolomitic, ferruginous, feldspathic and glauconitic varieties. Overlying is a resistant bioherm zone, containing large hemispherical stromatolite domes ranging in diameter from 5-8 m and in height from 2-6 m. The stromatolitic forms are columnar, domal and planar microbial laminar. Inter-bioherm facies consist of thin- to medium-bedded dolostone interbedded with mudstone.

Plumb and Roberts (1992) estimated the thickness for the lower unit in MOUNT MARUMBA at 250 m. In MILINGIMBI, the lowest unit of the Cottee Formation is overlain directly by the Shadforth Sandstone. The middle and upper units present to the south are not preserved here, suggesting that erosion removed at least 120 m of sediments prior to deposition of the Shadforth Sandstone. This supports the interpretation of a sequence boundary at the base of the Shadforth Sandstone in MOUNT MARUMBA (Sweet and others 1999).

The depositional environment was shallow marine, often above wave base. Bioherms grew in at least 2-6 m of water.

**Shadforth Sandstone (Psh)**

The Shadforth Sandstone forms ridges and plateaus in southern MILINGIMBI. A 40 m thickness was measured to the south in the type section in MOUNT MARUMBA (Sweet and others 1999).

The Shadforth Sandstone is fine- to medium-grained, medium- to thick-bedded, grey-white to cream-orange, quartz arenite with some coarse sand to granular bands. Some beds in the upper part of the formation have a minor lithic component. Tabular crossbeds and low-angle trough crossbeds (including large-scale troughs) are common, as well as horizontal planar laminations of alternating finer and coarser material. Ripples are asymmetric with branching sinuous crests and wavelengths of 3-5 cm. Rare bevelled ripples occur. The fine-grained sandstones probably correlate with the Bonanza Creek Formation in MOUNT MARUMBA (Sweet and others 1999).

The Shadforth Sandstone unconformably overlies the Cottee Formation. The depositional environment for medium- to coarse-grained quartz arenite is interpreted as braided fluvial, whereas that for at least some fine-grained sandstone portions is likely to be marine, similar to the Bonanza Creek Formation in MOUNT MARUMBA.

**McCaw Formation (Pba)**

The McCaw Formation is poorly exposed in MILINGIMBI: only two outcrops were observed. The reference area is the McKay Hills in MOUNT MARUMBA (lat. 13°22′S, long. 134°03′E; Plumb and Roberts 1992). The McCaw Formation, described in detail in MOUNT MARUMBA, has a thickness of 150-400 m (Sweet and others 1999). The contact with the underlying Shadforth Sandstone is poorly exposed but may be conformable.

In MILINGIMBI the rocks are fine-grained, medium-bedded sandstone, commonly massive and crossbedded, with minor glauconite horizons and flat intraclastic molds. These units probably correlate with the basal beds in MOUNT MARUMBA, but the higher stratigraphic levels and mafic intrusions were not observed in MILINGIMBI.

A marine shelf setting is the interpreted depositional environment, consistent with the presence of glauconite and dolostones in the formation throughout its regional extent.

**Gundi Sandstone (Pgh)**

Kruse and others (1994) redefined the Gundi Sandstone on KATHERINE. Previously the unit was referred to as the Gundi Creek Greywacke Member (Ruker 1959) or Gundi Greywacke Member (Randall 1963). Walpole and others
(1968) defined the unit as a formation, the Gundi Greywacke. A 130 m thick type section was defined by Kruse and others (1994) in KATHERINE, the base of the section at lat. 14°13'S, long. 133°07'E. In MOUNT MARUMBA the thickness is 150-200 m, and in some areas up to 500 m (Sweet and others 1999).

The unit forms hills in southeastern MILINGIMBI, extending to MOUNT MARUMBA where it outcrops more extensively. Unlike the uniform unit documented on KATHERINE, the Gundi Sandstone on MILINGIMBI and MOUNT MARUMBA is a diverse unit comprising sandstone, conglomerate, minor mudstone, and mafic and felsic igneous units.

The Gundi Sandstone in MILINGIMBI appears to unconformably overlie the McCaw Formation, although variations in dip between the two formations may be the result of structural complications. The presence of Gundi Sandstone adjacent to the Kombolgie Subgroup (Marlguwa Sandstone) to the east is consistent with an erosional sequence boundary at the Gundi Sandstone base. An apparently unconformable base is noted in KATHERINE (Kruse and others 1994). The upper contact is not observed in MILINGIMBI, but is a regional unconformity below the Mount Rigg Group in MOUNT MARUMBA (Sweet and others 1999).

The basal unit comprises medium- to coarse-grained, medium- to thick-bedded, pink lithic and feldspathic sandstone with a mud matrix. Beds are predominantly trough crossbedded and both asymmetric and symmetric ripples are common. Thin interbeds of red-orange, dolomitic mudstone, mud partings and minor granular to cobble conglomerates occur in the sandstone.

At the top of the basal unit, interbedded ferruginous, maroon to red-brown, "shaly" layers are interpreted as altered basalt. These thin, fine-grained units are massive with a speckled appearance due to clay minerals after feldspar. In MOUNT MARUMBA, lineations and grooves on the upper surface of underlyng sandstone beds suggest that the speckled rock type may represent lava flows. Peperites and volcanoclastics have also been recorded.

The middle part of the Gundi Sandstone is mainly red-pink, medium-grained, medium- to thick-bedded, lithic and feldspathic sandstone with a matrix of clay and minor mafic minerals. The beds are trough- and tabular crossbedded, and have planar laminations. Coarse-grained and granular sands form individual thin layers, and some pebble lags are present. Ladder-style, interference and asymmetric ripples occur, with discontinuous and straight crests.

The upper unit is buff-grey to white, fine- to medium-grained, and medium- to thick-bedded quartz arenite. Large-scale tabular and trough crossbeds (up to 100 m across and 5-10 m in height) with steep foreset angles are characteristic. Both symmetric and asymmetric ripples are common.

Localised conglomerates, both clast- and matrix-supported, occur at various stratigraphic levels. The matrix is dominantly fine- to medium-grained sand. Rounded cobble- to boulder-sized clasts consist of lithified probable Gundi Sandstone, quartz-feldspar porphyry, quartz-rich sandstone and silicified mudstone.

Quartz-feldspar porphyry forms isolated exposures as well as clasts and is characterised by medium- to coarse-grained quartz and feldspar (weathered to clay) phenocrysts set in a fine-grained groundmass.

The depositional environment of the Gundi Sandstone is interpreted as shallow-marine, fluvial and of wind-blown origin. The large-scale crossbeds are thought to record aeolian dunes. Contemporaneous volcanism provided a source for the lithic and feldspar content of the sandstones. Conglomerate clasts were derived predominantly from fluvial reworking of the Gundi Sandstone and older Katherine River Group.

PALAEOPROTEROZOIC TO MESOPROTEROZOIC (STATHERIAN TO CALYMMIAN)

MOUNT RIGG GROUP

Walpole (1958) first described the rocks of the Mount Rigg Group based on reconnaissance of the Beswick homestead area in KATHERINE during 1951 and 1952. He recognised an unconformity at the base of the package and assigned the rocks to the middle Cambrian Daly River Group, Walpole and others (1968) defined the Mount Rigg Group in KATHERINE. Subsequent workers have revised the stratigraphy (Plumb and Roberts 1992, Kruse and others 1994, Sweet and others 1999, Abbott and others 1999).

A correlation has been made between the Mount Rigg and Nathan Groups based on lithological and metallogenic similarities (Jackson and others 1987, Plumb and others 1990). A basal sandstone overlain by stromatolitic and evaporitic units is common to both groups. A diagnostic stromatolitic unit (kussielia kussiensis) has been identified in both; and both are hosts to lead and minor copper mineralisation (the Eastern Creek deposits in the Balbirini Dolomite and the Bulman deposits in the Dook Creek Formation).

The Mount Rigg Group is a correlative of the Nathan Group which has units dated between 1615 and 1575 Ma (I.P. Sweet and R.W. Page, AGSO, pers. comm. 1999).

The Mount Rigg Group is located on the western margin of the McArthur Basin (Arnhem Shelf), largely within MOUNT MARUMBA. It unconformably overlies the Katherine River Group and is unconformably overlain by the Roper Group.

Two formations, the Bone Creek Sandstone and the Dook Creek Formation are mapped in MOUNT MARUMBA and ARNHEM BAY-GOVE. In southeastern MILINGIMBI a few isolated exposures feature rubbly, silicified carbonate rocks, chert and quartzose sandstone and are mapped as Dook Creek Formation. Poor outcrop precludes an adequate determination
of formation, thickness or depositional environment, hence the following is a summary of descriptions from ARNHEM BAY-GOVE (Rawlings and others 1997) and MOUNT MARUMBA (Sweet and others 1999).

**Bone Creek Sandstone (Don)**

The Bone Creek Sandstone extends from central KATHERINE onto MOUNT MARUMBA, where it forms a broad continuous northeast-trending belt of low ridges to the southwest and northeast of Bulman Gorge (Gapulyu). Previously known as the Bone Creek Formation (Randal 1963, Wapole and others 1968), the name was modified by Kruse and others (1994).

The Bone Creek Sandstone is predominantly thick-bedded, medium- to coarse-grained quartzose sandstone. Tabular crossbeds, trough crossbeds and ripples are common. Irregular, enterolithic chert masses and cryptalgal dolostone beds occur also.

**Dook Creek Formation (Boo)**

The widespread Dook Creek Formation is exposed in a northeast-trending zone extending through Beswick (KATHERINE) and Bulman (MOUNT MARUMBA). The nominated reference area is between the Waterhouse River and West Branch River on KATHERINE (Walpole and others 1968, lat. 14°27'S and long. 133°07'E). A definition and description is given in Plumb and Roberts (1992).

The Dook Creek Formation contains dolomitic siltstone and silty dolostone, intervals of stromatolitic and ooidal dolostone, plus lesser interbedded quartzose sandstone and siltstone (Sweet and others 1999; Abbott and others 1999). The dolomitic units are commonly extensively silicified.

**PROTEROZOIC IGNEOUS ROCKS**

**Oenpelli Dolerite (Edo)**

Mafic intrusives in the Alligator River area were mapped by Dunn (1962) and Bryan (1962). The Oenpelli Dolerite was defined and described in detail by Smart and others (1975), and petrographic and chemical studies where undertaken by Stuart-Smith and Ferguson (1978). The type locality is in MOUNT EVELYN (lat. 13°18'S, long. 132°34'E; Smart and others 1975). In MILINGIMBI the Oenpelli Dolerite forms distinctive, red-brown, hematite-rich soil and boulder outcrops in creeks and on hillsides.

The symmetrically layered sill is characterised by a central, ophitic quartz-bearing dolerite that forms the bulk of the intrusion and contains some granophyric dolerite differentiates (Stuart-Smith and Ferguson 1978). The dolerite decreases in grain size outwards to a porphyritic olivine dolerite. A microcrystalline chilled margin occurs in places at the dolerite contacts (Stuart-Smith and Ferguson 1978). In MILINGIMBI however only rocks similar to the central ophitic dolerite were observed. The differentiated sill of Stuart-Smith and Ferguson (1978) was not observed in MILINGIMBI, perhaps due to poor exposure or the unit not developing the layered sequence due to being less thick.

The Oenpelli Dolerite intrudes the Nimbuwah Complex and the Kombolgie Subgroup. Aeromagnetic data supports field observations that the Oenpelli Dolerite intrudes to the upper-most Kombolgie Subgroup. The contact relationship is usually sharp and no contact aureoles were observed in MILINGIMBI. Drill holes in southwestern MILINGIMBI show occasional chilled margins (Rippert 1992). In ALLIGATOR RIVER 50-100 m wide aureoles are recorded, which may be due to the thickness of the sill and the preservation of units.

In areas the dolerite has stepped between stratigraphic levels along faults. Faults were probable conduits for dolerite magma to intrude into the higher levels of stratigraphy. In the Goomadee River area, a prominent fault-bounded valley clearly shows the Oenpelli Dolerite has intruded along the fault. Whether fault movement accompanied the intrusion or the dolerite intruded after faulting is unresolved.

