SEDIMENTOLOGY, VOLCANOLOGY AND GEODYNAMICS OF THE REDBANK PACKAGE, McARTHUR BASIN, NORTHERN AUSTRALIA.

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Declaration

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David Rawlings
January, 2002

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David J Rawlings
Date: 29/1/2002
Abstract

The ~1815-1705 Ma Redbank package is a 3-6 km thick succession of shallow marine to braided fluvial sandstone and lesser conglomerate, mudstone, carbonates and rhyolitic-basaltic volcanics and high-level intrusions. It forms the base of the Palaeoproterozoic McArthur Basin in northern Australia.

In the southern McArthur Basin, the Tawallah Group is the best exposed stratigraphic component of this package. Coarse-grained facies at the base of the Group formed in a proximal-medial braided fluvial environment and are overlain by widespread sheets of supermature quartzarenite and intervening flood basalt. These enigmatic sandstone sheets contain features consistent with deposition in a complex high-energy shallow marine, fluvial and aeolian setting on an extensive low-gradient shelf. Overlying mudstones and carbonates were deposited on a shallow epeiric shelf and coastal sabkha fringe that onlapped basement tectonic ridges. A regional sequence boundary formed during subsequent regional uplift and local synsedimentary deformation, and was followed by deposition of another widespread quartzarenite sheet. The overlying succession of fine-grained sandstone, mudstone, carbonate and evaporitic redbeds suggest more diverse depositional settings. Marginal marine salina, near-shore peritidal, storm-dominated shelf and moderately deep water settings, with periodic restriction to the marine realm, fluctuating accommodation rates and minor synsedimentary faulting are all recorded.

Regional-scale dolerite sills and an extensive stacked succession of basalt sheets were emplaced sequentially as widely-dispersed invasive flows under a thin blanket of wet unconsolidated sediment and peperite. Volcanism was locally associated with uplift and emplacement of polymict debris flows and breccia bodies. This was followed by deposition of a complex association of clastic sediments and felsic volcanics and intrusion of high-level plutons (upper Tawallah Group). Sheet-like rhyolitic lavas with abrupt talus-lined margins evolved via non-explosive eruption and long-term viscous flow. This was facilitated by low water content and high and continuous eruption temperature and effusion rate. Complex ephemeral alluvial and debris flow aprons formed adjacent to the lavas, recording the generation, erosional denudation and final burial of a dynamic high-relief volcano-tectonic landscape. Epiclastic materials were reworked in bordering lakes and low-relief braidplains that prograded radially away from the volcanic centres. Periods between magmatic events were characterised by deposition of widespread immature sandstone sheets in extensive high-energy ephemeral to perennial braided fluvial settings and the development of low-relief regional disconformities. Concurrent pluton emplacement in the northern McArthur Basin generated a series of structural domes with peripheral deformation. Accommodation space for intrusion was provided by decollement at ductility transitions, upward flexuring, outward gravity slide and vertical displacement of overlying sediments.
Detailed stratigraphic and facies analysis of the Tawallah Group has enabled the development of a tectonostratigraphic framework for the entire Redbank package. Four second order subdivisions are recognised (Yirrumanja, Liverpool, Costello and Mitchell mesopackages) that facilitate a clearer, integrated regional understanding of the lithology, timing and geographic distribution of basin phases. The package concept is also applied to the composite McArthur Basin system as a whole. Five distinct and regionally coherent basin phases are recognised (Redbank, Goyder, Glyde, Favenc and Wilton packages). These were deposited in a dynamic tectonic environment over a period of \( \approx 350 \) m.y.

Geochemical characterisation of Proterozoic igneous phases in northern Australia has confirmed many lithostratigraphic correlations in the McArthur Basin. Felsic units show temporal and spatial variation in geochemistry that reflects partial melting of heterogeneous Archaean mafic lower crust due to the emplacement of large basaltic magma chambers and radiogenic heating. The McArthur Basin contains five main mafic igneous phases with typical flood basalt attributes, spanning a period of \( \approx 480 \) m.y. Magmas were derived by partial melting of chemically-stratified lower lithosphere and do not exhibit a plume or rift signature.

A convergent intracratonic setting is proposed for the Redbank package. Basin architecture reflects diverse subsidence mechanisms operating inboard of the active southern margin of the North Australian Craton (Strangways arc). Wedge-shaped and magmatic-related basin architectures formed during subduction. Subsidence was influenced by dynamic topography, thermally- and mechanically-driven viscoelastic behaviour of heterogeneous crust, magmatic underplating, lithospheric phase transformations, and local transtension and isostatic loading. Local growth-fault architecture formed by incipient back-arc extension. Magmatism was driven by a persistent thermal anomaly related to insulative heating and a transient convective roll emanating from the Strangways arc, that eroded the lower lithosphere and generated a magma pool. Migration of magma into lower-crustal magma chambers and to the surface took place at transtensional sites along lithosphere-scale strike-slip faults. Regional unconformities and elongate and wedge basin architectures formed in the Redbank package during periodic terrane accretion events at the Strangways arc. Subsidence was influenced largely by transmission of in-plane stress through the lithosphere to produce lithosphere-scale folding, viscoelastic deflections of the lithosphere, and transtensional strike-slip and flexural back-bulge basins. Local elongate magmatic grabens are interpreted as impactogens resulting from indentor tectonics.
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CHAPTER 1
INTRODUCTION
1. Introduction

1.1 INTRODUCTION

The intracratonic McArthur Basin is the largest and best-exposed element of the Palaeo- to Mesoproterozoic north Australian platform cover (Plumb, 1979a). Sediments deposited in this basin host important stratiform Pb-Zn-Ag mineralisation at McArthur River (HYC) within the McArthur Group. A sedimentary-bimodal volcanic pile, herein termed the Redbank package, is currently regarded as the ‘rift phase’ that preceded deposition of the McArthur Group ‘sag phase’ carbonates. Regional geodynamics provides a first order control on geometry and timing of sedimentary and volcanic facies, uplift and subsidence patterns, burial history and diagenesis, fluid flow, and metal and hydrocarbon mobility in sedimentary basins (Klein, 1991a,b&c; Ingersoll and Busby, 1995; Leighton, 1996). It is widely recognised that the stratigraphic, lithologic and structural architecture of the Redbank package was the template for later base metal mineralisation (Rogers, 1996; Large et al., 1998). Therefore, a better understanding of the complete architecture of the McArthur Basin is essential for the success of any regional mineral or petroleum exploration program.

Previous studies of the McArthur Basin have involved cursory regional mapping or detailed studies of small field areas to solve specific geological problems. Consequently, they have not adequately described the basin-scale architecture or provided a coherent geodynamic synthesis. This thesis aims to address this problem by presenting a detailed study of the stratigraphy, geochemistry, sedimentology and volcanology of the Redbank package. These aspects are combined to erect an integrated tectonostratigraphic framework and geodynamic model for the basin.

1.2 LOCATION, CLIMATE AND PHYSIOGRAPHY

The field area encompassed by this study is the entire extent of the McArthur Basin (~180 000 km²) in the Northern Territory (NT) of north-central Australia (Figure 1.1). The region is sparsely populated, with small townships (e.g., Borroloola), mines (e.g., McArthur River), pastoral stations (e.g., Tanumbarini) and Aboriginal outstations (e.g., Gandganganiki). The northern McArthur Basin is exposed within the Arnhem Land Aboriginal Reserve, a remote and rugged area having few roads and tracks (Figure 1.1); the area is, for the most part, only accessible via helicopter and boat. In contrast, the southern McArthur Basin is more accessible, with a number of unsealed roads that are passable during the ‘dry season’. Terrain is mostly of low relief and sparsely vegetated, allowing good cross-country access by 4WD vehicle.

The ‘top end’ of the NT has a humid monsoonal climate, with a ‘dry season’ from May to October and a ‘wet season’ from November to April, where high rainfall makes unsealed roads generally impassable. Mean annual rainfall is in the range of 1000-1800 mm (Bureau of Meteorology, 1988). Daily maximum temperature varies from ~34°C in December to ~26°C in July, while the average daily minimum ranges from ~27°C in January and February to ~17°C in August. Humidity remains high year-round. Most water courses in the ‘top end’ are seasonal, with scattered water holes remaining
Figure 1.1 Location map for the McArthur Basin study area in northern Australia, showing the principal geographic features of the region.
during the 'dry season'. Some rivers that have large catchment areas (e.g., McArthur River; Figure 1.1) and those fed by springs (e.g., Roper River) flow all year round.

Vegetation reflects the monsoonal climate, but pronounced geological control is also evident (Aldrick and Wilson, 1990). Much of the lowland area is covered by open Eucalyptus woodland. Major water courses are lined by tall eucalypts and paperbarks. Rocky sandstone outcrops and ridges support pockets of spinifex grass, low shrubs and relatively sparse trees. The perennial species are generally fire resistant and much of the annual growth, particularly near communities and roads, is burnt using traditional Aboriginal fire lighting practices during the 'dry season'.

The study region contains more than 60 'land systems' but is dominated by three major physiographic subdivisions, the Gulf Fall, Coastal Plain and Ranges (Aldrick and Wilson, 1990). The majority of outcrops accessed during the current study are within the Ranges, incorporating dissected hilly country with topographic relief in the order of 200-400 m above sea level.

1.3 PREVIOUS WORK AND CONCURRENT STUDIES

Geological studies in the McArthur Basin have largely been fuelled by the discovery and development of the McArthur River Pb-Zn-Ag deposit (HYC; Figure 1.1). Systematic 1:250 000 scale mapping by the Bureau of Mineral Resources (BMR; now the Australian Geological Survey Organisation - AGSO) followed the discovery of HYC in 1955 (e.g., Walpole, 1962; Plum and Rhodes, 1964; Figure 1.2). These studies were the earliest basin-scale investigations into the region and established for the first time a basic lithostratigraphic and tectonic framework; the basis of many subsequent studies. Minor modifications to this framework have resulted from local studies on the McArthur Group, which is considered the most prospective horizon for mineralisation (e.g., Brown et al., 1969; Corbett et al., 1975; Walter et al., 1988).

Detailed sedimentological studies, section measuring and mapping of the McArthur Group were carried out by the BMR in the mid-1980s, resulting in a number of changes to early stratigraphic schemes and geologic models for the basin. The results were published as a comprehensive report on the geology of the southern McArthur Basin and accompanying 1:100 000 map of the Abner Range region (Jackson et al., 1987; Figure 1.2). Further refinement of geological maps and stratigraphy resulted from systematic second-edition mapping conducted jointly by the Northern Territory Geological Survey (NTGS) and AGSO since 1988, under the umbrella of the National Geoscience Mapping Accord (e.g., Ahmad and Wygralak, 1989; Pietsch et al., 1991a; Haines et al., 1993 & 1999; Figure 1.2). During this time, I was employed by the NTGS and undertook geoscientific investigations throughout the basin. Notably, the NTGS-AGSO mapping is the only significant assessment of the northern McArthur Basin, within the Arnhem Land Aboriginal Reserve (Figure 1.1). More recently, the NTGS has continued mapping in the southern McArthur Basin in the Tanumbirinti and Robinson River 1:250 000 mapsheets (Figure 1.2), with the current study contributing significantly. These geological maps are in preparation (Rawlings, in prep.; Rawlings et al., in prep) and a 1:1 000 000 tectonostratigraphic map of the McArthur Basin is complete (Rawlings, 2001).
Figure 1.2 Geological mapsheets of the McArthur Basin region, showing the most recently published explanatory notes. The study area of Rogers (1996) is also shown for comparison. References in bold are those which I have been directly involved in the collection of data and publication of the explanatory notes. * indicates mapsheet areas where additional data has been collected during the current study.
Concurrent to NTGS-AGSO mapping, detailed multi-disciplinary studies of the southern McArthur Basin and Mount Isa Inlier were carried out as part of the joint government-industry funded Australian Minerals Industry Research Association (AMIRA) project P384-384A on sediment-hosted base metal deposits. This project involved: geophysical modelling of basin architecture (Leaman, 1998); detailed structural and sedimentological studies of the Tawallah and McArthur Groups within small field areas (Bull, 1993 & 1998; Bull and Rogers, 1996; Rogers, 1996; Winefield, 1999); lithogeochemical studies of the host sequences to several northern Australian stratiform base metal deposits (Large and McGoldrick, 1998; Large et al., 1998); geochemical modelling of mineralising fluids (Cooke et al., 1998 & 2000); and the development of a genetic model for HYC (Large et al., 1998). The current study, although not directly affiliated with the AMIRA project, has some overlap in terms of logistics, supervision and stratigraphic coverage. However, the scope of this thesis is much broader, encompassing the entire basal volcano-sedimentary section of the McArthur Basin.