An Rb-Sr isotopic study of 16 samples in the Alligator River area determined the age of the Oenpelli Dolerite as 1688±13 Ma (Page and others 1980, AGSO 1997).

The Oenpelli Dolerite in MILINGIMBI is a 50-200 m-thick flat-lying sill. In areas the dolerite dips steeply due to intrusion along a fault. Smart and others (1975) described the Oenpelli Dolerite as an extensive series of discordant ellipsoidal bodies, similar to lopoliths, having dimensions of 30-35 km by 10-15 km and a maximum thickness of 500-1500 m. Stuart-Smith and Ferguson (1978) described the Oenpelli Dolerite as a continental tholeiitic magma. They proposed an origin due to partial melting of upper mantle material with a slow and/or intermittent rise feeding a fractionated body at a shallow crustal level.

There are two main areas of exposure in MILINGIMBI. An extensive exposure occurs in the southwest and extends into ALLIGATOR RIVER. The second scattered exposure extends from the northwest to the southeast of the mapsheet. Aeromagnetic patterns define the unit, allowing the sill to be traced across MILINGIMBI despite areas of poor exposure. The two areas are assumed to form the same sill or different sills with the same feeder. The scattered exposures in the northwest include a small body referred to as the Wurugoij Dolerite by Needham and others (1975). Its similarity in texture, mineralogy and magnetic response to the Oenpelli Dolerite suggests it is part of an extensive sill, therefore it is included as the Oenpelli Dolerite.

The dolerite is dark-grey to green-black, fine- to coarse-grained, massive and ophitic consisting largely of euhedral bladed plagioclase, up to 2-5 cm long, identified by Needham (1988) as labradorite, and tabular to bladed clinopyroxene, with interstitial granophytic quartz. The plagioclase is sericitised and the clinopyroxene is largely altered to amphibole. Minor tabular zoned plagioclase, euhedral to angular opaques and accessory apatite needles up to 2 cm
long also occur. Secondary minerals include hematite, rutile and chlorite.

**Maningkorrrr Phonolite**

A 4 km² area (lat. 12°09′S, long. 133°35′E) in the Nimbuwah Complex is intruded by numerous phonolites. Needham and others (1975) defined the dykes as the Maningkorrrr Phonolite. Their petrography and chemistry is described by Stuart-Smith and Needham (1984) and Needham (1988).

A similar unit in ALLIGATOR RIVER, the Mudginberri Phonolite, has an Rb-Sr age of 1316±40 Ma (Pages and others 1980).

The dykes are parallel-sided, 30-50 cm wide (some up to 1 m wide), steeply dipping and trend northeast and northwest. The contacts are sharp with the Nimbuwah Complex and show no obvious evidence of contact metamorphism. A thin outer part of some dykes shows a layering or foliation but the cores are massive.

The phonolite is grey-blue to grey-green, fine- to medium-grained and commonly porphyritic. Phenocrysts of alkali-feldspar (anorthoclase or albite), minor sanidine, nepheline and clinopyroxene occur in a groundmass of sanidine, anorthoclase, clinopyroxene and minor nepheline, magnetite and accessory sphene (Needham and others 1975).

**Dolerite dykes**

In southeastern MILINGIMBI, northeast and east-northeast-trending narrow magnetic lineaments, aerial photograph lineaments and major joints that coincide with magnetic anomalies are interpreted as dolerite dykes. The dykes are common but are rarely exposed.

The dykes intrude the Palaeoproterozoic Katherine River Group, but do not appear to intrude the Neoproterozoic Wessel Group. Magnetic lineaments extending into the Arafura Basin succession are probably related to the underlying Katherine River Group. Outcrops of the Wessel Group show no northeast lineaments. The relationship of the dykes with the Mount Rigg Group in MILINGIMBI is unknown due to lack of outcrop.

The age of the dykes is poorly constrained. Needham (1982) documented similar dykes in ALLIGATOR RIVER and correlated them to a 1370±30 Ma quartz dolerite. Rawlings and others (1997) interpret the dykes to have intruded along pre-existing faults and joints during an east-west extensional event ('Post-Roper Inversion'). It is possible that the dykes may correlate with the Derim Derim Dolerite that intrudes the Roper Group in URAPUNGA, ROPER RIVER and MOUNT MARUMBA which is dated at 1324 Ma (Sweet and others 1999, Abbott and others 1999).

Two sets of dykes occur in MILINGIMBI; northeast-trending dykes, mainly in the northwest, and east-northeast-trending dykes in the southeast. They may represent two separate phases of dyke emplacement or a change in the regional stress field during a continuous phase of intrusion.

It is assumed the dykes are dolerites with vertical to subvertical attitudes.

**ARAFURA BASIN STRATIGRAPHY**

The stratigraphy of the Arafura Basin is presented in Table 3. Due to poor exposure on MILINGIMBI, the following section summarises descriptions from ARNHEM BAY-GOVE (Rawlings and others 1997) and includes some observations from MILINGIMBI.

**NEOPROTEROZOIC**

**WESSEL GROUP**

The Wessel Group is a succession of shallow-marine sandstone, mudstone and minor carbonate that comprise the oldest rocks in the Arafura Basin. It is the only part of this basin, along with the Middle Cambrian Jigaimara Formation, that is exposed onshore. The Wessel Group crops out in an arcuate belt from WESSEL ISLANDS-TRUANT ISLAND, through northern and western ARNHEM BAY-GOVE, to eastern and northern MILINGIMBI and JUNCTION BAY. The Arafura Basin extends beneath the Arafura Sea to the north, where thicker successions, including the Goulburn and Arafura Groups and ungrouped rocks as young as Permian-Triassic, have been intersected in petroleum exploration wells (Bradshaw and others 1990). These wells have not penetrated to the depth of the onshore succession, with the sole exception of Arafura 1, which probably bottomed in the upper Elcho Island Formation.

In ascending stratigraphic order, the Wessel Group comprises the Buckingham Bay Sandstone, Raiwalla Shale, Marchinbar Sandstone and Elcho Island Formation. The Buckingham Bay Sandstone lies unconformably over various formations of the McArthur Basin.

The Wessel Group was originally considered to be of Neoproterozoic age after Rb-Sr and K-Ar minimum dates of 790 and 770 Ma respectively were determined for a single glaucotite from the Elcho Island Formation (McDougall and others 1965). However, when Plumb and others (1976) reported Middle Cambrian trilobites in what was considered to be the Elcho Island Formation, the age of the entire Wessel Group was reinterpreted as Cambrian. This was supported by the presence of the trace fossil *Skolithos* in the Buckingham Bay Sandstone (Plumb and others 1976). However, *Skolithos* is now known to range back into the late Neoproterozoic (Crimes 1987), and Rawlings and others (1997) considered that the structures in the Buckingham Bay Sandstone could be inorganic.

The recent discovery of the carbonaceous fossil *Chuaria* in the Raiwalla Shale on MILINGIMBI indicates a Neoproterozoic age for this formation and brings into question the age of the entire Wessel Group. The fossiliferous succession on Elcho Island was not observed during BMR mapping in the early 1960's, hence it was not considered in the original concept of the Elcho Island Formation, and the Jigaimara Formation was proposed to separate this unit from
the Wessel Group (Rawlings and others 1997). It is possible that part of the upper Wessel Group may be Early Cambrian, however the lack of any known fossils or trace fossils is more consistent with a Neoproterozoic age. Thus there is probably a significant hiatus below the Jigimara Formation, the basal contact of which is not exposed.

**Buckingham Bay Sandstone (Esh)**

The Buckingham Bay Sandstone is the basal unit of the Wessel Group. It crops out in a broad, gently dipping arc in northern MILINGIMBI and ARNHEM BAY-GOVE. Outcrop is poor and much of the surface exposure has disintegrated to sand. The Buckingham Bay Sandstone overlies various units of the McArthur Basin with a marked angular unconformity. There are no complete sections through the formation. Plumb and Roberts (1992) nominated a reference area on the northwestern side of Flinders Peninsula around the mouth of the Kurala River (around lat. 12°13'S, long. 135°53'E; GR NG940500). The formation is estimated to be about 350 m thick near the type area.

The basal unit consists of sandstone that is massive to flat-bedded, cross-bedded, medium- to coarse-grained, and medium- to thick-bedded (bedding thins upsection and in places is thin-bedded at the top). It is white to pale pink and yellowish (with local reddish iron oxide staining) and in places rippled or pebbly. It is moderately well sorted and tends to be slightly lithic. Mud clast horizons are common. The basal unconformable contact with older rocks is locally marked by a basal conglomerate or regolith breccia several metres thick that has poorly sorted angular clasts up to boulder size in a sandy matrix.

Higher in the succession, pale grey, medium-grained, thick-bedded, massive to weakly flat-bedded sandstone is interbedded with recessive, ferruginous and micaceous, thin-bedded, fine-grained sandstone and mudstone. Surface dissolution of small concretions has developed common pitted surfaces, with small voids averaging about 5 mm in diameter. In some areas red-brown, weakly ferruginous and micaceous sandstone becomes more common. It tends to be medium-grained, thick- to very thick-bedded, massive to flat-bedded or displaying large crossbeds of various types, including low-angle, trough, and symoidal (with possible tidal bundles). Near the top of the formation, the lithology tends to be more uniform, comprising medium-grained, medium- to thick-bedded sandstone, weathering from white to reddish and yellowish. **Liesegang** banding is common as are large-scale trough and tabular crossbeds.

No body fossils have been found in the Buckingham Bay Sandstone. Dunnet (1965) and Plumb and Roberts (1992) reported the presence of vertical tube-like structures, interpreted as the trace fossil *Skolithos*. This has been cited as evidence for a Cambrian age of the Wessel Group (Plumb and others 1976). Such structures were observed to be common at intervals throughout the formation. They are large, occasionally reaching 1 m in length, and tend to be closely spaced, but unlike "regular" *Skolithos* they are bent in places and are often inclined (in consistent directions) at varying angles. The angle of inclination may increase upward through the bed. Beds containing the tubes are usually massive and largely devoid of other structures. Although *Skolithos* has been recorded in late Neoproterozoic rocks ( Crimes 1987), Rawlings and others (1997) suggested that these tubes may be abiotic, related to dewatering from fluidised sand. The common massive nature of the sandstone and inclination of tubes supports the model for fluidisation and flow within the sand bed.

The interpreted depositional environment for the Buckingham Bay Sandstone is high-energy shallow marine.

**Raiwalla Shale (Psr)**

The Raiwalla Shale is a unit of interbedded mudstone and very fine- to medium-grained sandstone that overlies the Buckingham Bay Sandstone with a sharp concordant contact (the actual contact is concealed). The name was first applied by Plumb (1965) and Dunnet (1965) and later defined by Plumb and Roberts (1992) who nominated a reference area around the Woolen River in ARNHEM BAY-GOVE. Overlying deposits of Cretaceous and younger age commonly obscure the Raiwalla Shale. An accurate thickness cannot be given due to very shallow dips and poor outcrop, but it may be 1000 m thick.

The Raiwalla Shale is comprised of mudstone interbedded with fine- to medium-grained, usually thin-bedded, flaggy sandstone. Mudstone is micaceous, flat- to wavy-laminated, fissile (shaly) and typically of silt grain size. When fresh, the mudstone is khaki green to grey, but in most exposures has become reddened and ferruginised by surface weathering. Sandstone interbeds vary from mainly fine-grained (in places medium-grained) and thin- to medium-bedded, with a few parts containing thick beds. Beds typically display flat to wavy lamination and some crosslamination, and wave and current ripples are common on bed tops. When fresh, sandstone is typically grey in colour but weathers to white, yellow, brown, purple and red (some are quite ferruginised) with surface exposure. The sandstone varies from quartz-rich to lithic (siltstone fragments) and micaceous.