In 1995, AGSO embarked on the ambitious task of applying sequence stratigraphic concepts to the Proterozoic basins of northern Australia, under the banner of the North Australian Basin Resource Evaluation (NABRE) project. One module of this project was directed specifically toward a better understanding of the 'basement template' underlying the McArthur Group, and includes geophysical, geochronological and geochemical studies of the Tawallah Group and its immediate substrate (Scott et al., 1998a; Tarlowski and Scott, 1999). Fluid flow studies are also presently under way as part of an extension project (AMIRA P552). The current PhD study has contributed significantly to the NABRE project in several areas, including: definition of stratigraphic, geochemical, volcanological and sedimentological attributes of the Tawallah Group and the development of tectonic models. This collaboration resulted in the publication of two papers in a special issue of the Australian Journal of Earth Sciences on north Australian basin systems (Jackson et al., 2000a; Scott et al., 2000; Appendix 10).

Compared to the McArthur Group, there are few previous studies dedicated to the underlying foundation of the Tawallah Group. In his PhD study, Rogers (1996) assessed the structural, geochemical and sedimentological aspects of this group over a small field area (<2000 km²) in the central deformed corridor of the southern McArthur Basin (Figure 1.2). Fieldwork during Rogers' study concentrated on the lower Tawallah Group. Jackson (1982 & 1985) carried out a regional study of the Wollogorang Formation, with special emphasis on sedimentology and palaeogeography. Numerous mineral exploration programs and some academic projects have taken place to assess the economic potential of the Tawallah Group, but to date only small moderately economic deposits and prospects have been recognised (Ahmad et al., 1984; Australian Geophysical Pty Ltd, 1968; Hopwood, 1971; McMahon, 1970; Knutson et al., 1979). The current study coincided with exploration and evaluation of Cu-Co-Ni prospects in the Running Creek area by CRAE/Rio Tinto in 1995-1997 (Figure 1.3; Morris, 1996; Rawlings et al., 1996), who provided me with logistical support and access to drill core.
Figure 1.3 Simplified geological map of the southern McArthur Basin showing distribution of the Tawalla Group, the main subject of the current study. Modified after Piamb (1988), Hettsch et al. (1991a) and Rawlings (in press).
Models for the tectonic and structural development of the McArthur Basin were proposed by Plumb and co-workers (Plumb, 1979a&b; Plumb et al., 1980 & 1990; Plumb and Wellman, 1987; Plumb, 1994; Hinman et al. (1994), Etheridge and Wall (1994) and Rogers (1996). These models were based on incomplete regional geological and geophysical map patterns, and limited isopach and microstructural analysis. The regional datasets have been significantly improved by NTGS and AGSO mapping programs, although detailed microstructural analyses are still limited.

1.4 SCOPE OF RESEARCH

The middle to upper Tawallah Group was targeted for detailed study because: (i) it is well exposed in the southern McArthur Basin; (ii) it contains key stratigraphic components and bounding surfaces of the Redbank package; (iii) drill core is available and; (v) access and logistics are good. Only limited work was carried out in the lower Tawallah Group, as detailed work has been undertaken by Rogers (1996) and NTGS. Similarly, a synthesis of the northern McArthur Basin is possible using existing data collected during NTGS regional mapping between 1991-1995.

The basin-scale approach of this study is designed to address the current lack of a regional tectonostratigraphic framework, which is the result of: (i) the local scope of previous studies, which focused on specific geological problems (e.g., microstructures, volcanology) and; (ii) the artificial nature of 'mapsheet-based' regional mapping, which demanded, but did not receive, coherent regional synthesis.

The major objectives of this study are to:

- undertake detailed sedimentological and volcanological facies analysis of individual formations of the middle to upper Tawallah Group to determine basin-scale depositional architecture and palaeo-environmental setting;
- carefully document regional lithostratigraphic variations and intraformational boundaries, such as disconformities;
- in concert with a review of relevant literature, use this data to construct a coherent tectonostratigraphic framework and 'event stratigraphy' for the Redbank package;
- analyse geochemical data for igneous units in the McArthur and Mount Isa Basins to facilitate inter-regional correlation and help constrain tectonic setting and magma genesis;
- develop a geodynamic model for the lower McArthur Basin that is consistent with tectonics of adjacent provinces.

1.5 METHODOLOGY

Approximately 14 months of fieldwork was completed in the southern McArthur Basin (Figure 1.3) during the 1995, 1996 and 1997 'dry seasons'. These field seasons coincided with mineral exploration in the Running Creek area by Rio Tinto and NTGS mapping in the Robinson River and Tanumbirini map sheets (Figure 1.3). Multi-scale colour aerial photography was utilised for navigation, mapping, macroscopic interpretation and targeting areas for further detailed work.
Access was provided mainly by 4WD vehicle and sometimes helicopter (courtesy of NTGS and Rio Tinto), using both fly-camps and exploration camps. About 50 stratigraphic sections were constructed and 70 drill cores logged to provide facies and thickness information. Graphic logs for many of these sections are included in the appendix. The assessment of regional structural trends and distribution of igneous formations was aided by NTGS-AGSO detailed airborne magnetic and radiometric data. Approximately 300 multi-element geochemical analyses of representative rock samples were carried out by the AGSO laboratory and are available from the ROCKCHEM database.

1.6 THESIS ORGANISATION

This thesis is arranged in two parts. The first part (Chapters 2 to 8) presents detailed descriptions and interpretations of sedimentary and volcanic formations of the Tawallah Group that are used to construct a well-constrained tectonostratigraphy. The second part (Chapters 9 and 10) considers more regional aspects, such as the interpretation of geochemical data for igneous units, to develop a geodynamic model for northern Australia in the period 1820-1700 Ma. Chapters are organised as follows.

- Chapter 2 - regional geology: reviews the current understanding of the stratigraphy of the McArthur Basin and tectonic framework of Australia and North Australian Craton.
- Chapter 3 - lower Tawallah Group: describes the facies architecture and stratigraphy of the lower Tawallah Group, integrating existing information with new data.
- Chapter 4 - Wollongorang Formation: presents a detailed analysis of the Wollongorang Formation, using facies and thickness variations to constrain the depositional environment and palaeogeography.
- Chapter 5 - Gold Creek Volcanics: describes in detail the stratigraphy and volcanology of the Gold Creek Volcanics. A new model for the emplacement of widespread basalt sheets is proposed.
- Chapter 6 - upper Tawallah Group: examines the interplay between felsic volcanism and sedimentary processes in the upper Tawallah Group. Interpretation of various data is used to reconstruct palaeogeography and geological history.
- Chapter 7 - Jimbu Microgranite: presents a case study of the interplay of high-level felsic plutonism, crustal deformation and sedimentation, based on the geology of the Katherine River Group in the Mount Marumba area of the northern McArthur Basin (Figure 1.1).
- Chapter 8 - tectonostratigraphic framework: the 'tectonostratigraphic package' concept is used to create a coherent tectonostratigraphic framework for the Redbank package, based on new data presented in earlier chapters and critically reviewed previous documentation for the northern McArthur Basin.
- Chapter 9 - igneous geochemistry: examines geochemical data from Proterozoic magmatic units
of northern Australia, including those beyond the McArthur Basin. A petrogenetic model for magmatism is presented, and correlation of craton-scale magmatic events is evaluated.

- **Chapter 10 - geodynamic model**: combines stratigraphic, facies and geochemical interpretations in earlier chapters to develop an integrated geodynamic model for the Redbank package. This chapter incorporates ideas on global basin-forming mechanisms and the tectonic setting of adjacent provinces in north-central Australia.

- **Chapter 11 - conclusions**: summary of the principal findings.
CHAPTER 2
REGIONAL SETTING
2. Regional setting

2.1 INTRODUCTION

This chapter provides an overview of the geology and tectonic setting of the McArthur Basin, including its immediate basement and cover sequences. Summaries are provided for the geologic and tectonic framework of the Australian continent and North Australian Craton. The stratigraphic section relies largely on the combined mapping of the Northern Territory Geological Survey (NTGS) and Australian Geological Survey Organisation (AGSO) carried out in the period 1988-1997, and the Bureau of Mineral Resources (BMR), who established the preceding lithostratigraphic framework. Figure 2.1 provides a spatial perspective of the areas covered by published NTGS-AGSO data sources. Portions of the text that are summarised from existing publications are duly referenced.

2.2 TECTONIC FRAMEWORK OF AUSTRALIA

Australia, as we now see it, is a mosaic of variously-sized 'crustal blocks' of varied age and origin, incorporated into a large cratonised landmass (Figure 2.2). However, the current Australian landmass is covered by an extensive capping of relatively young sedimentary basins and regolith. Exposure of bedrock is generally sparse on a local and regional scale, and much of the outcrop that does exist is concentrated in discrete geographical regions or inliers, constrained by geographical boundaries that may have no tectonic significance (e.g., Tennant Creek Inlier; Figure 2.3) and many such inliers are probably contiguous in the subsurface. To establish the real underlying tectonic framework requires careful lithostratigraphic and chronostratigraphic correlation between the discrete geographical domains. Despite the obvious progress in last two decades, such correlation is still in its infancy, as is evident in the artificially fragmented appearance of many of the published stratigraphic correlation diagrams (e.g., Plumb, 1990; Figure 2.4).

A formal tectonic framework and an accompanying tectonic map of Australia and New Guinea were published by the Geological Society of Australia (GSA) in 1971. The basic framework stands today, augmented by more detailed subdivisions and correlation, based on a larger geological map database and advancements from geophysical and geochronological studies. Central to the tectonic map is the concept that Australia has developed as a series of temporally and partly spatially overlapping tectonic cycles, each involving a "progression from unstable pre-cratonic conditions through cratonisation by orogenesis into stable cratonic conditions, marked by the deposition of platform cover sequences" (GSA, 1971). Each cycle resulted in the development of a continent-scale orogenic province and platform cover, illustrated in the time-space diagram Figure 2.5.

The tectonic map of Australia and New Guinea (GSA, 1971) shows the Australian landmass subdivided into a series of geographic areas, termed 'blocks, belts and basins'. Each may be composed of one or more components, termed tectonic domains, distinguishable by the geometry and lithology, degree of metamorphism and deformation, and implied tectonic setting of the
Figure 2.1 1:250 000 scale mapsheet areas in the McArthur Basin which have been utilised for the review of existing lithostratigraphic components. References in bold are those which I was directly involved in collection of data. * indicates mapsheet areas which additional data has been utilised from my PhD project. McArthur Basin is shaded.
Figure 2.2 Major crustal subdivisions of Australia and Papua New Guinea, showing the location of the North Australian Craton. After Plumb (1979a).