Carbonaceous impressions assigned to *Chuaria* have recently been collected on MILINGIMBI, indicating a Neoproterozoic age for the formation (Haines in press). The unit is correlated with the Cox Formation in the southern McArthur Basin, which overlies the Bukalara Sandstone (a Buckingham Bay Sandstone equivalent; Pietsch and others 1991). The Raiwalla Shale was probably deposited under shallow subtidal, marine shelf conditions. The base represents rapid deepening from very shallow conditions interpreted for the Buckingham Bay Sandstone. The contact is most likely a marine flooding surface. There is evidence of gradual upward shallowing through the unit, with increased storm influence in the upper half, and a transition into the shallower-water Marchinbar Sandstone.
Marchinbar Sandstone (Esm)

The Marchinbar Sandstone is an entirely sandstone succession that overlies the Raiwalla Shale. The name was first applied by Plumb (1965) and Dunnet (1965) and later defined by Plumb and Roberts (1992) who nominated a reference section on Marchinbar Island in WESSEL ISLANDS. The formation has an estimated thickness of 300 m in the vicinity of the Woolen River, ARNHEM BAY-GOVE. Outcrop is mainly restricted to places where creeks have eroded through the regional laterite capping.

The lower contact with the Raiwalla Shale is conformable and gradational. A contact observed in ARNHEM BAY-GOVE (GR NG043313), is erosional and marked by a thin granule and pebbly lag, suggesting a local disconformity.

The Marchinbar Sandstone is composed largely of clean white quartz arenite, dominantly medium-grained, but includes some fine-grained beds mainly near the base. Red, ferruginous and fine matrix-rich horizons are a minor component of the formation. Mudclasts are common near the base and decrease in abundance upwards. Most of the unit is medium-bedded, although thin- and thick-bedded horizons are also present. Horizontal lamination, trough crossbedding and wave and current ripples are all common. Rare desiccation cracks were also observed.

The Marchinbar Sandstone was considered to be Early Cambrian, and now a Neoproterozoic age is inferred on the basis of the biostratigraphic age for the underlying Raiwalla Shale (Haines in press). Sedimentary features suggest a high energy, shallow marine environment. The Marchinbar Sandstone marks the top of a shoaling cycle that begins in the lower Raiwalla Shale.

Elcho Island Formation (Ese)

The Elcho Island Formation comprises siliciclastic and minor carbonate rocks and is the youngest unit of the Wessel Group. It crops out along the coast of Elcho, Howard and Banyan Islands and in places inland. The formation was named by Plumb (1965) and Dunnet (1965) and later defined by Plumb and Roberts (1992) who nominated a reference area at the cliff outcrops on Elcho Island. It was redefined on ARNHEM BAY-GOVE (Rawlings and others 1997).

The contact with the underlying Marchinbar Sandstone is sharp and, at the only recognised location where it is well exposed (GR NG043313), erosional, having a thin granule to pebbly lag in the basal bed. There is no evidence of angular discordance or incision, but it is possible that the boundary is locally disconformable. A thickness of 650-700 m was estimated for the Woolen River area.

The sparsely exposed Elcho Island Formation is invariably highly weathered and ferruginised, mainly comprising sandstone that is fine-grained, thin- to medium-beded, friable, red-brown, purple and orange. It overlies more resistant and coarser, white sandstone on the dip slope marking the top of the Marchinbar Sandstone. Lithologies include friable sandstone, mudstone and chert. The thinly

Table 3 Stratigraphy of the Arfakor Basin on MILINGIMBI (after Rawlings and others 1997)

<table>
<thead>
<tr>
<th>UNIT, WITH MAP SYMBOL</th>
<th>LITHOLOGY</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
<th>STRATIGRAPHIC RELATIONSHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOULBURN GROUP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jigalmar Formation (Egj)</td>
<td>Chert and silicified calcareous siltstone; laminated and fossiliferous</td>
<td>Marine shelf environments</td>
<td>Base and top not exposed, probably unconformably overlies the Elcho Island Formation</td>
</tr>
<tr>
<td>WESSEL GROUP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elcho Island Formation (Ese)</td>
<td>Sandstone: fine- to coarse-grained, thin- to medium- bedded, commonly calcareous or dolomitic; minor mudstone interbeds, carbonate horizons (leached and silicified), chert breccia</td>
<td>Shallow marine with occasional exposure and evaporitic conditions</td>
<td>Base and top not exposed; probably conformable lower contact</td>
</tr>
<tr>
<td>Marchinbar Sandstone (Esm)</td>
<td>Sandstone: fine- to medium-grained, medium-bedded, planar laminated to planar crossbedded</td>
<td>Shallow water, high energy marine setting</td>
<td>Gradational lower contact</td>
</tr>
<tr>
<td>Raiwalla Shale (Esr)</td>
<td>Mudstone: grey to maroon, micaceous, interbedded with fine- to medium-grained, thin-bedded sandstone</td>
<td>Subtidal marine shelf, shallowing at top; storm-influenced intervals conditions</td>
<td>Conformable lower contact</td>
</tr>
<tr>
<td>Buckingham Bay Sandstone (Esb)</td>
<td>Sandstone: fine- to coarse-grained, medium-to thick-beded, planar crossbedded, rare mudstone interbeds</td>
<td>High energy shallow marine conditions</td>
<td>Unconformably overlies the McArthur Basin succession</td>
</tr>
</tbody>
</table>
laminated chert, sometimes containing voids after evaporite minerals, probably represents silicified carbonate. The white to yellowish mudstone probably represents the final product of leaching of silty to muddy carbonate.

Most coastal exposures consist of siliciclastic rocks, ferruginised to varying degrees. The dominant lithology is brown to dark red, thin- to thick-bedded (mostly medium-bedded), fine- to very coarse-grained sandstone with granule horizons. Some beds are glauconitic and micaceous. Sedimentary structures include trough and tabular crossbeds, wave and current ripples, current lineations and load casts.

The age of the Elcho Island Formation is poorly constrained between Neoproterozoic (lower Wessel Group) and Middle Cambrian (overlying Jigaimara Formation). As no fossils or trace fossils have been found in the lower Wessel Group, as redefined, a Neoproterozoic age seems likely. The Elcho Island Formation was deposited under shallow marine shelf conditions, which at times reached the point of exposure and desiccation. Periodic evaporative conditions are indicated by halite pseudomorphs near the base and top.

PALAEozoIC (CAMBRIAN)

GOULBURN GROUP

After Middle Cambrian trilobites were discovered in beach pebbles (in situ outcrop was later located at low tide) at Warnya Point on Elcho Island, WESSEL ISLANDS, Plumb and others (1976) concluded that the succession belonged to the Elcho Island Formation. As a result, a Cambrian age was applied to the entire Wessel Group, previously thought to be Proterozoic on limited radiometric evidence, as discussed earlier. However, new evidence that at least the lower Wessel Group is Neoproterozoic (Haines in press) prompts a reassessment of the age and stratigraphic relationships of the entire lower Arafura Basin succession.

No fossils or trace fossils have been found below the level of trilobite fauna, with the exception of possible Skolithos in the Buckingham Bay Sandstone which may be inorganic as discussed earlier. It is thus likely that units below the fossiliferous carbonates are Neoproterozoic and that the contact, which is not exposed, is a disconformity or unconformity. This is supported by evidence from offshore petroleum exploration well Arafura No. 1, which intersected a calcareous unit containing a Middle Cambrian fauna correlating with that collected on Elcho Island (Van Roye 1983; Bradshaw and others 1990). The underlying beds, from 3596 m to total depth at 3635 m, consist of interbedded sandstone and mudstone which Van Roye (1983) considered to be Neoproterozoic based on radiometric dating of contained micas. The sharp contact at 3596 m corresponded with a significant seismic reflector (Line 82AS-18 in Van Roye 1983) and might be a stratigraphic break. Elsewhere in northern Australia, similar Middle Cambrian successions unconformably overlie Proterozoic rocks, or poorly constrained units such as the Antrim Plateau Volcanics (e.g., Kruse and others 1994).

The name Goulburn Group was first proposed by Petroconsultants (1989) and published by McLennan and others (1990) and Bradshaw and others (1990). Nicoll and others (1996) extended the original concept of the Goulburn Group, including the Jigaimara Formation as its lowest unit. As defined the Goulburn Group contains the Jigaimara, Naninghura, Milingimbi and Moooroonga Formations in ascending order, and ranges in age from early Middle Cambrian to Early Ordovician. All except the basal part of the Jigaimara Formation, which crops out in ARNHEM BAY-GOVE and MILINGIMBI, are known only from petroleum exploration wells in the Arafura Sea north and northwest of the map sheet area. The Goulburn Group is inferred to lie disconformably or unconformably over the Wessel Group.

Jigaimara Formation (Egj)

The Jigaimara Formation is described in ARNHEM BAY-GOVE as a succession of fossiliferous, silicified and leached limestone and calcareous siltstone (Rawlins and others 1997). Minor exposures occur on islands near Milingimbi township, northeast MILINGIMBI. The formation overlies the predominantly clastic Elcho Island Formation. The contact is obscured but is inferred to be a disconformity or unconformity. No overlying unit is exposed on MILINGIMBI or ARNHEM BAY-GOVE. Outcrops are flat lying and only a few metres thick. However, about 200 km northwest of ARNHEM BAY-GOVE, a thickness of 370 m (between 3126 m and 3596 m) is tentatively assigned to this formation in petroleum exploration well Arafura No. 1 (Van Roye 1983). A 1128 m thick dolomite unit, with no biostratigraphic control, is assigned by Bradshaw and others (1990) to the Goulburn Group. The type area of the Jigaimara Formation is at GR NG172478 on the western tip of Banyan Island.

All outcrops are silicified and consist of white to grey-brown chert and cherty siltstone. Outcrops are all brecciated to various degrees (jigsaw-fit to chaotic) and have a siliceous matrix. Individual clasts are commonly well laminated and possible microbial laminae were also observed. Enigmatic donut-shaped structures, about 20 cm in diameter, may be of algal origin. The fossiliferous interval penetrated in Arafura No. 1, referred to above, was not cored but consists of interbedded limestone, shale and dolostone (Van Roye 1983).

Trilobite fossils (mostly fragmentary) were collected on Banyan Island (GR NG172478) and at two localities on Howard Island (GR NG398640, NG329582). Plumb and others (1976) identified seven species of trilobite as well as bradoriids, hyolithids, brachiopods and sponge spicules at the Warnya Point locality, and indicated that the fauna belong to the pre-Ptychagnostus gibbus portion of the Templetonian Stage (Middle Cambrian). The fauna is similar to that of the Beetle Creek Formation and widespread correlative units in the Georgina and Daly Basins (Plumb and others 1976).

The Jigaimara Formation was deposited in a quiet subtidal marine setting following a transgression of regional extent.
YOUNGER STRATIGRAPHIC UNITS

PRE-CRETACEOUS (AGE UNCERTAIN)

Liverpool Breccia

A circular structure 3.5 km northwest of the Liverpool River (Plate 10) at lat. 12°24'S, long. 134°03'E is a partially exhumed, eroded impact crater (Shoemaker and Shoemaker 1997). Rix (1965) initially recognised the impact crater. The geology of the crater has been documented by Guppy and others (1971) and Shoemaker and Shoemaker (1997). A brief examination of the structure was made during this mapping program.

The crater consists of a ring-shaped ridge, diameter 1.6 km, rising to about 50 m above the surrounding sandplain and breached in a number of places by streams (Plate 10). The ridge is a breccia, predominantly made of sandstone clasts. The identification of the crater material as "limestone outcrops" on the 1:100 000 Tomkinson topographic map (Sheet 5773) is incorrect; the misidentification presumably derives from the fact that many supposed meteorite craters in Arnhem Land are in fact solution-collapse karst features in carbonate rocks. The only proven impact craters in the region are Liverpool, Strangways, and Goyder craters (Haines 1996). Another structure 7 km west of Gupilyu in MOUNT MARUMBA is probably also of impact origin (Sweet and others 1999).

The rim material has been named the Liverpool Breccia (APPENDIX 1). It consists of a breccia of sandstone that was part of the ejecta from the crater (Plate 11). The breccia clasts are unsorted, and range in size from a few millimeters to 7 m. Most are angular (some subangular) and usually roughly equant, although some are elongate and slab-like. There is a subordinate matrix of coarse- to fine-grained sand. Guppy and others (1971) described 10 cm-wide zones of pulverized sandstone cutting some blocks.