Figure 2.3 Distribution of northern Australian Palaeo- to Mesoproterozoic units, showing those which predate and postdate the Barramundi Orogeny. Much of the Arunta is not differentiated. After Echeridge et al. (1987).
Figure 2.4 Simplified block diagram showing spatial and temporal relationships between components of the North Australian Craton (after Plumb, 1979a).
Figure 2.5  Time-space tectonic diagram for Australia, from Fisher and Warren (1975).

contained rock packages. There are three main types of tectonic domain - orogenic, transitional and cratonic. Orogenic domains are belts of “intense tectonism, involving the filling and deformation of orogenic basins or the development of metamorphic and igneous complexes prior to cratonisation” (GSA, 1971). Three subtypes were defined by Plumb (1979b) - geosynclines, orogens and metamorphic belts. Transitional domains are “late to post orogenic developments associated with cratonisation, transitional in time, place and style between orogenic and cratonic tectonism”. They are characterised by emplacement of granitic batholiths and extensive silicic volcanism, weakly overprinted by tectonism. Cratonic domains are relatively stable areas formed at the cessation of an orogenic cycle. They are generally only mildly deformed and in many cases incorporate a thin but widespread sedimentary platform cover sequence, together with minor small plutons and basalt sheets. They can include narrow ‘mobile zones’ in which there is intensified deformation and stratal thickening.

Based on a number of chronostratigraphic constraints, each tectonic domain can be linked to the tectonic provinces shown in Figure 2.5. An orogenic province is “a group of broadly contemporaneous orogenic domains of similar tectonic history and style that, together with associated transitional domains, forms the youngest basement to an immediately overlying platform cover” (GSA, 1971). A platform cover is “a group of sedimentary basins which developed more or less at the same time and in the same way. Its deposits overlie the immediately preceding orogenic province and associated transitional domains and spread across older orogenic provinces and platform covers” (GSA, 1971). Using this tectonic framework, it is possible to place the component tectonic
domains of any given outcrop belt into the temporal and spatial context of the evolving Australian craton. With the increasing sensitivity of isotopic geochronology and more detailed studies of geology, correlation between tectonic blocks has become progressively more precise (Plumb, 1985 & 1990; Plumb et al., 1990). In some cases, it has enabled the correlation of isolated but contiguous outcrop belts, including some of the larger northern Australian basins, which are separated from each other by vast Phanerozoic cover sequences.

With the increasing wealth of geophysical data in Australia, it has become possible divide the ‘magnetic basement’, largely obscured by Phanerozoic basins, into its component tectonic elements. A recent example is the map of Australian crustal elements (Shaw et al., 1996), which delineates upper-crustal elements, primarily based on composite geophysical domains, each showing a distinctive pattern of gravity and magnetic anomalies. Boundaries between elements are interpreted to mark crustal-scale changes in composition or structural pattern, which in many cases correlate with geological features. The advantage of this map to traditional geologically-based maps, is that boundaries may be accurately extrapolated under the younger sedimentary basins. Elements are characterised according to their magnetic and gravity character, imposed during the last major cratonisation or orogenesis, and placed into a chronotectonic framework on the basis of known geological constraints, allowing substantial revision of the tectonic framework of the Australian continent.

On a broad collective basis, Australia has been divided into a manageable number of genetically and temporally distinct areas or provinces by several authors (Rutland, 1976; Plumb, 1979b; Rutland et al., 1990). These schemes are fundamentally similar, but the divisions of Plumb (1979b; Figure 2.2) are probably the most convenient from a geographic viewpoint and are adopted herein. In this framework, the current study area lies within the North Australian Craton (henceforth NAC), which is described below. On the map of Australian crustal elements (Shaw et al., 1996), the study area lies within the North Australian mega-element, which encompasses a similar geographic area to the NAC.

2.3 GEOLOGY OF THE NORTH AUSTRALIAN CRATON

Much of the nomenclature in this section is defined in Plumb (1979a&b). The NAC (Figure 2.2) incorporates Archaean basement domains, Palaeoproterozoic precratonic domains (North Australian Orogenic Province) and Palaeo- to Neoproterozoic transitional and cratonic domains (North Australian Platform Cover; Figure 2.5). It was cratonised at ~1.870 Ma during the Barramundi Orogeny (Eweridge et al., 1987; Page and Williams, 1988). The various components of the NAC and their time-space relationships are shown in Table 2.1, Figure 2.2 & 2.4.

The NAC is bounded to the south by the Central Australian Mobile Belt (Figure 2.2), which includes elements of the Central Australian Orogenic Province (e.g., Arunta Inlier) and Central Australian Platform Covers (e.g., Ngalia and Amadeus Basins). Platform covers of the NAC include units equivalent in depositional age to the Central Australian Orogenic Province (Figure 2.5), however, they do not record the Neoproterozoic cratonisation age of the latter (Plumb, 1979b).
<table>
<thead>
<tr>
<th>Domain</th>
<th>Archean basement</th>
<th>Orogenic</th>
<th>Transitional</th>
<th>Cratonic (platform cover)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic province</td>
<td>North and West Australian Orogenic Provinces</td>
<td>North Australian Orogenic Province</td>
<td>North Australian Orogenic Province; locally interdigitates with the North Australian Platform Cover</td>
<td>North Australian Platform Cover</td>
</tr>
<tr>
<td>Tectono-stratigraphic distribution and components</td>
<td>Pine Creek Inlier (Rum Jungle-Warehouse Complex, Mannum Complex, Woorner Granite)</td>
<td>Pine Creek Inlier (Pine Creek 'goesyncline', Lachlan Block)</td>
<td>Pine Creek Inlier (Edith River and El Shara Groups, Callie-Bukulalap)</td>
<td>Mount Isa and South Nicholson Basins (including Laura Hill Platform)</td>
</tr>
<tr>
<td></td>
<td>Geelam-Tanami Province (small granite inliers)</td>
<td>Tennant Creek Inlier (Tennant Creek Block)</td>
<td>Tennant Creek Inlet (parts of the Ashburton and Dartmouth Provinces)</td>
<td>Tennant Creek Inlet (parts of the Ashburton and Dartmouth Provinces)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Halls Creek Province (partly)</td>
<td>Halls Creek Province (partly)</td>
<td>McArthur Basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granite-Tanami Block (partly)</td>
<td>Granite-Tanami Block (partly)</td>
<td>Birrindudu Basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anwen Inlier (Anwen Block)</td>
<td>Anwen Inlier (granite batholith)</td>
<td>Kimberly Basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Murphy Inlier (metamorphic portion)</td>
<td>Murphy Inlier (volcanic portion)</td>
<td>Victoria Basin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mount Isa and McArthur Basins (small metamorphic inliers)</td>
<td>Mount Isa and McArthur Basins (small volcanic inliers)</td>
<td>Probable continuity between the various blocks under younger basins.</td>
</tr>
<tr>
<td>Thickness</td>
<td>Unknown</td>
<td>-5-10 km (poorly constrained)</td>
<td>1-5 km</td>
<td>5-15 km</td>
</tr>
<tr>
<td>Rocktypes</td>
<td>Metasedimentary rocks, migmatites, granite and granitic gneisses with metasedimentary enclaves and minor amphibolites.</td>
<td>Dominated by thick turbidite successions, with minor carbonatites, felsic and mafic volcanics and ashes.</td>
<td>Regional-scale granite batholiths, comagmatic volcanic provinces and lavas with minor mafic lavas and sedimentary rocks.</td>
<td>Archaean extensive platforms of sandstone, limestone, chert and lesser mafic and felsic volcanics.</td>
</tr>
<tr>
<td>Metamorphism and deformation</td>
<td>Amphibolite to granulite facies (and locally anatectic) metamorphism and polyphase deformation. Related to several orogenic phases, including the Barramundi Orogeny.</td>
<td>High-T-low-P greenschist to granulite facies (and locally anatectic) metamorphism and polyphase deformation. Related to the mildly diachronous Barramundi Orogeny.</td>
<td>Weak or absent, except along mobile zones such as in the Halls Creek Province.</td>
<td>Generally weak to absent, but metamorphic grade increases toward the eastern margin of the Edna Inlier. Moderately deformed along mobile zones such as in the Halls Creek Province.</td>
</tr>
<tr>
<td>Age</td>
<td>2700-2500 Ma (Orogenesis)</td>
<td>-2000-1880 Ma (deposition)</td>
<td>-1870-1800 Ma (deposition and emplacement)</td>
<td>-1820-1400 Ma (deposition)</td>
</tr>
<tr>
<td>-1870 Ma (Barramundi Orogeny)</td>
<td>-1880-1850 Ma (Barramundi Orogeny)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relationships</td>
<td>Base unknown</td>
<td>Unconf ormable on Archean basement.</td>
<td>Generally unconf ormably overlain by transitional domain or platform covers.</td>
<td>Unconf ormable on transitional and orogenic domains, but locally the transitional domain and platform covers are interdigitated.</td>
</tr>
</tbody>
</table>
| References                     | Fraser (1980); McAndrew et al. (1985); Needham et al. (1983); Page et al. (1980, 1993 & 1996); Richards et al. (1977); Stephenson & Johnson (1976) | Ahmad & Wygrala (1990); Blake et al. (1979); Davison et al. (1993); Needham et al. (1983); Page & Perticone (1988); Page & Williams (1988); Page (1988); Perticone & Edgerton (1988); Rawlings et al. (1997); Sturz-Smith et al. (1993) | Ahmad & Wygrala (1990); Blake (1987); Blake et al. (1979 & 1987); Blake & Page (1983); Davison et al. (1993); Needham & Sturt-Smith (1983); Rawlings et al. (1997); Sturz-Smith et al. (1993) | Blake (1987); Blake et al. (1979 & 1987); Davison et al. (1995); Faita et al. (1993 & 1999); Jackson et al. (1996); Perring et al. (1991a, 1994 & 1997); Plumb et al. (1992); Rawlings (1994); Rawlings et al. (1997); Sweet (1977); Blake (1987); Blake et al. (1979 & 1987); Davison et al. (1995); Faita et al. (1993 & 1999); Jackson et al. (1996); Perring et al. (1991a, 1994 & 1997); Plumb et al. (1992); Rawlings (1994); Rawlings et al. (1997); Sweet (1977);
The position of the eastern boundary of the NAC is contentious (Figure 2.2). There are numerous inconsistencies in the literature as to where to place the Mount Isa Inlier (e.g., Plumb, 1979a; Rutland, 1976). It clearly contains elements of the North Australian Orogenic Province (i.e., units metamorphosed or deformed during the Barramundi Orogeny, e.g., Yaringa Block) and North Australian Platform Cover (Mesoproterozoic basins such as the Mount Isa Basin; McConachie et al., 1993) and is generally accepted to correlate with the weakly deformed McArthur Basin. However, units in the southeastern portion of the Cloncurry Orogen of McConachie et al., 1993) also show substantial evidence of tectonism associated with evolution of the Central Australian Orogenic Province (Isan Orogeny), suggesting a greater affinity with the Central Australian Mobile Belts (Figure 2.2).

Units of the adjacent Northeast Orogens (Figure 2.2), including the Georgetown and Coen Inliers (Figure 2.3), are now interpreted to contain correlative rocks of the North Australian Platform Cover which underwent protracted deformation into the Palaeozoic (Widunall et al., 1988). However, the most significant deformation, the Ewamin Orogeny, took place at 1620-1550 Ma (Black et al., 1979), at about the same time as deformation in the Mount Isa Inlier (Blake et al., 1990). The overall grade of metamorphism associated with the Ewamin Orogeny increases from west to east, toward an inferred Proterozoic continental margin.

The NAC is at least partly developed on Archaean crust, assigned to the West Australian Orogenic Province, which records orogenesis and cratonisation prior to 2500 Ma (Plumb, 1979b; Scott et al., 2000). Equivalents of the West Australian Platform Cover appear to be absent due to the vast areal extent of the North Australian Platform Covers. Archaean high-grade gneiss and granite are recognised within the Pine Creek Inlier and Granites-Tanami Province, and Archaean basement is inferred under the Kimberley Basin (Gellatly et al., 1970; Plumb et al., 1990, Figure 2.3). Sm-Nd isotopic signatures for some metamorphic and granitic rocks of the Tennant Creek Block (McCulloch, 1987) and Halls Creek Province (Page and Sun, 1994) suggest the presence of an extensive Archaean crustal basement beneath the NAC. Analysis of SHRIMP U-Pb zircon isotopic systematics also reveals the presence of an extensive Archaean basement (Scott et al., 2000).

The NAC is overlain by late Neoproterozoic to Palaeozoic basins of the Central Australian Platform Cover, and thin Mesozoic and Cainozoic deposits (Figure 2.5). These cover substantial areas of the craton (Figure 2.3), hindering the correlation of its various components.

The north Australian mega-element, as represented on the geophysically-based map of Australian crustal elements (Shaw et al., 1996), is a large area characterised by "subdued magnetic response" with peripheral zones of "closely-spaced, linear, short-wavelength anomalies, which show broad swings in trend". Its southern boundary (Figure 2.2) is evident as a sharp truncation of the north-south geophysical trends that characterise the north Australian mega-element, by EW-trending long-wavelength gravity anomalies of the central Australian mega-element, probably representing a major strike-slip fault system (Shaw et al., 1996). The northern margin of the central Australian mega-element consists of strips of the structurally dismembered north Australian mega-element, evident in geophysical overprinting. The southeastern and eastern boundaries
with the Tasman and north Queensland mega-elements respectively are gradational and characterised by significant geophysical overprinting. These boundaries are interpreted to be minor on a crustal scale, not penetrating the full thickness of the crust (Shaw et al., 1996). This is also in accordance with the increasing predominance of younger cratonisation ages toward the east and subsequently progressive dissolution of the Barramundi signature of the north Australian mega-element.

2.4 BASEMENT TERRANES OF THE MCArTHUR BASIN

2.4.1 PINE CREEK INLIER

The McArthur Basin is underlain in the northwest by the Pine Creek Inlier (Figure 2.6), which includes sequences of the precratonic and transitional domains, and Archaean inliers (Table 2.1).

The Pine Creek succession comprises ~10 km of fine-grained siliciclastics and minor carbonates, deposited in shallow evaporitic to deep marine settings (Needham and De Ross, 1990). The upper part of the succession, a deep marine turbidite package, is generally regarded as the rapid subsidence (syn-extension) phase of basin development, directly attendant to orogenesis (Needham et al., 1988). The Pine Creek succession also includes numerous mafic sills and felsic to mafic volcanoclastic units. All units were variably and multiply deformed and metamorphosed during the Barramundi Orogeny at ~1880-1870 Ma. Grades of metamorphism range from greenschist to amphibolite facies (Page et al., 1980; Needham et al., 1988; Pietsch and Edgoose, 1988), culminating in partial melting of the sedimentary package and generation of peraluminous granites (Page et al., 1980). Subsequent sedimentation and felsic volcanism of the Edith River-El Sherara Groups transitional domain took place in a terrestrial to shallow water setting (Needham and Stuart-Smith, 1985), and was accompanied by the emplacement of an extensive I-type granite suite, the Cullen Batholith (Wyborn et al., 1988).

2.4.2 ARNHLEM INLIER

The Arnhem Inlier (Rawlings et al., 1997; Madigan and Rawlings, 1994) is basement to the northeastern part of the McArthur Basin (Figure 2.6). It includes folded turbidites, greenschist to granulite-facies metasedimentary rocks and associated anatexic granite, and a younger granite batholith (Giddy suite; Wyborn, 1997). The turbidites are interpreted as the partial protolith for the metamorphic and anatexic units of the Inlier, and are thought to be contiguous with parts of the Pine Creek and Murphy Inliers (Rawlings et al., 1997). Metamorphism and deformation took place at ~1870 Ma during the Barramundi Orogeny (Etheridge et al., 1987; Page and Williams, 1988), interpreted by Rawlings et al. (1997) to be an episode of zonal thermal metamorphism.

A high-level granite batholith of distinctive A-type chemistry was emplaced as broad concordant sheets into the sedimentary and metamorphic units at ~1840 Ma. Thin erosional remnants of possible comagmatic felsic volcanics and associated epiclastic rocks are also preserved. These belong to the 1870-1820 Ma suite of Wyborn et al. (1987) and the 'Transitional phase' of volcanism of Rawlings (1994a).
McArthur Basin

- Shelves
- Fault Zones
- post-McArthur Basin units
- Basement units

Figure 2.6 Principal tectonic elements and geological divisions of the McArthur Basin - Mount Isa Inlier region, northern Australia, including basement terranes. Modified after Plumb et al. (1980 & 1990), Pietsch et al. (1991a) and Rawlings et al. (1997).
2.4.3 MURPHY INLIER

The Murphy Inlier (or Murphy Tectonic Ridge; Figure 2.6) is thought to have been a depositional barrier between the southeastern McArthur Basin and the adjacent Mount Isa Basin (Plumb and Derrick, 1975; Ahmad and Wygralak, 1989). The oldest component of the Inlier, the turbiditic Murphy Metamorphics (Ahmad and Wygralak, 1990), were deformed and metamorphosed to greenschist facies during the Barramundi Orogeny. They are unconformably overlain by the felsic Clifftale Volcanics and have been intruded by the comagmatic ~1860-1840 Ma I-type Nicholson Granite, similar to the Cullen Batholith and numerous granite plutons of the Mount Isa Inlier (Wyborn et al., 1988).

2.4.4 OTHER INLIERS

A number of small fault- and unconformity-bound inliers of basement rocks are exposed in the McArthur Basin (Figure 2.6). They contain mainly felsic volcanic and intrusive rocks, of comparable composition and geochemistry to other units of the 'Transitional phase' of volcanism (Rawlings, 1994a). They include the Scrutton Inlier, comprising the ~1850 Ma Scrutton Volcanics in the BFZ (Pietzsch et al., 1991a) and the Urapunga Inlier comprising the ~1850 Ma Urapunga Granite and Mount Reid Rhyolite in the Urapunga Fault Zone (Page et al., 2000).

2.5 MCArTHUR BASIN

The Palaeo- to Mesoproterozoic McArthur Basin (Figure 2.6) is a ~5-15 km thick platform cover sequence of mostly unmetamorphosed sedimentary and lesser volcanic rocks deposited on the North Australian Craton between ~1815-1450 Ma (Plumb, 1979a&b). Exposures of the basin cover an area of about 180 000 km² in a roughly northwest trend from the Queensland-Northern Territory border, along the west coast of the Gulf of Carpentaria, to the north coast of Arnhem Land. It is bounded by older Palaeoproterozoic rocks of the Murphy Inlier in the southeast, the Pine Creek Inlier in the northwest, and the Arnhem Inlier in the north. Elsewhere, rocks of the McArthur Basin extend beneath Neoproterozoic and Phanerozoic cover or the sea, such that its subsurface extent is poorly known. The McArthur Basin is divided geographically and tectonically into the southern and northern McArthur Basin, bisected by the EW-trending Urapunga Fault Zone (Figure 2.6).

The most comprehensive study of the southern part of the basin is documented in Jackson et al. (1987), whilst the northern part of the basin, within Arnhem Land, is discussed in Plumb and Roberts (1992), Rawlings et al. (1997) and Haines et al. (1999). Recent amendments to regional basin stratigraphy are outlined in Pietzsch et al. (1994), Rawlings et al. (1997) and Rawlings (1999). Interpreted correlations between the McArthur Basin and other Proterozoic basins of northern Australia are summarised by Plumb (1985) and Plumb et al. (1990).

The McArthur Basin is a mixed carbonate-siliciclastic succession with minor volcanic units near the base. Rock types include quartzose sandstone, mudstone, dolostone and minor mafic and felsic volcanic rocks. Deposition took place in a variety of intracratonic settings, ranging from fluvial and lacustrine to shallow marginal marine. It is currently divided into a number of groups on the basis of apparently major regional discontinuities, and on geographic distribution
of rock units (Figure 2.7 & 2.8). The oldest groups are dominated by thick tabular quartzose sandstone units, and most contain lesser siliciclastic-dolomitic mudstone and basaltic-rhyolitic volcanics and high-level intrusives. They range up to 6 km thick and are the most areally extensive units in the McArthur Basin. Overlying stromatolitic and evaporitic dolomite-dominated groups are generally confined to elongate outcrop belts (see below) and host important stratiform base metal mineralisation. The youngest component of the McArthur Basin is a widespread cyclic siliciclastic sequence deposited as a broad platform over the older groups.

2.5.1 Tectonic framework

Several tectonic elements, which controlled sedimentation and deformation within the McArthur Basin to various extents, are shown in Figure 2.6 (Plumb and Derrick, 1975; Plumb et al., 1980; Plumb et al., 1990; Plumb and Wellman, 1987; Rawlings et al., 1997). The meridional-trending Walker Fault Zone (WFZ) and Batten Fault Zone (BFZ) bisect the northern and southern McArthur Basin respectively, flanked by tectonically 'stable' shelves to the east and west. In the northern McArthur Basin, the WFZ is flanked by the Caledon Shelf to the east and the Arnhem Shelf to the west, whilst in the southern McArthur Basin, the BFZ is flanked by the Bauhinia Shelf to the west and Wearyan Shelf to the east. Most workers argue that these tectonic features were inherited from the underlying orogenic and transitional domains (e.g., Plumb et al., 1980; Etheridge et al., 1987; Rogers, 1996).

The BFZ and WFZ are 50-80 km wide and 100s of kilometres long, within which up to 10 km of section is preserved compared with ~4 km on the marginal shelves (Plumb and Wellman, 1987). The rocks in the WFZ and BFZ are more deformed than rocks on the shelves, which are characterised by lateral uniformity of facies and thickness, and minor deformation. Thickening of units within the fault zones is constrained to specific sedimentary intervals, interpreted to have been deposited within intracontinental 'rift' structures, defined as the Walker and Batten Troughs (Plumb and Wellman, 1987). The basal Tawallah Group and correlatives maintain a thickness of 3-6 km in both the fault zones and the shelves, whilst the overlying McArthur Group and correlatives thicken to ~5 km in the fault zones (Plumb and Wellman, 1987; Haines et al., 1999). Markedly attenuated equivalents of this package lap onto the shelves which were, at times, sites of erosion (Rawlings et al., 1997). Pietsch et al. (1991a) presented an alternative model, in which the thick succession of McArthur Group preserved in the BFZ was the result of later differential uplift of the bounding shelves. The WFZ and BFZ are separated by the EW-trending Urupunga Fault Zone, which is itself characterised by attenuated sequences and locally exposed basement, the Urupunga Tectonic Ridge (Plumb and Wellman, 1987).