The deposit has an unbedded appearance, but in near-vertical exposures crude bedding is visible in places. In the western side of the ring (GR LG955929), where a stream has cut through, two distinct layers are present in a cliff. The lower layer has an exposed thickness of 2.5 m, and is dominated by boulder-sized clasts up to 4.5 m long. The slab-like blocks lie in various orientations, including standing on end. The rock appears more compacted than the underlying bed. The upper layer contains smaller blocks on average, which nevertheless range up to about 3 m long. Shoemaker and Shoemaker (1997) mapped and described the breccia units in detail. They refer to the lower layer as an authigenic breccia and the upper layer as an allogenic breccia. The clasts in the allogenic breccia are less crushed or deformed relative to the underlying unit, suggesting the upper unit may be from higher on the crater wall and exposed to lower shock stress (Shoemaker and Shoemaker 1997).

The basal contact of the breccia with the underlying Gumarrinbang bedrock was observed on the southeast exterior side of the ring (GR LG970290), where it is an irregular surface with several metres of relief. Shoemaker and Shoemaker (1997) describe a sharp boundary between the underlying Gumarrinbang Sandstone and the authigenic breccia. The allogenic breccia has an undulating and sharp contact surface, resting on the underlying breccia and, in places, the Gumarrinbang Sandstone.

Petrographic studies of the breccia, reported by Guppy and others (1971), disclosed shock deformation features indicating shock pressure of at least 100 kb. No coesite or stishovite, however, indicative of rock shocked to the point of incipient melting, were found. Nor have the present or previous surveys found shatter cones, impact melts, or meteoritic material.

Shoemaker and Shoemaker (1997) noted that the impact structure is 6% wider in the northeast-southwest direction, the depositional basin within the crater is offset about 100 m to the northeast and the initial crater wall was shallower on the southwest side. They suggested the crater resulted from an oblique impact from the southwest.

There has been no significant erosion, probably no more than 100-200 m of the crater wall has been lost to erosion, and the original crater would be no more than 20% larger than the current diameter (Shoemaker and Shoemaker 1997).

Within the breccia ring are outcrops of undeformed sandstone that probably filled the original crater. The deposits are well-bedded, well-sorted, fine- to coarse-grained quartz arenite, with both planar lamination and trough crossbedding, resembling Kombolgie Subgroup sandstones. Beds are unaffected by impacted formation and dip gently at 5-8° towards the centre, and therefore must postdate the impact. Guppy and others (1971) interpreted the beds as Cretaceous sediments, deposited soon after crater formation. Some Cretaceous rocks in Arnhem Land do resemble the Kombolgie Subgroup bedrock from which they were derived, but so far no Cretaceous fossils (wood, marine burrows or shells) have been found in the beds within the crater. The sediments could be post-impact Palaeoproterozoic in age or may belong to the Arafura Basin succession (Shoemaker and Shoemaker 1997).

The age of the impact crater is poorly constrained. Guppy and others (1971) suggested the structure is Cretaceous. They interpreted Cretaceous sandstone in the centre of the crater, and suggested the well-preserved rim is due to rapid burial before erosion could take place. Shoemaker and Shoemaker (1997) considered that the position of the crater just beyond the Arafura Basin suggests it was probably formed on the exposed Gumarrinbang Sandstone of the Kombolgie Subgroup, before the deposition of Neoproterozoic Buckingham Bay Sandstone (Shoemaker pers. comm. 1997). The maximum age is Palaeoproterozoic, given by the age of the Gumarrinbang Sandstone which the impact formed on.
MESOZOIC (CRETACEOUS)

Cretaceous sediments (K)

Cretaceous sedimentary rocks are exposed intermittently in mesas and plateaus across much of the northern part of the Northern Territory. They form a flat-lying, largely undeformed siliciclastic coastal plain to shelf succession resting on mainly Proterozoic rocks. Cretaceous rocks are exposed as weathered outcrop on the flanks of laterite-capped ridges, in stream cuts, and as low rubbly outcrop.

Noakes (1949) gave the name Mullaman Group to Mesozoic sediments in the Katherine-Darwin region. Later workers revised the name to the Mullaman beds, used to describe all Mesozoic sediments in the northern Northern Territory (Skwarko 1966). The term ‘Mullaman beds’ became meaningless in the northeastern Northern Territory after Hughes (1978) assigned two distinct lithological units to other formations. On the basis of detailed studies by Krassay (1994), rocks of the Mullaman beds along the western and southwestern margins of the Gulf of Carpentaria have been subdivided into the Walker River and Yirrkala Formations.

Skwarko (1966) provided the first detailed palaeontological work on the Mullaman beds, which he divided into the ‘Inland Belt’ and ‘Coastal Belt’ on the basis of their geographical position and fossil assemblages.

Recently, Krassay (1994) developed a new informal stratigraphic nomenclature that supersedes that of Skwarko (1966). The Cretaceous succession was subdivided into 24 facies (Krassay unpublished data), which in turn are grouped vertically into 8 facies successions. The only other work has been isolated studies of local areas as part of exploration mapping and shallow drilling undertaken sporadically by companies over the past two decades.

Regional studies (Frakes and Krassay 1992, Krassay 1994, Krassay unpublished data) provide evidence for an Aptian to Cenomanian age for these rocks on the basis of microfaunal analyses and associated regional stratigraphic correlations.
In MILINGIMBI, the Cretaceous rocks form resistant mesa-like outcrops in the east and north, and minor scattered exposures in the southern areas. The exposure of Cretaceous rocks is insufficient to correlate with formations of Krassay (1994), hence they are referred to as undifferentiated Cretaceous. They consist of pebbly sandstone with interbedded sandstone and siltstone. Rocks are a red, orange or mottled colour due to staining by iron and manganese oxides. Sandstones include silicified quartz arenite; silty, predominately fine- to medium-grained sandstone with minor pebble beds; and medium-bedded, massive sandstones with planar lamination and trough crossbedding. Siltstones are massive to planar-laminated and commonly bioturbated.

Most Cretaceous exposures have a thin ferruginised capping. The outcrops are flat-lying, but in ARNHEM BAY-GOVE dips up to 35° are recorded locally, suggesting minor tectonism since the Cretaceous (Rawlings and others 1997).

The Cretaceous rocks unconformably overlie the Nimbuwah Complex, Katherine River Group and Wessel Group. The depositional environment is interpreted as a coastal plain to marine shelf.

CAINOZOIC

Cainozoic deposits cover more than half the land area of MILINGIMBI. Inland deposits, of mainly sandy to gravelly soil and laterite are generally up to a few metres thick, but some coastal deposits are substantially thicker. These deposits have been subdivided into units that can be identified on aerial photographs. In southwestern MILINGIMBI, incised river meanders in the Kombolgie Subgroup have associated Cainozoic and Quaternary deposits.

Palaeogene-Neogene sediments (Cz, CzI)

Undifferentiated Cainozoic deposits (Cz) include predominately sandy to gravelly skeletal soils and ferruginous detritus. Pisolithic and massive ferricrete and laterite (CzI), formed under conditions of intense chemical weathering, are widespread. These deposits are well developed over extensive areas where topography is flat-lying to undulating and are probably mainly underlain by Cretaceous sedimentary rocks.

Quaternary sediments (Qr, Qu, Qc, Qb)

Active and recently active cheniers (Qr) comprised of shelly sand are scattered along the northern and eastern coastline.

Alluvial gravel, sand, silt and clay (Qu) are found in active channels, flood plains and outwash sheet deposits around ranges. Fine-grained deposits formed in local depressions are included in this category. Areas of Qu flanking major rivers and creeks fan laterally towards the coastal zone where they grade into coastal sediments.

Active deposits forming on intertidal and supratidal flats and in tidal channels (Qc) cover extensive areas near the coast and extend tens of kilometres inland, surrounding the tidal reaches of major rivers. These deposits are largely unvegetated, apart from stands of mangroves adjacent to streams and the coast. They consist of unconsolidated grey, clayey, silty and sandy sediments with common shell debris. A thin salt dusting forms on the surface of supratidal flats when not inundated. Slightly elevated grassy black soil plains (Qb), interpreted as old coastal deposits stranded by slow regression of the coastline, are common immediately inland from Qc deposits. Some of these areas are slowly accreting by the addition of floodplain silts.

GEOPHYSICS

MILINGIMBI is covered by airborne magnetic and radiometric surveys as part of the regional McArthur Basin airborne geophysical survey. The surveys were flown by contractors for the NTGS during 1990 and 1992, as 'Mitchell Ranges' (Kevron Geophysics Pty Ltd) and 'Milingimbi' (Geoterrex Pty Ltd). East-west flight lines were spaced at 500 m with a nominal terrain clearance of 100 m. Data was processed by the contractors and is available in digital and hardcopy form from NTGS as total magnetic intensity (TFI), contour maps, flight path maps, stacked profiles and radiometric datasets (K, Th, U and total count). The datasets covering Arnhem Land have been microwaved, stitched, gridded into a single dataset and TMI reduced to pole by AGSO.

Radiometrics

A regional radiometric image of MILINGIMBI is shown in Figure 6. A low concentration of radioactive elements (dark pattern) dominates the radiometric image of MILINGIMBI. The low signatures are mainly related to Cainozoic deposits which conceal the underlying bedrock signature in parts of northeast MILINGIMBI, and the Kombolgie Subgroup in southwest MILINGIMBI. Localised high K signatures reflect the feldspar, mica and clay content characteristic of granite, volcanics and certain sedimentary units.

The Cainozoic sediments can be differentiated by their variation in radiometric elements. U and Th are concentrated in laterite and residual sand deposits, shown on the image by green, blue and magenta hues. The active intertidal and supratidal sediments have a higher K signature (red hue) than the older vegetated coastal 'black soil' plains. Coastal dunes and transported sand lack radiometric elements, indicated by the dark pattern. Active streams have a dark pattern or reflect the source material. The Cretaceous sediments and residual sand developed on the Cretaceous have relatively high Th.

The Kombolgie Subgroup, although dominated by a dark pattern due to low K, U and Th in the clean quartz arenite units, has areas with a minor K content. A thin distinct K/U signal corresponds to the very thin Gilruth Volcanic Member and can be traced across MILINGIMBI. Proterozoic linear dunes are shown by a 'blue' U signature. In northwest MILINGIMBI, a strong K signature indicates the Nungbalgarri Volcanics and a strong U signature is due to
laterite developed on volcanics. Subtle changes in the K signature distinguish the Oenpelli Dolerite from the Nungbaltgarri Volcanics.

In central and northeast MILINGIMBI, the Nimbuwah Complex is characterised by K-rich minerals. Active alluvial streams in the northeast reflect the Nimbuwah Complex as the source material. Sands developed on the Nimbuwah Complex are characterised by a mottled texture and reflect the K-rich character of underlying granites. A distinct K/U signature associated with the Nimbuwah Complex in central MILINGIMBI is the Oenpelli Dolerite.

The Arafura Basin succession is obscured by Cainozoic cover. The Elcho Island Formation has no characteristic signature. The Raiwalla Shale has a weak K signature. The Marchinbar Sandstone, and to a lesser extent the Buckingham Bay Sandstone have a characteristic dark signature indicating very low K, U and Th contents.

Magnetic

A total magnetic intensity image of MILINGIMBI is shown in Figure 7. The MILINGIMBI image is separated into two main areas. The northeastern area has a lower magnetic intensity and frequency pattern than the southwestern area. The change in magnetic frequency defines the extent of the Arafura Basin in the northeast.

Southwestern MILINGIMBI, dominated by the Kombolgie Subgroup, is characterised by strong linear features and its generally higher magnetic signature may be related to the effect of igneous units. An area of lower magnetic frequency corresponds to the McKay Sandstone and the ferruginous units of the Marlgowa Sandstone. The prominent positive and negative narrow linear features are dolerite dykes. The dykes are vertical to subvertical and trend mainly northeast in the west, as compared to east-northeast in the southeast. North- and northwest-trending linear structures are interpreted as major faults probably infilled by dolerite dykes. The Oenpelli Dolerite contact is clearly indicated by a magnetic edge effect. Distinct changes in magnetic intensity may reflect areas where the Oenpelli Dolerite intruded along faults and formed subvertical to vertical dykes. The Nimbuwah Complex has lower magnetic intensity and a higher frequency pattern than the Kombolgie Subgroup.