The tectonic framework and terminology of troughs, fault zones and shelves, developed by Plumb et al. (1980) and Plumb and Wellman (1987), is used throughout this thesis. However, it should be noted that this framework was devised principally in reference to the palaeogeographical development of the McArthur Group and equivalents and, while it is useful for geographical location in regional discussions, there is no implied control on the distribution patterns of other elements of the McArthur Basin succession.
Figure 2.7 Regional geological divisions of the McArthur Basin, northern Australia, showing spatial distribution of various groups. Does not include established or inferred subsurface extent. Tectonic framework modified after Plumb et al. (1988 & 1990); Pietusch et al. (1991a) and Rawlings et al. (1997).
Figure 2.8 Established lithostratigraphy of the McArthur Basin, modified after Jackson et al. (1987), Pietsch et al. (1994), Kruse et al. (1994), Rawlings et al. (1997), Abbott et al. (in prep.), Sweet et al. (1996) and Carson et al. (1996). Published SHRIMP U-Pb zircon ages after Kruse et al. (1994), Pietsch et al. (1994 & 1997), Rawlings et al. (1997), Page and Sweet (1998), Rawlings and Page (1999), Jackson et al. (2000a&b) and Page et al. (2000). *denotes units which are assigned to the incorrect formation on recent geological mapsheets; incorrect stratigraphic names are indicated by inverted commas; correct names are in parentheses. ^denotes new or revised stratigraphic names which are included in the appendix. Diagram not drawn to scale.
2.5.2 Lithostratigraphy

Groote Eylandt Group

The Groote Eylandt Group (Pietsch et al., 1997) is a succession of essentially undeformed, flat-lying to gently-dipping, coarse-grained fluvialite to shallow water siliciclastics and lesser felsic and mafic volcanic rocks (Figure 2.8). It forms the oldest known component of the McArthur Basin, lying unconformably on -1840 Ma basement in the Groote Eylandt region (Figure 2.7). Lateral contiguity of the sequence beyond the Caledon Shelf is conjectural and a maximum composite thickness of 1650 m has been suggested by Pietsch et al. (1997). The age of the basal part of the Groote Eylandt Group is constrained by the 1814±8 Ma Bickerston Rhyolite, however, the inferred Statherian age of the upper part of the Group is only constrained by correlation with the Tawallah Group (Pietsch et al., 1994; Rawlings et al., 1997).

Edith River Group

Although not traditionally included in the McArthur Basin, at least part of the Edith River Group can be considered a valid component of this succession on geochronological and lithostratigraphic grounds (Jagodzinski, 1999). The Edith River Group is a mildly deformed felsic volcanic and coarse-grained siliciclastic interval that is up to ~1500 m thick. It is exposed at the western extremity of the McArthur Basin (Figure 2.7), but its lateral extent is difficult to determine, as it is largely obscured by younger cover units. The internal stratigraphy, volcanology and geochronology are discussed in Needham and Stuart-Smith (1985), Jagodzinski (1992 & 1999), Friedmann and Grotzinger (1994) and Kruse et al. (1994). The Edith River Group lies unconformably on the ~1870 Ma Pine Creek succession and is turn unconformably overlain by the Katherine River Group (Needham and Stuart-Smith 1985; Kruse et al., 1994), providing a minimum age of 1720±7 Ma (Rawlings and Page, 1999).

Tawallah Group

The Tawallah Group (~1790-1710 Ma) is the oldest segment of the southern McArthur Basin, unconformably overlying various Orosirian basement units, including the Cliffsdale Volcanics (Murphy Inlier; Ahmad and Wygrala, 1989), Scrutton Volcanics (Pietsch et al., 1991a) and Urapunga Granite (Page et al., 2000), providing a maximum age for the Tawallah Group of ~1850 Ma. It is in turn unconformably overlain by the Statherian McArthur Group in the Batten Fault Zone (BFZ) and by a variety of younger units elsewhere. The minimum age for the Tawallah Group is constrained by the oldest date obtained from the overlying McArthur Group (~1650 Ma; Page et al., 2000). The youngest internal SHRIMP zircon age obtained for the Tawallah Group is 1713±7 Ma for the Tanumbirini Rhyolite near the top of the Group (Figure 2.8; Page and Sweet, 1998). However, a younger age of 1708±5 Ma has been obtained for rhyolite clasts in the overlying Nyanantu Formation (Page et al., 2000).

The Tawallah Group is dominated by shallow marine to fluvial sandstone, with lesser mudstone, dolostone, mafic and felsic igneous intervals, and forms a regionally-extensive
'platform' 2.5-6 km thick. Resistant sandstone ranges and plateaux of Tawallah Group occur in a belt stretching from the Murphy Inlier (Qld-NT border) in the southeast, to the Hells Gate Hingeline in the northwest. Outcrop is essentially continuous over the BFZ, Wearyan Shelf and eastern Bauhinia Shelf (Figure 2.7). An area of ~60 000 km² is currently exposed, however, as it is largely concealed by younger units, it probably has a significantly wider extent. Based on geophysical evidence (Plumb and Wellman, 1987), the subsurface distribution of the Tawallah Group can be extrapolated westward onto the Bauhinia Shelf proper. The absolute northwestern and southeastern distribution limits are the Urapunga Fault Zone (Tectonic Ridge) and Murphy Inlier (Tectonic Ridge) respectively, however, the Tawallah Group is probably contiguous with the KRG in the northern McArthur Basin. It is also considered to be quasi-contiguous with the Tennant Creek Inlier to the south and Mount Isa Inlier to the southeast (Plumb and Wellman, 1987; Pietsch et al., 1994; Figure 2.3). Continuation of the succession to the north, under the Gulf of Carpentaria, is more conjectural. Field studies and geophysical interpretation (Plumb et al., 1980; Plumb and Wellman, 1987; Haines et al., 1993) support uniform thickness and facies characteristics throughout the BFZ and bounding shelves. Within the BFZ, the Tawallah Group has been more intensely deformed by brittle faults than on the adjacent shelves, where outcrop is generally flat-lying or gently-dipping (Rogers, 1996).

The lithostratigraphic components of the Tawallah Group are summarised in Figure 2.8. The oldest siliciclastic units, the Westmoreland Conglomerate and Yiyintyi and Sly Creek Sandstones, constitute about two-thirds of the total composite thickness of the Tawallah Group (~2.5 km), with an intervening 0.1-1.6 km thick flood basalt unit, the Seigal Volcanics. These are overlain by a more diverse sequence of sandstone, dolostone, mudstone and bimodal volcanic and high-level intrusive units (McDermott Formation through to Burash Sandstone). A number of local and regional hiatuses and erosional unconformities are recognised within the Tawallah Group (Ahmad and Wygralak, 1989; Haines et al., 1993; Bull and Rogers, 1996; Rogers, 1996; Jackson et al., 2000a).

**Donydji Group**

Outcrop of the Donydji Group is restricted to the Mitchell-Flinders Thrust Belt, an elongate meridional deformed zone in northeast Arnhem Land (Figure 2.6 & 2.7; Rawlings et al., 1997). It comprises 2-3 km of coarse-grained fluvialite to shallow marine siliciclastics and bimodal (felsic-mafic) igneous rocks that unconformably overlies the ~1870 Ma Mtirrmina Complex (Figure 2.8). It is in turn conformably overlain by the Parsons Range Group. The minimum age of the Donydji Group is well constrained by ~1710 Ma ages for concordant igneous units (Fagan Volcanics) at the top of the Group (Rawlings et al., 1997). Lateral continuity of the Donydji Group with obscured Katherine River Group immediately to the west (Arnhem Shelf) and Spencer Creek Group to the east (Caledon Shelf) has been interpreted on the basis of geophysical evidence (Plumb, in Rawlings et al., 1997; Figure 2.7).
Katherine River Group

The Katherine River Group is characterised by a relatively undeformed, regionally-extensive 'platform' of shallow marine to fluvial quartzose sandstone, and lesser bimodal volcanic and high-level intrusive rocks and mudstone. The Group crops out in western Arnhem Land (northern McArthur Basin, Figure 2.7), where it has a composite thickness of ~2-5 km (Kruse et al., 1994; Sweet et al., 1999b). It lies unconformably to disconformably on various Orosirian basement units of the Pine Creek Inlier and is unconformably overlain by the Mount Rigg Group (Figure 2.8). The minimum age for the Katherine River Group is constrained by the ~1710 Ma West Branch Volcanics near the top of the Group (Kruse et al., 1994). On the basis of field and geophysical data, the Katherine River Group is inferred to have uniform thickness and facies characteristics over a broad area of the Arnhem Shelf, but thins against bounding features such as the Pine Creek Inlier and Urapunga Tectonic Ridge (Plumb and Wellman, 1987; Kruse et al., 1994).

Spencer Creek Group

The Spencer Creek Group (Rawlings et al., 1997), which is exposed on the northeastern peninsula of Arnhem Land (Figure 2.7), comprises 1200-1500 m of shallow water sandstone and mudstone, and extrusive or high-level intrusive felsic igneous rocks. It unconformably overlies the ~1870 Ma Bradshaw Complex and is unconformably overlain by the Mount Bonner Sandstone (age uncertain; Figure 2.8). Age constraints for the Spencer Creek Group are poor due to inconclusive relationships of contained felsic igneous units (Rawlings et al., 1997). These igneous units have SHRIMP zircon ages of ~1720-1710 Ma, and provide only a minimum age for most of the Group. Although outcrop is restricted to an isolated inlier on the northern Caledon Shelf, geophysical interpretation suggests the Spencer Creek Group is an attenuated but contiguous subsurface equivalent of the Donydji Group ~70 km to the southwest (Plumb, in Rawlings et al., 1997).

Parsons Range Group

The Parsons Range Group (Haines et al., 1999) is an undeformed sequence of shallow marine and fluvial sandstone and minor mudstone and carbonate which lies conformably between the Donydji and Balma Groups (Figure 2.8). Outcrop is restricted to three small areas within the WFZ in eastern Arnhem Land (Figure 2.7), such that its depositional geometry is conjectural. The Group reaches a maximum thickness of ~6 km in the Parsons Range area, where it is interpreted to have been deposited during an early phase of rifting of the Walker Trough (Rawlings et al., 1997; Haines et al., 1999). Thickness variations beyond the Parsons Range have been interpreted from geophysical analysis, with the sequence inferred to thin rapidly away from the depocentre (Plumb, in Rawlings et al., 1997). Grossly attenuated lateral equivalents have been tentatively identified onlapping the Caledon Shelf (Rawlings et al., 1997). The age of Parsons Range Group is constrained by SHRIMP zircon geochronology for the underlying Pagan Volcanics (~1710 Ma; Rawlings et al., 1997) and upper part of the overlying Balma Group (1620±21 Ma; Haines, 1994).
McArthur Group

The McArthur Group (Jackson et al., 1987; Pietsch et al., 1991a) is a ∼4.5 km thick succession of interbedded stromatolitic and evaporitic dolostone, sandstone, mudstone and minor tuffaceous mudstone, deposited mainly in shallow water environments. The McArthur Group is weakly to strongly deformed and outcrop is restricted to the BFZ (Figure 2.6 & 2.7). It unconformably overlies the Tawallah Group, providing a maximum age of ∼1710 Ma. It is unconformably overlain by the ∼1590 Ma Nathan Group throughout the McArthur Basin, except at the type section in the Abner Range area (Jackson et al., 1987), where a paraconformable contact is evident (Haines et al., 1999). SHRIMP zircon ages that have been determined for the McArthur Group include 1648±3 Ma (Taraola Sandstone; Page et al., 2000), 1640±4 Ma (Barney Creek Formation; Page and Sweet, 1998), 1625±2 Ma and 1614±4 Ma (Stretton Sandstone and Amos Formation respectively; Page et al., 2000).

The McArthur Group is divided by a local unconformity into two approximately equal parts, the Umbolooga Subgroup and the overlying Botten Subgroup (Figure 2.8; Jackson et al., 1987). Although deposition of both subgroups is generally regarded as having been fault-controlled and constrained within the Botten Trough, the Botten Subgroup is more restricted in its distribution, apparently as a result of intensified marginal fault movements (Jackson et al., 1987). Most units were deposited in a restricted intracontinental lacustrine to marine setting, variably affected by tidal and supratidal processes. At least two units are interpreted as sub-wavebase euxinic in origin, the Barney Creek Formation and the Carabiriini Member of the Lynott Formation (Brown et al., 1969; Bull, 1998). However, alternative shallow saline lake/lagoon models have been proposed by Logan and Williams (1984) and Jackson et al. (1987). The McArthur Group contains the HYC sediment-hosted Zn-Pb-Ag deposit at McArthur River.

Balma and Habgood Groups

The Balma and Habgood Groups (Haines et al., 1999; Rawlings et al., 1997) crop out in northeast Arnhem Land, and although separated by 30 km of younger cover rocks, are thought to be contiguous in the subsurface. They comprise similar ∼5 km thick successions of interbedded mudstone, dolostone and sandstone of shallow water origin, with moderately deep-water and emergent conditions prevailing in some units. There is also a minor tuffaceous component to these two groups. The Balma and Habgood Groups conformably overlie the Parsons Range Group, and are in turn unconformably overlain by the Nathan Group. Outcrop is restricted to the WFZ (Figure 2.6 & 2.7). Haines et al. (1999) interpreted syndepositional fault activity to be responsible for a number of internal disconformities and conglomerate fans within the Balma and Habgood Groups (Figure 2.8). Reactivation of these fault systems during subsequent basin inversion events has led to varying degrees of deformation within the WFZ and Mitchell-Flinders Thrust Belt (Figure 2.6).

The age of the upper Balma Group is constrained internally by SHRIMP zircon dates of 1620±21 and 1599±11 Ma for tuffaceous mudstone beds (Haines et al., 1999). The maximum and minimum ages are provided by the underlying Dondji Group (∼1710 Ma;
Rawlings et al., 1997) and overlying Nathan Group (-1590 Ma; Jackson et al., 2000b) respectively. Although facies represented in each group are distinct, Haines (1994) has correlated units within the Balma, Habgood and McArthur Groups on sequence stratigraphic and geochemical grounds.

Vizard Group

The Vizard Group (Abbott et al., in prep.) is exposed over an area of ~100 km² in the Urupunga Inlier (Figure 2.7). It comprises at least ~1 km of dolomitic, silicilastic and minor reworked tuffaceous rocks deposited in moderately deep water to shallow and locally emergent conditions. The true thickness of the Vizard Group is difficult to determine due to extensive younger cover, and the uncertainty as to how much of the sequence has been structurally or erosionally removed. The exposed units are similar in many respects to the medial McArthur Group, with which the Vizard Group has been correlated (Figure 2.8; Haines, 1994; Abbott et al., in prep.). The Vizard Group lies unconformably between the Katherine River Group (below) and Nathan Group (above).

The current distribution of the Vizard Group appears to be at least partly controlled by the EW-trending Urupunga Fault Zone and Hells Gate Hinge Line (Figure 2.6), possibly as a result of structural imbrication during basin inversion, although potential eastward extensions are largely covered by younger cover units. Outcrop is generally only weakly deformed, although thrust repetitions are evident (Abbott et al., in prep.). It is not certain what control, if any, these fault systems had on deposition of the Vizard Group, or whether this group is contiguous in the subsurface with the Balma and McArthur Groups, ~100 to the north and ~50 km to the southeast respectively.

The maximum and minimum ages of the Vizard Group are provided by the underlying Katherine River Group (~1710 Ma; Kruse et al., 1994) and overlying Nathan Group (~1590 Ma; Jackson et al., 2000b) respectively. At present the Vizard Group is internally constrained by dates on the Nagi (1634±4 Ma) and St Vigeon (1640±4 Ma) Formations, correlating well with the ~1640-1620 Ma medial McArthur Group (Page et al., 2000).

Nathan Group

Outcrop of the Nathan Group is widespread in the southern McArthur Basin (Jackson et al., 1987) and also extends northward into eastern Arnhem Land (Figure 2.7; Rawlings et al., 1997). Distribution is largely unrelated to the pre-existing tectonic framework of fault zones and shelves, however, significant deformation is restricted to the BFZ and WFZ (Figure 2.6). The Nathan Group, including the correlative Kaps Dolomite (Pietsch et al., 1991a), consists of similar dolomitic rocks to the McArthur Group and was deposited in a shallow marginal marine or continental sabkha setting (Jackson et al., 1987). The Group is composed of a basal fluvial chert-clast sandstone, overlain by 50-1600 m of shallow water stromatolitic and ooidal dolostone and minor silicilastic sandstone. Thickness variations are largely due to extensive post-depositional erosion (Pietsch et al., 1991a). A thin basaltic volcanic unit, the Yalwara Volcanics,
is recognised only in the Urapunga Fault Zone (Figure 2.6 & 2.8; Abbott et al., in prep.). The Nathan Group overlies the McArthur, Habgood and Balma Groups, and all older units, with regional disconformity or unconformity. The exception is the area of the Balbirini Dolomite type section, where a paraconformable boundary is evident. Statistical overlap in SHRIMP dates for the lower Balbirini Dolomite (1613±4 Ma and 1609±3 Ma; Jackson et al., 2000b) and Amos Formation (uppermost McArthur Group; 1614±4 Ma) suggest the lower Nathan Group has greater affinity with the underlying McArthur Group in this area (Haines et al., 1999). The 1589±3 Ma age for the middle Nathan Group supports the existence of a more prominent hiatus within this Group, rather than at the base (Haines et al., 1999). Consequently, only the middle to upper part of the Nathan Group mapped around the type section is equivalent to the Nathan Group mapped elsewhere.

Mount Rigg Group

The Mount Rigg Group (Plumb and Roberts, 1992; Kruse et al., 1994) crops out along the western margin of the northern McArthur Basin, mostly on the Arnhem Shelf (Figure 2.7). A section at least 500 m thick is exposed in central and southwestern Arnhem Land (Kruse et al., 1994; Sweet et al., 1999b), where it lies unconformably between the Katherine River Group (below) and Roper Group (above). Both unconformities are of regional extent, but neither are markedly angular. The Mount Rigg Group is generally undeformed, and is dominated by chertified stromatolitic and ooidal dolostone and sandstone, deposited in a shallow peritidal-shelf setting (Kruse et al., 1994). A basal fluvial to intertidal sandstone and conglomerate unit is recognised locally. The Mount Rigg Group, which has been tentatively correlated with the Nathan Group (Jackson et al., 1987; Plumb et al., 1990), is constrained in age between -1710 Ma (Katherine River Group; Kruse et al., 1994) and 1429±31 Ma (Roper Group; Kralik, 1982).

Roper Group

The youngest component of the McArthur Basin is the Roper Group, a widespread cyclic sequence of fine- and coarse-grained siliciclastic rocks deposited in a variety of shallow marine, nearshore to shelf environments (Powell et al., 1987; Jackson et al., 1988; Abbott and Sweet, 2000). Powell et al. (1987) and Jackson et al. (1988) have interpreted the Roper Group as an amalgamation of five coarsening-upward (progradational) cycles. However, the established lithostratigraphy of this group (Figure 2.8) is currently under review as a result of recent mapping in the Urapunga Fault Zone (Abbott et al., in prep.).

Distribution and depocentres of the Roper Group are significantly different to the underlying units of the McArthur Basin and appear largely unrelated to the former tectonic framework (Rawlings et al., 1997). Erosional remnants of the Roper Group are common throughout the northern and southern McArthur Basin and range up to 5 km thick (e.g., the Beetalo Sub-basin on the Bathinna Shelf; Figure 2.6 & 2.7; Plumb and Wellman, 1987). A notable feature of the Roper Group is the spatial abundance of dolerite-gabbro sills.
The Roper Group rests unconformably on Nathan Group (~1590 Ma; Jackson et al., 2000b) and various older units, and is unconformably overlain by Neoproterozoic to Mesozoic cover sequences (Kruse et al., 1994; Rawlings et al., 1997). Deformation is typically manifested as broad dome and basin structures, but intense deformation is recognised along the principal fault systems, such as the BFZ and Urapunga Fault Zone (Figure 2.6).

The age of the Roper Group is constrained by a Rb-Sr determination of 1429±31 Ma for diagenetic illite in the McMinn Formation (Figure 2.8; Kralik, 1982) and a SHRIMP U-Pb zircon date of 1492±4 Ma for the Mainoru Formation (Jackson et al., 1999). A minimum age of ~1280 Ma comes from K-Ar dating of a dolerite sill that has intruded the upper part of the Group (McDougall et al., 1965).

2.5.3 TECTONIC SETTING

Following cratonisation of the northern Australian orogenic domains during the Barramundi Orogeny, a fundamental framework of deep-seated NW-, NNW- to NNE- and NE-trending crustal structures had been established (Etheridge et al., 1987). Through subsequent reactivation, these structures became the major controlling influence on the depositional geometry of the succeeding McArthur Basin and the localisation of later deformation (Plumb, 1979a&b; Etheridge and Wall, 1994; Rogers, 1996). Most of the existing basin evolution models promote extensional tectonics, in which specific fault orientations acted as normal or growth structures and others acted as accommodation or transfer structures during various stages of basin formation. The models differ in the interpretation of extensional and compressional orientations, principally because of the difficulty in recognising primary extensional fault families and geometric relationships, which have been overprinted by later structural inversion. Subsequent compressional reactivation of the extensional fault systems is interpreted to have occurred at least three times during and after basin development (Plumb, 1994; Rogers, 1996).

2.6 COVER SEQUENCES

The McArthur Basin is unconformably overlain by a variety of younger epicratonic basins and Cenozoic regolith and soil. Late Neoproterozoic to Devonian continental and shallow marine siliciclastics and lesser carbonates and flood basalt of the Georgina, Daly and Arafura Basins (Freeman et al., 1990; Bradshaw et al., 1990) onlap the McArthur Basin in the south, west and north respectively. These basins are also exposed as thin erosional outliers within the McArthur Basin, suggesting their original dimensions may have been substantially larger or they may have originally merged. The McArthur Basin is also unconformably overlain by thin remnants of marine and terrestrial siliciclastics of the Mesozoic Dunmarra and Carpentaria Basins (NTGS, 1990; Thomas et al., 1990). Cenozoic deposits cover about 40% of the known extent of the McArthur Basin, comprising sandy to gravelly soil, regolith, coastal deposits, dunes fields and laterite, generally no more than a few tens of metres thick. Around Gove, in eastern Arnhem Land, lateritised Carpentaria Basin rocks form the important Gove bauxite deposit.
2.7 SUMMARY

The North Australian Craton developed through a process of vertical and lateral accretion, orogenesis, cratonisation and platform sedimentation. It is bounded to the south by the Central Australian Mobile Belt and incorporates Archaean to Palaeoproterozoic basement domains and Palaeo- to Mesoproterozoic platform cover sequences, including the 1815-1450 Ma McArthur Basin. The margins of the McArthur Basin are defined mostly by younger cover sequences, indicating that it is largely a geographic feature which is more extensive in the subsurface. Basement locally defines the basin margin and also occurs as inliers and elongate tectonic ridges within the basin. The McArthur Basin is a 5-15 km thick sequence of siliciclastic, carbonate and bimodal volcanic rocks that were deposited in a shallow marine to fluvial intracratonic setting. The basin has been divided into 14 lithostratigraphic groups and 130 formations and members. Some groups were deposited within meridional fault zones or troughs, whilst others formed widespread platforms.