Sediments of the Arafura Basin obscure the short wavelength, near-surface magnetic features prevalent in the underlying McArthur Basin units, which are exposed around the southern basin margin. Linear features evident in the basin area represent faults and dykes in the underlying units, some of which are continuous with those exposed in the marginal area. Isolated circular anomalies of high magnetic intensity in the northeast are interpreted as vertical pipe-like structures. A faintly dappled higher frequency pattern forms an arc across the northeast and corresponds to the Marchinbar Sandstone.

Figure 6 Total count radiometric image of MILINGIMBI
Gravity

Gravity surveys over Arnhem Land were collected at wide spacing by the Bureau of Mineral Resources (now AGSO) as part of the Australian national gravity database. No detailed interpretation is attempted due to the widely spaced data. Interpretation of the data is restricted to broad regional effects and relative gravity anomaly relationships.

On MILINGIMBI, a positive Bouguer anomaly in the northwest forms a north- to northeast-trending 'axis' that corresponds to the Nimbuwah Complex. The gravity features are consistent with the interpretation of a central basement "high" forming a paleoaridge with basins either side. Also, in the northwest, the basement is close to the surface giving a positive Bouguer anomaly. Localised gravity lows can be attributed to basins filled with The Kombolgie Subgroup.

GEOCHEMISTRY

Geochemical analyses of the Nimbuwah Complex, Oenpelli Dolerite and Nungbalgarri Volcanics were examined in order to classify the rocks and assess geochemical trends. Analyses were extracted from the ROCKCHEM database (AGSO) and cover the distribution of the units across the Alligator River region and MILINGIMBI. Representative analyses are shown in Appendix 2.

Nimbuwah Complex

Intrusives of the Nimbuwah Complex are I-type granites with a near-neutral redox trend (Figure 8a, b). They show a distinct calcalkaline trend and range from monzogranite to granodiorite (Figure 8c, d). Harker diagrams of major elements (Figure 9) show trends consistent with fractional crystallisation from a moderately homogeneous source magma.

Oenpelli Dolerite

The Oenpelli Dolerite geochemical trends are consistent with intraplate tholeiitic magma (Figure 10a-c). Analyses consistently plot within the basalt field of the volcanic classification of Le Bas and others (1986; Figure 10d). A spider diagram for the Oenpelli Dolerite (Figure 10e) shows a generally flat trend with weak enrichment of LIL elements relative to REE and weak troughs for both Nb and Sr. Harker variation diagrams (Figure 11) show trends consistent with fractional crystallisation.

Nungbalgarri Volcanics

Unlike the Oenpelli Dolerite, the Nungbalgarri Volcanics have a distinct calcalkaline trend (Figure 10a-c). Within the volcanic classification of Le Bas and others (1986; Figure 10d) most analyses define a trend from basaltic andesite to basaltic trachyandesite, and a few analyses are significantly more mafic. A spider diagram (Figure 10f) shows significant enrichment in LIL elements relative to the REE. Marked negative anomalies of Nb and Sr are due to either a depleted source rock or crustal contamination. Harker diagrams (Figure 11) show a different trend to the crystal fractionation trend of the Oenpelli Dolerite and probably indicate crustal contamination.

TECTONICS

The tectonic framework of MILINGIMBI is divided into three terrains (Figure 4): the Nimbuwah Complex of the Pine Creek Inlier in the northwest, the Arnhem Shelf of the McArthur Basin in the southwest, and the Arafula Basin in the northeast.

Pine Creek Inlier

The Palaeoproterozoic Pine Creek Inlier units underwent compressional and extensional tectonism and related igneous activity, lasting from 1870 to 1800 Ma (Etheridge and others 1987, Needham and others 1988). Due to poor exposure in MILINGIMBI, structures were difficult to study. To the east, in the Alligator River region, the tectonic history (e.g., Needham 1988) is better understood due to better exposures, including in the Nabarlek and Ranger mines, and more drill core.

The Alligator River region consists of two main structural and metamorphic terrains, the Nanambu and the Nimbuwah Complexes. The Nimbuwah Complex is characterised by granite, gneiss and schistose units of medium- to high-grade metamorphism, gently dipping foliations and west-verging recumbent folds (Needham 1988). The Archaean Nanambu Complex comprises medium-grade schists with steeply dipping foliations and tight to isoclinal folds. The folding and faulting orientation and style is related to the rigid basement rocks of the Nanambu Complex and the diapiric growth of the Nimbuwah Complex which caused additional folding and associated amphibolite-facies metamorphism.

The 1870 to 1850 Ma regional event defined as the Barramundi Orogeny (Etheridge and others 1987) is also known as the Nimbuwah Event (Needham and others 1988) of the Top End Orogeny (Needham and De Ross 1990). The regional metamorphic event featured east-west compression, resulting in thrusting, west-verging recumbent folds, northwest-trending upright folds, southwest-trending upright to inclined folds and north- to northwest-trending faulting (Stuart-Smith and others 1980).

Microstructural work determined four phases of deformation in the Nimbuwah Event (Needham 1988). Bedding (S0) was assumed to be the preserved mineralogical and textural banding. Poorly preserved S1 foliations, defined by phyllosilicates, are subparallel to S0. They are rare in the mica schist but dominant in the quartzfeldspathic schist. S2 and S3 were isoclinal folded forming mainly west-verging recumbent folds (F1). Low angle thrusting was associated with these folds and produced a dominant phyllosilicate schistosity (S3). Almandine and magnetite porphyroblasts show deformation, rotation and cutting textures suggesting that metamorphism accompanied deformation. Tight, upright folds (F2) in the Nanambu Complex and reclined folds in
Nimbuwah Complex have an associated S₃ axial planar foliation, that developed a crenulation cleavage. Large unstrained mica, kyanite and staurolite porphyroblasts cut the S₃ fabric, indicating that temperature increased after deformation. The fold axes of the three folding events trend generally north. Poorly developed kink folds and associated S₃ cleavage are the latest structures recognised (Needham 1988).

The granitic and gneissic Nimbuwah Complex is poorly exposed in MILINGIMBI. The rocks vary from massive to strongly foliated. The foliation trends north-northwest, dipping moderately to steeply to the northeast and southwest, although minor west-northwest-trending foliations with moderate to steep dips to the north and south were observed. The orientation of the foliation is parallel or subparallel to the north-northwest fold axes described on ALLIGATOR RIVER.

McArthur Basin

The tectonic evolution of the McArthur Basin was dominated by brittle Proterozoic deformation. The McArthur Basin is dominated by two north-trending 50-80 km wide fault zones, the Walker Fault Zone in the north and the Batten Fault Zone in the south (which correspond to palaeograbs of the Walker Trough and Batten Trough; Plumb and Roberts 1992). These fault zones are separated by the east-trending Urapunga Fault Zone (Urapunga Tectonic Ridge).

The Walker and Batten Fault Zones are characterised by major north-trending faults which separate domains of open folds (fold axes subparallel to major faults) from north-trending steep to subvertical strata (Plumb and others 1980). Most of the folding, warping and tilting is fault related. Cleavage development was only observed in the Walker Fault Zone (Rawlings and others 1997). Relatively undeformed shelves flank the fault zones: the Arnhem Shelf to the northwest, the Caledon Shelf to the northeast, the Wearyan Shelf to the southeast and the Bauhinia Shelf to the southwest.

The Katherine River Group and equivalents were deposited in a basin-wide extensional event. The younger Nathan and Roper Groups also occur basin-wide, whereas the McArthur Group and equivalents and the Parsons Range Group occur more locally and tend to be fault-bounded (Rawlings and others 1997).

Plumb (1994) proposed a tectonic model of asymmetric syn-depositional rifts where north-trending bounding, strike-slip fault systems formed pull-apart basins. Syndepositional faulting resulted in differential subsidence in the troughs and controlled the thickness of units. Accumulated locally in these grabens (Walker Trough and Batten Trough) were up to 12 km of sediments, compared to 4 km on the shelves (Rawlings and others 1997). The Urapunga Fault Zone may represent a rigid block that resisted the extensional movements. Reactivation of older fault systems resulted in faulting with little displacement and fracturing.
Bull and Rogers (1996) interpreted a four-stage evolution in the Batten Fault Zone, southern McArthur Basin. The lower Tawallah Group was deposited in an east-trending extensional graben. A 'mid-Tawallah Inversion', (east-west compression), affected the lower succession and subsequent east-west extension resulted in deposition of the upper Tawallah Group. The final northwest-southeast compressional event, 'Post-Roper Inversion', at the end of the Roper Group closed the basin.

A comparison of tectonic models is presented in Table 4, also showing depositional phases of the McArthur Basin.

The Katherine River Group and Mount Rigg Group form the Arnhem Shelf succession in MILINGIMBI. The Mount Rigg Group is poorly exposed and no significant structural information was obtained. The Katherine River Group (predominantly the Kombolgie Subgroup) in southwest MILINGIMBI features bedding that is generally horizontal or dips gently southeast and has spectacular eroded joint and fault patterns. Field exposures of the faults are rare and generally show multiple reactivation with little significant displacement. Locally steeply-dipping units with variable dip directions are usually related to faults. The Arnhem Shelf developed a network of faults and joints in response to reactivation of structures in the basement during several periods of regional compression and extension (Plumb and Roberts 1992).

The Kombolgie Subgroup in MILINGIMBI shows three main orientations of major faults and an extensive network of joints/fractures.

Northwest-trending faults:
Several northwest-trending faults were observed in MILINGIMBI. The Bulman Fault Zone in the southwest, for example, can be traced for 130 km northwest into ALLIGATOR RIVER and 100 km southeast into MOUNT MARUMBA. Several other structures continue for 100 km southeast into the Roper River area (Plumb and Roberts 1992). Deformation associated with the Bulman Fault Zone is mainly local fracturing and brecciation of the Kombolgie Subgroup. No significant displacement was observed in MILINGIMBI. Northwest-trending faults, particularly the Bulman Fault, have a long history and may be associated with old basement faults and/or the initial basin formation, which were reactivated by the 'Post-NathanShortening' and 'Post-Roper Inversion' events (Plumb and Roberts 1992).

East-northeast- to east-trending faults:
Several major east-northeast-trending faults such as the Ranger and Sawcut Faults extend west into ALLIGATOR
Figure 9 Harker diagrams (major elements as oxides versus SiO$_2$) for the Nimbuwah Complex: a) Al$_2$O$_3$, b) CaO, c) Total Fe as FeO, d) K$_2$O, e) MgO, f) Na$_2$O, g) P$_2$O$_5$, h) TiO$_2$
Figure 10 Geochemical classification diagrams for the Oenpelli Dolerite (open circles) and the Nungbalarri Volcanics (solid triangles): a) AFM classification showing separation of calcalkaline and tholeiitic differentiation trends. b) Nb-Zr-Y plot showing basaltic classification scheme of Meschede (1986) c) Ti-Zr-Y plot showing basaltic classification scheme of Pearce and Cann (1973) d) SiO₂ versus total alkalis, showing the volcanic classification scheme of Le Bas and others (1986) e) Spiderdiagram normalised to primordial mantle for the Oenpelli Dolerite f) Spiderdiagram normalised to primordial mantle for the Nungbalarri Volcanics

RIVER. The Marlgowata Sandstone on the Mann River (lat. 12°52'35"S, long. 134°03'09"E) is folded near a major fault and forms a monoclinal structure in which bedding dips moderately to the northwest. The structures are probably due to deep-seated thrust faults. Slickenside lineation on flat-lying bedding surfaces indicates horizontal movement along the bedding plane. Major thrust faults may be translated along bedding planes at higher stratigraphic levels.

The Gumarrirbang Sandstone near the outstation Gumarrirbang (lat. 12°19'32"S, long. 134°00'09"E) is disrupted by major fault zones. Bedding is overturned with
variable dip directions. The zone has a fault breccia comprising subangular to angular, pebble-cobble clasts of Kombolgie Subgroup in a sand matrix. The amount of movement and direction on these faults is unknown.