The geology of individual formations in the Tawallah Group will be examined in detail in the following chapters. This integrated stratigraphic, sedimentological and volcanological analysis forms the basis of a new tectonostratigraphic framework for the basal volcanosedimentary part of the McArthur Basin, the Redbank package, outlined in Chapter 8. Rather than supersede the lithostratigraphy, the object of the new framework is to show how correlative groups and formations may interrelate, and to facilitate development of a new geodynamic model for the basin (Chapter 10).
CHAPTER 3

LOWER TAWALLAH GROUP
3. Lower Tawallah Group

3.1 INTRODUCTION

This chapter provides a geologic description and interpretation of the lower Tawallah Group. Figure 3.1 shows the general location of field areas that are discussed below. The lithostratigraphic components of the lower Tawallah Group are summarised in Figure 3.2 & 3.3. The oldest siliciclastic units, the Westmoreland Conglomerate and Yiyintyi and Syl Creek Sandstones, constitute about two-thirds of the total composite thickness of the Tawallah Group (~2.5 km), with an intervening 0.1-1.6 km thick flood basalt unit, the Seigal Volcanics. These are overlain by a more diverse sequence of sandstone, dolostone, mudstone and mafic volcanic-shallow intrusive units (McDermott Formation through to Settlement Creek Volcanics). A number of local and regional erosional unconformities are recognised within this interval (Rogers, 1996; Ahmad and Wygralak, 1989; Haines et al., 1993; Jackson et al., 2000a).

Due to time and logistical constraints, fieldwork for the current study was concentrated on formations of the middle to upper Tawallah Group (Wunumbantyla Sandstone through to Burrah Sandstone; Figure 3.2). Consequently, this chapter relies to some extent on previous work, including data collected by the author during regional mapping between 1988 and 1995 (Pietsch et al., 1991a&b; Haines et al., 1993; Rawlings et al., 1993) and by Jackson et al. (1987) and Rogers (1996) as cited. Although this chapter is partly review in form, the geology and relationships of the lower Tawallah Group are crucial to the tectonostratigraphic framework and geodynamic model proposed for the Redbank package in Chapters 8 and 10. As a result, there is justification for presenting this chapter separately from the review of regional geology (Chapter 2).

The stratigraphic interval covered in this chapter was chosen because it is capped by the Wollogorang Formation, which represents a reliable regional marker with only minor lateral facies variation. Data for this chapter that was collected during the current study is mainly from the Wunumbantyla Sandstone, Aquarium Formation and Settlement Creek Volcanics. Hence, there is a bias toward the description of these formations and only a brief review of information from other units that is relevant to later chapters.

3.2 LITHOSTRATIGRAPHY

3.2.1 WESTMORELAND CONGLOMERATE

The Westmoreland Conglomerate is a ~2 km thick conglomerate-sandstone package that crops out as shallow-dipping northeast-striking ridges along the southeastern margin of the McArthur Basin, adjacent to the Murphy Inlier (Ahmad and Wygralak, 1989; Figure 3.1). The Westmoreland Conglomerate unconformably overlies Palaeoproterozoic basement units including the Murphy Metamorphics, Nicholson Granite and Clifdale Volcanics and is in turn conformably overlain by the Seigal Volcanics (Ahmad and Wygralak, 1989). A combined
Figure 3.2 Lithostratigraphy of the Tawallah Group. Formations discussed in this chapter are bold. Stratigraphic column is revised after Haines et al. (1993). *new or revised name, defined herein. Established SHRIMP U-Pb zircon geochronological data from Jackson et al. (1997)¹, Page and Sweet (1998)², and Page et al. (2000)³.
thickness of between 100 and 1800 m is comprised of 5 firing-upwards cycles of immature lithic sandstone and clast- to matrix-supported, pebble to boulder conglomerate (Ahmad et al., 1984; Wygralak et al., 1988). Each cycle is a complex facies mosaic of debris flow, sheet-flood and channel-fill deposits, representing prograding alluvial outwash fans and braidplain produced by episodic uplift of an adjacent hinterland, including the Murphy Tectonic Ridge (cf. Blair and McPherson, 1994). Southwesterly-directed palaeocurrents, parallel to the trend of the Murphy Inlier, suggest that the principal sediment source area was a northerly extension of the Mount Isa Orogen (Ahmad and Wygralak, 1989).

The Westmoreland Conglomerate probably correlates with the Yiyintyi Sandstone, the basal clastic package of the Tawallah Group in the BFZ (Jackson et al., 1987; Figure 3.3, section 3.2.2). Similar lithofacies cycles are evident in both units, even though they are widely separated, and they are interpreted to represent proximal and distal portions of a large-scale siliciclastic apron. The Westmoreland Conglomerate also correlates with the much thinner (~50 m) Wire Creek Sandstone at the base of the Peters Creek Volcanics, which crops out ~30 km south of the Westmoreland Conglomerate outcrop belt (Sweet et al., 1981; Jackson et al., 2000a; Figure 2.6). This large thickness variation emphasises the topographic control exerted by the Murphy Tectonic Ridge at this time.

3.2.2 YIYINTYI SANDSTONE
The Yiyintyi Sandstone is a 2-4 km thick package of quartzarenite, cropping out in the Batten-Tawallah-Yiyintyi-Costello Ranges in the central and northern BFZ (Figure 3.1). Detailed measured sections and facies analysis presented in Pietsch et al. (1991a), Haines et al. (1993) and Rogers (1996) form the basis of the description below.

The Yiyintyi Sandstone unconformably overlies Scrutton Volcanics with a locally-developed basal conglomerate (Rawlings et al., 1993). It is conformably overlain by Seigal Volcanics, and intruded by coeval dolerite dykes. Thickness varies from 2200 m (measured section; Figure 3.4) to 4000 m, and a four-fold subdivision and 500 m-scale cyclical appearance are unilaterally evident (Haines et al., 1993). The lower two sandstone units are typically pebbly, with large-scale (1-5 m amplitude) trough cross-bedding, and are interpreted as braided fluvial (alluvial fan) in origin (Haines et al., 1993; Rogers, 1996). The upper two units have a lesser pebble component, smaller bedforms and finer grainsize and have been interpreted as high-energy, wave- and tide-influenced shallow marine (Jackson et al., 1987; Haines et al., 1993) or medial-distal braidplain deposits (Rogers, 1996). According to Rogers, the discriminating factor between these two palaeoenvironmental alternatives is the absence of intervals of mudstone or siltstone, mudstone drapes and hummocky cross-stratification (HCS) and the apparent absence of intermediary facies between the inferred fluvial and shallow marine units. The depositional setting is discussed further in section 3.3.

Haines et al. (1993) presented evidence for unimodal and bimodal palaeocurrent patterns in the Yiyintyi Sandstone, but noted an overall inconsistency in direction. Bipolar
Figure 3.4 Summarised measured section through the Yilintyi Sandstone in the Costello Range.
Measured section MY90/4, modified after Haines et al. (1993). Fault repetitions and dykes omitted.
Legend in Appendix 2.
trends, generally evidence for shallow marine tidal-influence, are not apparent. Dominantly southwesterly-directed palaeocurrents for the lower Yiyintyi Sandstone in the Yiyintyi Range are consistent with B. Roberts' observations (in Jackson et al., 1987) that the main sediment source was to the northeast. Similar southwesterly patterns are evident in the coeval Westmoreland Conglomerate (Ahmad and Wygrala, 1989). In contrast, palaeocurrents from the lower Yiyintyi Sandstone in Tawallah Range are directed to the northeast and southeast (Haines et al., 1993), suggesting a reversal in depositional polarity. Petrographic studies by Rawlings et al. (1993) are consistent with a mature first-cycle provenance dominated by silicic volcanic, plutonic and metamorphic sources. These probably equate to temporal equivalents of the underlying Scrutton Volcanics, Palaeoproterozoic granites and 'Barramundi-ke' meta-sedimentary basement units.

Lateral facies and thickness changes within the Yiyintyi Sandstone are difficult to establish, as this unit is concealed by younger cover on the Bauhinia and Wearyan Shelves and outcrop in the BFZ is segmented by block faulting. However, there is an apparent increase in thickness from ~2 km in the south (Tawallah Range) to >4 km in the north (Yiyintyi Range) of the northern BFZ (Figure 3.3). A uniform sheet-like lateral continuity of the package beyond the northern BFZ is interpreted on the basis of magnetic and gravity data (Plumb and Wellman, 1987), but seismic profiles are required to assess this fully.

On the basis of lithostratigraphy, the Yiyintyi Sandstone is correlated with the Westmoreland Conglomerate (Murphy Inlier; Figure 3.2; Jackson et al., 1987), Woodah and Alyinga Sandstones on Groote Eylandt (Pietsch et al., 1997; Figure 2.7 & 2.8) and Mamadawerre Sandstone (lower Katherine River Group) on the Arnhem Shelf (Carson et al., 1999; Sweet et al., 1999a&b).

3.2.3 Seigal Volcanics

The Seigal Volcanics comprise a widespread 100-1600 m thick flood basalt unit, exposed around the Murphy Inlier and Tawallah Ranges areas (Figure 3.1). In the Tawallah Ranges, Seigal Volcanics lie conformably on Yiyintyi Sandstone and are conformably or disconformably overlain by Sly Creek Sandstone (Pietsch et al., 1991a). They exhibit a sheet-like morphology, but thickness increases gradually from north to south over ~100 km (Figure 3.3); 100 m is exposed in Yiyintyi Range, 200-500 m in Tawallah Range and 300-400 m in Batten Range (Jackson et al., 1987; Haines et al., 1993; Figure 3.1). The volcanics are poorly exposed, but appear to be a composite basalt-microdolerite section, characterised by a systematic vertical variation in grain size and vesicle content. Haines et al. (1993) suggested that individual flow units could be distinguished on the basis of upward-increasing size and abundance of vesicles. Localised vertical gas-escape pipes and common polygonal jointing are also present in the basalt sheets. All sections of the Seigal Volcanics appear to be devoid of associated breccias, sedimentary beds and erosional hiatuses, suggesting dominantly rapid subaerial deposition (Rawlings et al., 1993). However, hyaloclastite breccia is present locally, indicating emplacement into local restricted water bodies.
New data from the Murphy Inlier

The following description is based largely on new field data from the type area (China Wall) and drill core from near Westmoreland (Figure 3.1). Along the northern flank of Murphy Inlier, Seigal Volcanics lie conformably on Westmoreland Conglomerate and are conformably to disconformably overlain by Rossmere Sandstone, which was not differentiated from the McDermott Formation by Ahmad and Wygrala (1989). The volcanics are unconformably overlain by Wumunmantyala Sandstone locally. The Seigal Volcanics range in thickness from ~1600 m in the northeast (Sweet et al., 1981) to ~900 m in the southwest at the China Wall type area (Figure 3.5), where some of the section has been removed by the ‘Wumunmantyala surface’ (Figure 3.3). This formation can be subdivided into a lower basalt-dominated unit and an upper mixed basalt-sediment unit, separated by the Carolina Sandstone Member.

Lower Seigal Volcanics

A thin (2-3 m) red/brown or green mudstone bed commonly marks the base of the Seigal Volcanics. In DDH 6SL4 (Figure 3.6), this bed has been disrupted into a peperitic mass by the overlying basalt (Plate 3.1A-B). In outcrop, the lower 200-800 m of Seigal Volcanics is a monotonous package of brown to grey, weathered aphyric basalt and microdolerite with scattered vesicles (Figure 3.5). However, internal architecture is revealed in drill core (Figure 3.6), comprising 5-20 m thick cycles of vesicular basalt (sheet margins) and massive fine- to medium-grained dolerite (sheet interiors). The latter is typically microvesicular in thin-section (see below). Boundaries between vesicular and massive domains are typically gradational and subtle; discrete (erosional) bounding surfaces and intervening sedimentary beds are generally absent.