The east-northeast-trending faults may relate to 'Post-Nathan Shortening', characterised by north-northeast trending thrust faults. They were reactivated in the 'Post-Roper Inversion'.

East-trending faults occurring in the south of MILINGIMBI plus similar faults interpreted from magnetics in the north are probably associated with the 'Post-Nathan Shortening'.

North-trending faults:
A major north-trending fault was traced from northern MILINGIMBI south into MOUNT MARUMBA. A late-stage dextral strike-slip movement of the fault was indicated by displacement of northeast-trending faults, observed on aerial photographs. Discontinuous north-trending faults occur across the Kombolgie Subgroup. These faults may be related to the initial extensional basin-forming event and display a history of reactivation. The dextral strike-slip
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<th>NORTHERN McARTHUR BASIN</th>
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</thead>
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<tr>
<td>EXTENSIONAL EVENT AND DEVELOPMENT OF BASINS</td>
<td>D.; ‘Batten Trough Extension’, east-west extension formed a north-trending half graben. Northeast-trending transform structures rotated fault blocks differentially on either side of the structure. North-trending faults were produced, as well as some southeast/northwest structures and east-west transform faults</td>
<td>D.; ‘Walker Trough Extension’, Northwest-southeast extension, dextral strike-slip faulting to produce a pull-apart style basin (Walker Trough)</td>
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<tr>
<td><em>Supersequence 1</em> (~1815-1710 Ma) Extensive shallow marine to fluvial sediments and volcanics deposited in an extensional shelf setting</td>
<td>Tawallah Group</td>
<td>Katherine River Group</td>
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<td>Donydji &amp; Spencer Groups</td>
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<td>Groote Eylandt Group</td>
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<tr>
<td>‘TAWALLAH EVENT’</td>
<td>D.; ‘Mid Tawallah Inversion’ due to east-west compression inverting the early normal structures to create early topography. Early tectonism is recognised from fault patterns, brecciation and pervasive silification in the lower succession</td>
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<tr>
<td><em>Supersequence 2</em> (~1700-1685 Ma) Shallow marine to fluvial succession deposited within a deepening graben</td>
<td>Unconformity</td>
<td>Parsons Range Group</td>
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<td><em>Supersequence 3</em> (~1660-1620 Ma) Shallow- to moderately deep-water environment. Deposition of carbonates, siliciclastics and reworked tuff, confined to north-northeast-trending paleo-graben (Walker and Batten Troughs)</td>
<td>McArthur Group</td>
<td>Balma and Habgood Groups</td>
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<td><em>Supersequence 4</em> (~1615-1575 Ma) Shallow-water to marginal marine environment. Deposition into a broad ‘post-rift’ sag basin which extended across shelves and troughs</td>
<td>Nathan Group</td>
<td>Nathan and Mount Rigg Groups</td>
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<td>POST-NATHAN SHORTENING</td>
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<td>D.; West-northwest – east-southeast shortening, inversion of the troughs. North-northeast-directed thrusting, Northeast/northwest-trending conjugate shears and joints developed. Folding, thrusting and local developed cleavage in the Walker Fault Zone</td>
</tr>
<tr>
<td><em>Supersequence 5</em> (~1500-1450 Ma) Shallow near-shore marine environment. Deposition into a sag basin</td>
<td>Roper Group</td>
<td>Roper Group</td>
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<td>POST-ROPER EXTENSION</td>
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<td>East-west extension and emplacement of dykes (e.g. Derim Derim Dolerite, 1324 Ma; Sweet and others 1999) into pre-existing joints</td>
</tr>
<tr>
<td>POST-ROPER INVERSION</td>
<td>D.; northeast-southwest compression reactivated structures; dextral wrench and north-directed thrust faulting, northeast-trending transform structures. This closed the McArthur Basin and gave the present day geometry</td>
<td>D.; northeast-southwest compression resulted in the reactivation of structures, conjugate faulting and folding</td>
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<td></td>
<td>D.; north-trending dextral faulting and associated north-directed thrusting, reactivation of faults</td>
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movement is probably associated with the ‘Post-Roper Inversion’.

Joints:
The Arnhem Land plateau shows well-developed joints in the flat-lying Kombolgie Subgroup. There main joint orientations on MILINGIMBI are a north-northeast-trending set and a northeast-northwest-trending conjugate set. Plumb and Roberts (1992) interpreted the joint pattern as a product of strike-slip shear due to reactivation of pre-existing basement structures. Development of joints is probably associated with the ‘Post-Nathan Shortening’ and ‘Post-Roper Extension’. The northeast-trending joints were later filled with dolerite dykes.

Arafura Basin

In MILINGIMBI, the Arafura Basin is represented by the undeformed Wessel Group. Primary bedding dips gently and the strike varies from north to north-northeast. The change in strike direction may reflect the original depositional shape of the basin. No folds or significant faulting were observed. Minor faults in east MILINGIMBI are possibly syndepositional structures. The basin development completely postdates the structural events of the McArthur Basin.

GEOLOGICAL HISTORY

The geological history of MILINGIMBI is summarised below (dates are approximate only):

1. 2500-2200 Ma: Uplift and erosion to expose Late Archaean granitic rocks.
2. 2100-1880 Ma: Rifting and subsidence of Archaean granitic basement, forming an intracratonic basin. Sediments of the Pine Creek Inlier were deposited in this basin.
3. 1870-1850 Ma: Barramundi Orogeny. East-west compression resulted in multiple fold generation and regional metamorphism. Intrusion of shallow level I- and S-type granites, including the I-type Nimbuwah Complex.
4. 1850-1815 Ma: Uplift and erosion of the Nimbuwah Complex and other basement units.
5. 1815-1710 Ma: Northeast-southwest extension and development of basins. Deposition of extensive shallow marine and fluvial sequences and extrusion of volcanics of the lower to middle Katherine River Group.
6. 1700-1685 Ma: Development of north-trending fault systems during rifting to form pull-apart basins of the Walker Trough, east of MILINGIMBI. Deposition of the Parsons Range Group in localised basins; attenuated successions extended onto the Arnhem Shelf.
7. 1688 Ma: Intrusion of the extensive Oenpelli Dolerite sill.
8. 1660-1620 Ma: deposition of carbonates and siliciclastic sediments of the McArthur Group into deepening grabens to the east.
10. 1615-1575 Ma: Deposition of shallow marine and supratidal platform deposits of the Nathan and Mount Rigg Groups in a broad, post-rift sag basin.
12. 1500-1450 Ma: Deposition of Roper Group shallow-marine sandstone and mudstone in a sag basin to the east of MILINGIMBI.
14. “Post-Roper Extension”: east-west extension resulted in emplacement of dykes into pre-existing joints.
16. Lengthy hiatus – unconformity.
17. Late Neoproterozoic-Middle Cambrian: deposition of shallow-marine sandstone, mudstone and carbonates of the Wessel Group and Goulburn Group in the Arafura Basin.
18. Lengthy hiatus – unconformity.
19. Cretaceous: deposition of a thin layer of sandstone and mudstone.

ECONOMIC GEOLOGY

Following the discovery of a large bauxite deposit at Gove (in ARNHEM BAY-GOVE; Rawlings and others 1997) and large manganese deposits on Groote Eylandt in 1952 and 1962 respectively, early (1964-1970) exploration in MILINGIMBI focused on these metals. The discovery of large world-class uranium deposits between 1969 and 1973 in the adjacent Alligator Rivers Uranium Field has encouraged vigorous uranium exploration in western MILINGIMBI over the past twentyfive years.
Uranium

MILINGIMBI lies within the northeastern portion of the Alligator Rivers Uranium Field, host of several world-class unconformity-related uranium-gold deposits (Needham 1988). The larger deposits occur in fault and shear zones in Palaeoproterozoic deformed and metamorphosed rocks (mainly Cahill Formation) that underlie the Kombolgie Subgroup. The lower member of the Cahill Formation, characterised by carbonaceous and carbonate units, hosts the Ranger, Jabiluka and Koongarra deposits. These deposits are located close to outcropping uranium-rich Archaean domes and to the unconformity at the base of the Kombolgie Subgroup. The mined-out Nabarlek deposit (19 km west of MILINGIMBI) is hosted within altered muscovite-biotite-quartz-feldspar schist and amphibolite assigned to the Myra Falls Metamorphics (Wilde and Noakes 1990). The uranium-rich (up to 40 ppm) Nabarlek Granite is located 6 km west and 450 m north of the Nabarlek orebody.

During the early 1970s airborne geophysical surveys over the central and western areas of MILINGIMBI were carried out by Union Carbide Exploration Ltd (Whitehead 1971), McIntyre Mines (Aust) Ltd (Purdie 1972a,b) and EZ (Aust) Ltd (Maynard 1971). The former two surveys detected numerous radiometric anomalies that were followed up by ground work that revealed radioactivity over outcropping granitic rocks (Nimbawah Complex), mafic volcanics (Nungbalgarri Volcanics) and laterite not related to uranium mineralisation.

Extensive exploration work, including percussion/diamond drilling, between 1987 and 1990 by Uranerz (Aust) Ltd in the Goomadeer River area led to the discovery of several prospects containing uranium-gold mineralisation, in places with paladium (Rippert 1992). The most significant mineralisation was located at the Devils Elbow U-Au-Pd prospect (GR LG421057) where rock chip samples returned assays up to 5.80% U₃O₈, 38.1 g/t Au and 28.02 g/t Pd (Taylor 1990). The mineralisation lies within a series of subvertical northwest trending faults within hydrothermally altered fine-grained amygdaloidal basalt assigned to Nungbalgarri Volcanics. The results from two drill holes (KLD007 & KLD019) were not encouraging; the best intersection returned 950ppm U₃O₈ over 5 m (from 116 m depth) at the contact with the underlying Mamadawere Sandstone (Taylor 1990). Poor ground access to the Ferricrete Anomaly (U-Au) some 700m southeast of Devils Elbow prospect curtailed the proposed follow-up drilling program.

AFmeco Mining & EXploration Ltd (EL3347) and PNC Exploration Ltd (EL5890) have conducted the most recent (1997-1999) uranium exploration over the Nimbawah Complex in northwestern MILINGIMBI. Follow-up ground work over selected radiometric anomalies on EL3347 has revealed minor anomalous uranium and gold values in hydrothermally-altered Oenpelli Dolerite (Alonso & Kastellorizos 1998).

The potential for Alligator River style unconformity-related uranium deposits appears limited on MILINGIMBI mainly due to the lack of favourable reactive lithologies present in basement units underlying the Kombolgie Subgroup. However, the potential for Westmoreland-type uranium-gold deposits (see Ahmad and Wygrala 1989) is reasonably good. The upper and lower contacts of the Nungbalgarri Volcanics with sandstone units in the Kombolgie Subgroup, in the vicinity of regional faults, would represent a good exploration target for this style of mineralisation.

Bauxite

The northern coast of the Northern Territory hosts a world-class bauxite deposit (350 Mt at 51% Al₂O₃) located at Gove. Numerous subeconomic deposits occur on Croker Island (130 km northwest) and Marchinbar Island (200 km northeast). The former two have developed over shaly Cretaceous units, while the latter was probably derived from Raiwalla Shale (Ferenczi in prep.). Both these rock units are present in central and eastern MILINGIMBI.

In 1964 United Uranium NL (Sturm 1965) conducted a ground and helicopter regional reconnaissance survey over the coastline between Coburg and Milingimbi, targeting bauxitic laterite, manganese and heavy mineral beach sands. Nopisolitic laterites were located, and only minor tubular laterite was reported at Maningrida. McIntyre Mines (Aust) Ltd conducted an auger drilling program over Cretaceous sediments in the vicinity of Ramingining that resulted in the discovery of the Milingimbi bauxite prospect (GR MG903364). This prospect contains a relatively thin (1 m) sandy pisolitic laterite layer (Bates 1971). Chip sampling from a 3.2 m deep test pit returned 22.7% Al₂O₃ over 2.4 m, including 0.9 m grading 32% Al₂O₃ from 1.2 m depth (Bates 1971).

In 1972 CRA Exploration Ltd conducted an auger drilling program over subcropping Raiwalla Shale in the vicinity of the Blyth (Herenberg 1973). Results indicated that the potentially economic laterite zone was probably removed by post-Eocene erosion.

Manganese

On Groote Eylandt, 140 km southeast of MILINGIMBI, large (340 Mt at 49.5% Mn) sedimentary manganese deposits are hosted at the base of Cretaceous shallow marine sediments. Based on this geological model, Union Carbide Exploration conducted regional traverses over Cretaceous subcrop in MILINGIMBI, however, no manganese ore was detected (Whitehead 1971). This is probably due to the dominance of coarser grained continental sediments over potentially manganese-bearing finer grained marine sediments.

Diamonds

During 1971 Stockdale Exploration Ltd conducted a large regional stream sediment program in central MILINGIMBI. The sampling program focused on the identification of Kimberlite indicator minerals (garnet, ilmenite and chrome diopside) and diamonds (Stracke 1971). The survey identified
two samples from Guyuyu Creek containing borderline kimberlitic garnet and one sample from Imimbar Creek containing kimberlitic ilmenite. Follow-up sampling did not recover additional indicator minerals or diamonds (Stracke 1971).

**Groundwater**

Current groundwater exploration, to supply Aboriginal communities with reliable water for consumption, Palaeoproterozoic units and are situated in fault zones. The units of Arafura Basin appear to be poor aquifers. The unconformity of the Cretaceous sediments with underlying Wessell Group shows rich vegetation, indicating an aquifer discharge zone. The Water Division of the Power and Water Authority can be contacted for specific information on water bores and water potential on MILINGIMBI.

**ACKNOWLEDGEMENTS**

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The fieldwork would not have been possible without technical support from Niela Nielsen, Tim Cardona, Jason Brown, Dave Harris (AGSO), Dave Campbell and Jane Mitchell. Access to remote areas was assisted by the staff of Jayrow Helicopters. Staff from the Land Access unit of the Department of Mines and Energy also provided great assistance to our work in Arnhem Land.

Leesa Carson and Steve Cox drafted the text figures and David Young, Alexandra Borowick and Dennis Gee edited or gave comments on the text. Russell Poole produced the accompanying map and Kiris Rahikainen formatted the text.

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APPENDIX 1
DEFINITIONS OF NEW AND REVISED STRATIGRAPHIC UNITS

These definitions have been approved by the Stratigraphic Names Sub-Committee of the Geological Society of Australia, Northern Territory Division. References are included in the main reference list.

KOMBOLGIE SUBGROUP (redefinition of unit)

Proposers: L.J. Carson and A.T. Brakel

Derivation of name: Kombolgie Creek in MOUNT EVELYN (lat. 13°30'S, long. 132°23'E), the reference area nominated by Walpole and others (1968).

Synonym: Formally mapped collectively as Kombolgie Formation by Walpole and others (1968). Plumb and Roberts (1992) divided it into three successions: (i) lower arenite succession, (ii) upper arenite succession, (iii) volcanic members at the base of the upper arenite succession and within it. In KATHERINE and ALLIGATOR RIVER, the Kombolgie Formation was subdivided as two sandstone intervals; lower sandstone (Ehkl) and an upper sandstone (Ehkh2) separated by volcanic members (Knese and others 1994, Needham and Stuart-Smith 1978). The McKay Sandstone was not included in the Kombolgie Formation, although it was considered to grade laterally into the upper part of the Kombolgie Formation (Plumb and Roberts 1992).

Constituent formations: In ascending order in MILINGIMBI: Mamadawerre Sandstone, Nungbalgarri Volcanics, Gumarrinbang Sandstone (including Gilruth Volcanic Member), Marigowa Sandstone, McKay Sandstone. In KATHERINE, the Kombolgie Subgroup also includes the McAddens Creek and Birdie Creek Volcanic Members.
(which both appear to be equivalent to the Nungbargarru Volcanics), and the Henwood Creek Volcanic Member (which appears to be equivalent to the Gilruth Volcanic Member of the Gumarrungbang Sandstone). Note that the Goomadeer Volcanic Member of Plumb and Roberts (1992) was not recognised during 1995-1996 fieldwork (see discussion in definition of Nungbargarru Volcanics).

**Distribution:** Extends from western MILINGIMBI across eastern ALLIGATOR RIVER, through northern, central, southern and eastern MOUNT EVELYN, northwestern MOUNT MARUMBA, and south to northern KATHERINE.

**Reference area:** As for each constituent formation.

**Lithology:** Quartz arenite, both non-ferruginous and ferruginous, basalt and tuff.

**Thickness:** Variable. 750 m in the reference area of Walpole and others (1968), approximately 700 m including volcanic units in MILINGIMBI, estimated 630 m in MOUNT MARUMBA and over 800-1000 m in KATHERINE.

**Geomorphic expression:** Forms resistant plateaus and spectacular gorges of the Arnhem Land escarpment country.

**Relationships:** Unconformably overlies the granitic basement units of the Nimbuwah Complex. Conformably overlain by the Cottey Formation in southern MILINGIMBI and northwestern MOUNT MARUMBA, and unconformably overlain by the Shadforth and Gundji Sandstones in southeastern MILINGIMBI.

**Depositional environment:** Predominantly braided fluvial, becoming tidal shallow marine towards the top. Large-scale dune features near the Nungbargarru Volcanics and Gilruth Volcanic Member may be aeolian. The volcanic units are of subaerial extrusive origin.

**Age:** Palaeoproterozoic (Statherian), based on a 1648±29 Ma alteration age from the Nungbargarru Volcanics (Page and others, 1980, and above), and the 1870-1800 Ma age of the Barramundi Event that affected the underlying basement.

**Correlatives:** The Kombolgie Subgroup is equivalent to the Tawalah Group of the southern McArthur Basin.

**Comments:** The existence of quite distinct and mappable volcanic units, developed on major erosional and weathering surfaces, enables the former Kombolgie Formation to be divided into three sandstone formations. The former Nungbargarru Volcanic Member has been raised to formation status, and the McKay Sandstone, which appears to be partly equivalent to the upper Marlgwa Sandstone, has been included in the subgroup.

**MAMADAWERRE SANDSTONE** (new name)

**Proposers:** L.J. Carson and A.T. Brakel

**Derivation of name:** From Mamadawerre, an Aboriginal community, lat. 12°16’S, long. 133°59’E, 7.5 km west of the measured section (M95/01) through the lower part of the unit in MILINGIMBI.

**Synonymy:** Formerly mapped as Kombolgie Formation. In KATHERINE and ALLIGATOR RIVER it is referred to as the lower sandstone unit (Eklk1) (Kruse and others 1994, Needham and Stuart-Smith 1978).

**Distribution:** Northwestern MILINGIMBI, eastern ALLIGATOR RIVER, northern, central and southern MOUNT EVELYN, northern KATHERINE, and within the McKay and Shadforth Domes in MOUNT MARUMBA.

**Type section:** No uninterrupted section through the formation is known to date. It is well exposed in the Arnhem Land Escarpment, where it might be possible to specify a holostratotype section in future. Lower boundary stratotype - measured section M95/01 through the lower part of the formation, extending from the base at lat. 12°15′34″S, long. 133°43′29″E to a fault zone at lat. 12°15′49″S, long. 133°43′34″E. Upper boundary stratotype - at lat. 12°32′S, long. 133°56′10″E, the base of the measured type section (M95/05) of the Nungbargarru Volcanics, although the exposure of Mamadawerre Sandstone here is too small to be shown on the 1:250 000 map.

**Reference area:** In MILINGIMBI, outcrop from east to south of Mamadawerre, but here every section through the unit has either a faulted top or a faulted base. Another reference area for the upper boundary is at lat. 12°24′S, long. 133°38′E.

**Lithology:** Fine- to coarse-grained, medium- to thick-bedded, white to grey quartz arenite with large-scale, low-angle trough crossbedding and planar crossbedding. Scattered rounded quartz pebbles and thin gravel- to pebble-rich bands are common. Ripples, commonly asymmetric and symmetric with straight and curved crests, are also abundant. In MILINGIMBI the base of the formation has lags of quartz pebbles and cobbles in sandstone and minor pebble-cobble conglomerates.

**Thickness:** The measured reference section M95/01 in MILINGIMBI is disrupted by faulting, and the minimum thickness is 100 m. Drillhole KLD018 recorded 176 m in southwestern MILINGIMBI (Rippert 1992).

**Geomorphic expression:** Forms the spectacular cliffs, plateaus and gorges of Arnhem Land escarpment country.

**Relationships:** Unconformably overlies the basement units of the Nimbuwah Complex. Conformably overlain by the Nungbargarru Volcanics.

**Depositional environment:** Distal braided fluvial.

**Age:** Palaeoproterozoic (Statherian), based on the late Orosirian age of the Nimbuwah Complex, and the Statherian age of the Nungbargarru Volcanics.

**Correlatives:** Yiyintyi Sandstone of the Tawallah Group in the southern McArthur Basin.

**NUNGBALGARRI VOLCANICS** (redefinition of unit)

**Proposers:** L.J. Carson and A.T. Brakel

**Derivation of name:** From Nungbalgarrri Creek, which flows northeasterly in northwestern MILINGIMBI.

**Synonymy:** Formerly the Nungbalgarrri Volcanic Member (Rix 1965, Plumb and Roberts 1992) of the former Kombolgie Formation. With the elevation of the Kombolgie Formation
to subgroup status, the Nungbalgarri is now elevated to formation status, because it is a mappable unit, with thickness comparable to the enclosing Mamadawerre and Gumarrirngab Sandstones. The reference area for the Goomadeer Volcanic Member (Plumb & Roberts 1992) may have some uncertainty in its location. It appears to coincide with the Nungbalgarri Volcanics as mapped for the 2nd edition 1:250 000 Milingimbi map by NTGS/AGSO and thus may be a synonym. Alternatively, the rocks described as the Goomadeer Volcanic Member may have been local outcrops of Onpelli Dolerite if, as Plumb and Roberts (1992) suggest, they do occur at the top of the Nimbubwah Complex and at the base of the Kombolgie Subgroup. However, no unit matching that description was recognised during 1995–1996 fieldwork.

**Distribution:** Western MILINGIMBI, extending into adjoining ALLIGATOR RIVER and MOUNT EVELYN. There are also interpreted equivalents within the McKay and Shadforth Domes in MOUNT MARUMBA.

**Type section:** The complete measured section M95/05 exposed in a creek near lat. 12°32'32"S, long. 133°36'36"E, from the Mamadawerre Sandstone at the base (lat. 12°32'32"S, long. 133°36'10"E) to the Gumarrirngab Sandstone at the top (lat. 12°31'50"S, long. 133°37'30"E).

**Lithology:** Basalt, partly vesicular and/or amygdaloidal (commonly infilled with celadonite). Local minor quartz sandstone interbeds.

**Thickness:** 92.5 m in the type section. Drillholes KLD 005-008, 019 in western MILINGIMBI encountered thicknesses of 86 to 128 m (Rippert 1992).

**Geomorphic expression:** A recessive unit that forms low undulating hills.

**Relationships:** Conformable between the underlying Mamadawerre Sandstone and the overlying Gumarrirngab Sandstone.

**Depositional environment:** Subaerial, but pillow structures recorded by Needham and Stuart-Smith (1978) suggest localised subaqueous extrusion.

**Age:** Palaeoproterozoic (Statherian). A Rb-Sr total rock age, reset by alteration, gave an age of 1648±29 Ma (Page and others 1980).

**Correlatives:** Probably equivalent to the McAddens Creek and Birdie Creek Volcanic Members in KATHERINE.

**GUMARRIRNGAB SANDSTONE** (new name)

**Posers:** L.J. Carson and A.T. Brakel

**Derivation of name:** Gumarrirngab Aboriginal community (lat. 12°20'S, long. 133°59'E), is the closest named feature associated with this sandstone unit in MILINGIMBI.

**Synonym:** Formerly mapped as part of the Kombolgie Formation; in KATHERINE and ALLIGATOR RIVER it is the lower part of the upper sandstone unit (Fkb) (Kruse and others 1994, Needham and Stuart-Smith 1978).

**Distribution:** Extends from western MILINGIMBI into central and eastern MOUNT EVELYN, northern KATHERINE, and far northwestern MOUNT MARUMBA. There are also equivalents within the McKay and Shadforth Domes in MOUNT MARUMBA.

**Type section:** It has so far not been possible to measure an uninterrupted section through the formation. Faulting disrupts the outcrop area in MILINGIMBI. Lower boundary stratotype - at the top of the type section of the Nungbalgarri Volcanics (M95/05) exposed at lat. 12°31'50"S, long. 133°37'30"E. Upper boundary stratotype - partial section AB/02 at the top of the unit, measured by A. Brakel in MOUNT MARUMBA from lat. 13°11'17"S, long. 133°31'02"E, to the top (upper boundary stratotype) at lat. 13°11'41"S, long. 133°30'45"E (Sweet and others 1999).

**Lithology:** Predominantly fine- to medium-grained, medium- to thick-bedded, pink/grey to white quartz arenite. Coarse-grained to pebbly bands and minor pebble conglomerate lenses are common. Trough cross-bedding, large scale at the base, dominates the lower part of the succession. The middle to upper part of the unit is predominately planar-laminated with interbeds of trough and planar crossbedding. Graded beds with granular bases fine up to fine- to medium-grained quartz arenite. Asymmetric ripples vary from straight crested with wavelengths of ~3.5 cm to wavy and bifurcating crests with wavelengths of ~ 6-8 cm; symmetric ripples have straight and curved crests with wavelengths of 4-7 cm. A basal conglomerate unconformably overlies the Nimbubwah Complex in central MILINGIMBI; this incorporates pebbles and cobbles predominantly of quartz, minor sandstone and rare granite. This unit includes the weathered and altered basaltic volcanics of the Gilruth Volcanic Member at its top. Longitudinal dunes are preserved below the Gilruth Volcanic Member or equivalent level in some areas.

**Thickness:** Estimated thickness of 125 m in MILINGIMBI. The measured section AB/02 is incomplete and only documents the top 60 m of stratigraphy.

**Geomorphic expression:** Forms part of the escarpment plateau and some of the deeply incised gorges of Arnhem Land.

**Relationships:** Conformably overlies the Nungbalgarri Volcanics and is overlain conformably by the Marlgowa Sandstone. At a localised occurrence in central MILINGIMBI, the Gumarrirngab Sandstone unconformably overlies the Nimbubwah Complex.

**Depositional environment:** Most of the formation is interpreted as distal braided fluvial. An aeolian environment is interpreted for the large-scale longitudinal dunes preserved at the contact with the Gilruth Volcanic Member.

**Constituent Unit:** The Gilruth Volcanic Member is developed at the top of the formation in most areas.

**Age:** Palaeoproterozoic (Statherian), based on the age of the underlying Nungbalgarri Volcanics.

**Correlatives:** The Gumarrirngab Sandstone probably correlates with the lower units of the Sly Creek Sandstone of the 'Imwallah Group of the southern McArthur Basin. The Gilruth Volcanic Member probably correlates with the Henwood Creek
Volcanic Member in KATHERINE (Kruse and others 1994).

**MARLGOWA SANDSTONE** (new name)

*Proposer:* L.J. Carson and A.T. Brakel

*Derivation of name:* Marlgowa Aboriginal community (lat. 12°50’S, long. 133°54’E), which is the closest named feature to this sandstone unit in MILINGIMBI.

*Synonymy:* Formerly mapped as part of the Kombolgie Formation. In KATHERINE and ALLIGATOR RIVER it is the upper part of the upper sandstone unit (Pshk.) (Kruse and others 1994, Needham and Stuart-Smith 1978).

*Distribution:* Extends from central and southwestern MILINGIMBI into northwestern MOUNT MARUMBA, eastern MOUNT EVELYN and northern KATHERINE. There are also equivalents within the McKay and Shadforth Domes in MOUNT MARUMBA.

*Type section:* It has so far not been possible to measure an uninterrupted section through the formation, as faulting disrupts the outcrop area in MILINGIMBI. However, there is a succession in the southeast with apparently relatively few faults, from which lower and upper boundary stratotypes are nominated. Lower boundary stratotype - formation base at lat. 12°47’19”S, long. 134°28’40”E. Upper boundary stratotype - formation top at lat. 12°54’12”S, long. 134°31’34”E.

*Reference sections:* Three measured reference sections in MILINGIMBI are at different locations and represent different parts of the Marlgowa Sandstone column. Section M95/02 extends from the base of the formation at lat. 12°29’52”S, long. 133°47’41”E, through white quartz arenites to lat. 12°30’03”S, long. 133°47’42”E. M95/03 in ferruginous sandstones is probably located in the middle of the formation, and extends from lat. 12°37’40”S, long. 133°58’02”E, to lat. 12°38’16”S, long. 133°57’58”E; and M95/04 in ferruginous sandstones is possibly in the uppermost part of the unit, extending from lat. 12°52’37”S, long. 134°03’28”E, to lat. 12°52’13”S, long. 134°03’14”E.

*Lithology:* Ferruginous and non-ferruginous quartz arenites. The dominant white/grey quartz arenite component is medium to granular grained, thick to very thick bedded, with some coarse-grained to pebbly bands. It is predominantly trough cross-bedded, planar cross-beds and massive bedding are common, and there is minor overturned cross-bedding. Ripples have wavy crests, asymmetric profiles, and wavelengths of 2-3 cm. The ferruginous sandstones (Pshf) are interbedded with white/grey sandstone, and occur at different levels particularly in the uppermost part of the formation, where they are very common. They are red-brown to purple with a clay matrix and ferruginous cement, and have a greater proportion of biotite flakes and mafic minerals. The units are fine to medium grained, thin to medium bedded, with trough crossbedding. Ferruginisation ranges from uniform to motilled and irregular in habit.

*Thicknness:* Estimated thickness in the southeastern reference area on MILINGIMBI is 360 m, assuming no significant faulting. There is a 110 m measured thickness in white quartz arenite (M95/02) from the top of the Gilruth Volcanic Member through the lower Marlgowa Sandstone. The two sections measured through ferruginous sandstones are 93 m (M95/03) and 155 m (M95/04) thick, but they are separated by faults, and their position within the Marlgowa Sandstone is difficult to determine. The M95/03 section is probably located in the middle of the formation whereas M95/04 may represent the upper part of the formation.

*Geomorphic expression:* Forms part of the escarpment plateau and some of the deeply incised gorges of Arnhem Land.

*Relationships:* Conformably overlies the Gilruth Volcanic Member of the Gumarrimbang Sandstone. The McKay Sandstone is probably laterally equivalent to the upper ferruginous sandstones of the Marlgowa Sandstone, at least in part. Observed contacts of the McKay Sandstone overlying the Marlgowa Sandstone are conformable. The Cottee Formation in southern MILINGIMBI conformably overlies the Marlgowa Sandstone, supporting a McKay-Marlgowa lateral equivalence. The Gundii Sandstone unconformably overlies the Marlgowa Sandstone in eastern MILINGIMBI.

*Depositional environment:* Distal braided fluvial to shallow tidal marine.

*Age:* Palaeoproterozoic (Satherian), based on the age of the Nungbalgarri Volcanics, about 125 m below the base of the formation.

*Correlatives:* Upper part of the Sly Creek Sandstone of the Tawallah Group of the southern McArthur Group.

**LIVERPOOL BRECCIA** (new name)

*Proposer:* A.T. Brakel

*Derivation of name:* Liverpool Crater (lat. 12°24’S, long. 134°03’E), northern Arnhem Land.

*Synonymy:* None. Rix (1965) mapped the unit as part of the Kombolgie Formation.

*Distribution:* Exposed around the rim of the Liverpool impact crater.

*Type locality:* Southeastern exterior side of ring, from base to top of ridge (lat. 12°23’58”S, long. 134°03’10”E, GR 397000 8629050).

*Lithology:* Breccia of sandstone blocks derived from the underlying sandstone of the Gumarrimbang Sandstone of the Kombolgie Subgroup. The clasts range in size from a few millimetres to 7 m, and are mostly angular and roughly equant, although some are elongate. Shoemaker and Shoemaker (1997) have mapped an authigenic breccia overlain by an allogenic breccia.

*Thickness:* About 50 m (Guppy and others 1971).

*Geomorphic expression:* Circular ridge 1.6 km in diameter.

*Relationships:* Unconformably overlies Gumarrimbang Sandstone, with an irregular contact having several metres of relief. Undeformed sandstone in outcrops in the centre of the ring, were interpreted as Cretaceous in age by Guppy and others (1971), but are possibly Proterozoic and overlie the Liverpool Breccia with a sharp contact (Shoemaker and Shoemaker 1997).
**Distinguishing features:** The breccia lithology, and its distribution in a circular ridge, is unique in the region.

**Structural attitude:** Usually unbedded. Where crude bedding is visible, it lies within a few degrees of horizontal.

**Depositional environment:** The breccia was produced by bolide impact.

**Age:** The age is between that of the Palaeoproterozoic Gumarrimbung Sandstone and sandstone in the centre of the crater. The well preserved rim suggests that it was buried before much erosion could take place. The age of the sediments in the crater is uncertain. They could be Cretaceous (Guppy and others 1971), Neoproterozoic of the Arafura Basin, or older Proterozoic (Shoemaker and Shoemaker 1997).

### APPENDIX 2 GEOCHEMICAL ANALYSES

**Appendix 2A**  Representative geochemical analyses of the Nimbuwah Complex. Data from the AGSO ROCKCHEM database

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| Li | - | - | - | - | - | - | - | - | - | - | - |
| Rb | 97 | 124 | 116 | 158 | 215 | 183 | 176 | 106 | 203 | 111 | 123 |
| Sr | 338 | 355 | 360 | 295 | 322 | 292 | 295 | 376 | 160 | 282 | 348 |
| Pb | 23 | 21 | 23 | 25 | 36 | 39 | 38 | 30 | 43 | 23 | 27 |
| Th | 16 | 13 | 18 | 40 | 34 | 39 | 29 | 12 | 35 | 17 | 27 |
| U | 2 | 1 | 1 | 3 | 2 | 5 | 3 | 2 | 1 | 2 | 11 |
| Zr | 194 | 253 | 210 | 249 | 243 | 165 | 168 | 236 | 137 | 238 | 223 |
| Nb | 6 | 13 | 7 | 11 | 7 | 9 | 8 | 11 | 4 | 11 | 11 |
| Y | 17 | 34 | 20 | 12 | 8 | 17 | 15 | 21 | 10 | 24 | 25 |
| La | 96 | 44 | 68 | 81 | 83 | 71 | 55 | 60 | 72 | 58 | 56 |
| Ce | 174 | 84 | 130 | 158 | 160 | 128 | 107 | 115 | 131 | 107 | 109 |
| Nd | 59 | 34 | 45 | 54 | 48 | 41 | 35 | 42 | 50 | 41 | 38 |
| Sc | 10 | 16 | 10 | 6 | 8 | 5 | 8 | 15 | 3 | 12 | 13 |
| V | 21 | 49 | 34 | 35 | 31 | 20 | 24 | 38 | 7 | 43 | 35 |
| Cr | 196 | 206 | 191 | 201 | 153 | 203 | 201 | 167 | 226 | 23 | 18 |
| Mn | 196 | 499 | 301 | 342 | 283 | 265 | 301 | 496 | 156 | 374 | 354 |
| Co | - | - | - | - | - | - | - | - | - | - | - |
| Ni | 4 | 8 | 6 | 5 | 4 | 4 | 4 | 7 | 3 | 5 | 4 |
| Cu | 10 | 25 | 4 | 5 | 5 | 6 | 5 | 5 | 6 | 7 | 3 |
| Zn | 36 | 73 | 50 | 58 | 50 | 36 | 39 | 67 | 24 | 43 | 41 |
| Ga | 18 | 23 | 21 | 22 | 20 | 17 | 17 | 21 | 14 | 19 | 20 |
| Ge | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

44
Appendix 2B  Representative geochemical analyses of the Nungbalgarri Volcanics. Data from the AGSO ROCKCHEM database

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45
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