Carolina Sandstone Member

The Carolina Sandstone Member is a 2.5-20 m thick unit of thin-bedded fine-grained sandstone with ripples and mudcracks. Local coarse-grained and conglomeratic facies with trough cross-beds are also present. The lower erosional contact lies 800 m above the base of the Seigal Volcanics in the northeast and 200 m above the base in the southwest (Sweet et al., 1981), where the member bifurcates into a thick lower sandstone-conglomerate unit (Plate 3.1C) and a thin upper fine-grained sandstone unit, divided by 30-100 m of basalt. The apparent progressive southerly incursion of the lower Seigal Volcanics by the sandstone (Appendix 3.9) is accompanied by an increase in thickness, grain size and proportion of silicified sandstone clasts, probably recycled from the Westmoreland Conglomerate.

Upper Seigal Volcanics

The 500-800 m thick upper Seigal Volcanics comprise similar basalt-microdolerite sheets to the lower unit, but contain interdigitated red-brown muddy sedimentary beds (~5% by vol.). In outcrop, the package is grossly stratified on a 20 m-scale, giving the impression of stacked lava flows. Recessive basalt sheets are in many cases divided by resistant benches of silicified mudstone and basalt-sediment breccia, in which angular basalt clasts are dispersed in a sedimentary matrix. Sweet et al. (1981) interpreted these breccias as lava flow-top breccias subsequently infilled by
Figure 3.5 Schematic section through the Seljal Volcanics at the type area, China Wall. The distribution and thickness of peperite horizons is schematic only; however, other thicknesses are accurate.
Figure 3.6  Graphic drill-log for the lowermost Seigal Volcanics, below the Carolina Sandstone Member, in DDH 6SU/4, Westmoreland.
Plate 3.1 Various features of the Seigal Volcanics. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1.


C: Cobbly sandstone of the Carolina Sandstone Member, China Wall locality W25.

D: Photomicrograph of typical doleritic texture of the Seigal Volcanics. Large altered plagioclase laths and equant fresh pyroxene are surrounded by devitrified glass with acicular and microgranophyric texture. Thin-section 4060 (Westmoreland). Plain-polarised light.

E: Photomicrograph of devitrified glassy domain of basalt in the Seigal Volcanics, comprising the small acicular feldspar laths within brown cryptocrystalline groundmass. Thin-section 4046 (Westmoreland). Plain-polarised light.


G-H: Photomicrographs of fresh dolerite from a dyke within the Westmoreland Conglomerate. Laths of plagioclase and intergranular to subophitic pyroxene are separated by isotropic glassy domains. G is plain-polarised light while H is crossed polars. Thin-section 4064 (Westmoreland).
fine-grained sediment. As a result, many basalts sheets were inferred to represent lava flows emplaced into a shallow sea. Sweet et al. (1981) and Roberts et al. (1963) also interpreted some breccias as volcanic 'agglomerate'. However, clast-matrix relationships, such as matrix support, sediment baking, chilled clast margins, sediment-filled vesicles and diffuse bedding, are consistent with an invasive origin, in which basalt magma has been partly disaggregated during emplacement into a weaker unconsolidated sediment pile. Breccia of this type is referred to as peperite (Fisher, 1960; McPhie et al., 1993). A mosaic of furrows and striations imposed by the emplacement of the overlying basalt sheet, are evident on the top surface of some sedimentary beds (Sweet et al., 1981).

The contact of Rosie Creek Sandstone with underlying Seigal Volcanics at Piccaninny Creek (Figure 3.1) is characteristically diffuse and gradational. A massive basal breccia, consisting of untransported basalt fragments in a muddy matrix that lacks detrital material, is consistent with a hiatus and regolith development (cf. Retallack, 1988). This basal breccia is overlain sharply by coarse-grained white sandstone.

**Dykes in Westmoreland Conglomerate**

A number of dolerite dykes cross-cut the Westmoreland Conglomerate and basement units of the Murphy Inlier, comprising massive aphyric medium-grained dolerite with chilled margins. Geochemical data for one dyke (Chapter 9) are consistent with basalt of the upper Seigal Volcanics, suggesting they are feeders.

**Petrography**

Basalt and dolerite of the Seigal Volcanics are altered to various extents, however, in thin-section the primary mineralogy is generally evident from relics and residual mineral phases. Coarser-grained rocks (Plate 3.1D) are subophitic to intersertal with plagioclase laths (45-50%), equant olivine (5%) and interstitial clinopyroxene (25-35%). Fe-Ti oxides (5-10%) and a brown cryptocrystalline mesostasis of relic glass (up to 20%). Finer-grained sheet exteriors have intergranular textures, are generally plagioclase-phryic, and comprise more 'glassy' mesostasis (up to 50%; Plate 3.1E). Pyroxene and opaques are cryptocrystalline. Some basalt sheets in the upper Seigal Volcanics are weakly porphyritic, containing up to 10% euhedral phenocrysts of plagioclase of 2-15 mm diameter. Spherical or elliptical vesicles 2-10 mm in diameter and sporadic large vugs up to 20 cm diameter occur in the sheet margins. These are typically infilled by chlorite, with lesser quartz, carbonate, agate, zoelite, haematite and/or celadonite. Small (<2 mm) irregular chlorite-filled microvesicles are almost universally present, even in the coarse-grained holocrystalline dolerite sheet interiors, but are generally not recognisable in hand-specimen due to their size and shape (Plate 3.1F). In some instances, they resemble patchy or blebbly chlorite alteration.

Hydrothermal alteration has led to the introduction of secondary chlorite, K-feldspar, sericite, amphibole, quartz, carbonate, haematite, epidote and iddingsite in various quantities. The most intense alteration assemblage is dominated by K-feldspar-chlorite, which has generally replaced plagioclase and to a lesser extent pyroxene. In some cases however, plagioclase that has been pervasively altered to K-feldspar coexists with pristine clinopyroxene (Plate 3.1D).
In the Murphy Inlier, there appears to be a subtle but consistent textural difference between the lower and upper Seigal Volcanics. Rocks from the lower unit are generally coarser-grained and subophitic to interstenal with elongate plagioclase laths, whereas those in the upper unit are generally finer-grained and intergranular with stubby plagioclase and relatively large Fe-Ti oxide grains, and are locally porphyritic. Textures in the Tawallah Range outcrops, 200 km to the NW, are comparable to those of the lower Seigal Volcanics. Dolerite dyke rocks have petrographic affinities with the Seigal Volcanics but are generally fresher than their volcanic counterpart, with subophitic texture and residual olivine (Plate 3.1G-H).

Regional Synthesis

Internal stratification of the Seigal Volcanics has generally been interpreted to reflect rapid emplacement of successive basalt lava flows, typical of flood basalt provinces (Sweet et al., 1981; Ahmad and Wygralak, 1989). However, it is clear from drill core and outcrop features recognised during this study that individual basalt sheets are generally not bounded by a discrete erosional surface. Instead, sheets are bounded by either: (i) a zone of increased vesicularity or; (ii) a laterally continuous zone of peperite. These features are consistent with buildup of the basalt pile by two mechanisms: (i) vertical inflation or endogenous growth (cf. Self et al., 1997) and; (ii) emplacement of shallow basalt sills into wet sediment (cf. Rawlings, 1993).

Ahmad and Wygralak (1989) interpreted the lower Seigal Volcanics as subaerial and the Carolina Sandstone Member and upper Seigal Volcanics as shallow marine in origin, based on associated facies. Mudstone and fine-grained sandstone interdigitated with basalt sheets in the upper unit are consistent with subaqueous deposition of the sediments. However, as most sheets appear to have been emplaced below the sediment-water interface as shallow sills, they may have been largely free of contact with seawater explaining the scarcity of hyaloclastite breccia. Hyaloclastite in the Tawallah Range outcrops also supports local subaqueous emplacement.

Dolerite dykes intruding the Murphy Inlier and Westmoreland Conglomerate are interpreted as 'fissure' feeders to the Seigal Volcanics (Sweet et al., 1981; Chapter 9). The increase in thickness of the volcanic succession to the southeast of the McArthur Basin, and presence of significant internal unconformities around the Murphy Tectonic Ridge, suggests this was the principal site of effusion for the Seigal Volcanics. However, it may also reflect volcanic infill of a shallow-tilted topography.

The similarity of basalt stacking patterns, igneous textures and stratigraphic position favour correlation of the lower Seigal Volcanics around the Murphy Inlier with the entire Seigal Volcanics in the BFZ. This is also evident from geochemical trends (Chapter 9). The peperitic upper Seigal Volcanics appear to be absent in the BFZ, and a thick sandstone blanket (Sly Creek Sandstone) occupies this stratigraphic position (Figure 3.3).

In the Mount Isa Inlier (Figure 2.6), the correlative Eastern Creek Volcanics (Chapter 9) have a similar but considerably thicker (~7 km) stratigraphy. The basalt-dominated Cromwell Member (base) and Pickwick Member (top) are divided by a major siliciclastic package averaging
750 m thick (Lena Quartzite; Derrick et al., 1977). Thinner siliciclastic units are also present in the upper Cromwell Member and throughout the Pickwick Member. The Lena Quartzite and the various siliciclastic units are interpreted to be braided fluvial in origin and occupy significant (<1 m.y.) hiatuses in the basaltic volcanism (Eriksson and Simpson, 1993). A review of descriptions of the basalt units (Derrick et al., 1977; Eriksson and Simpson, 1993) suggests similar thick endogenously flows and peperitic margins may be the norm, but interstratified breccias are currently interpreted as lahars and pyroclastic deposits.

On the basis of lithology, geochemistry and stratigraphic position, the Seigel Volcanics correlate with similar flood basalt units in the northern McArthur Basin (Rawlings, 1994a; Pietsch et al., 1994), including the Bartalumba Basalt (Groote Eylandt; Figure 2.7 & 2.8) and Nungbalgarti Volcanics (Katherine River Group), as well as the lower Peters Creek Volcanics (Lawn Hill Platform; Figure 2.6; Jackson et al., 2000a) and Eastern Creek Volcanics (Mount Isa Inlier; Derrick et al., 1977). These correlative formations represent a voluminous and extensive volcanic event, similar in magnitude to the 175 000 km$^3$ Columbia River flood basalt province (Hooper, 1997). However, based on the likely internal hiatuses, emplacement was probably spread over a longer period of time than most flood basalt sequences.

3.2.4 Sly Creek Sandstone

The Sly Creek Sandstone is a quartzarenite unit, up to 770 m thick, exposed only in the northern and central BFZ (Figure 3.1 & 3.3; Pietsch et al., 1991a). It is absent on the Wearyan Shelf, and outcrops formerly mapped as Sly Creek Sandstone (Ahmad and Wygralak, 1989; Jackson et al., 1987) are now assigned to Wununmuntyala Sandstone on the basis of lithostratigraphy and correlative sequence boundaries (Jackson et al., 2000a). The following description is based on Jackson et al. (1987), Pietsch et al. (1991a), Haines et al. (1993), Rawlings et al. (1993) and Rogers (1996).

The Sly Creek Sandstone lies with conformity or mild disconformity between Seigel Volcanics (below) and Rosie Creek Sandstone (above; Figure 3.3). The basal contact is sharp and erosional with a local 2 m thick breccia (Rogers, 1996), and the lowermost Sly Creek Sandstone is locally pebbly or cobbly with northerly-directed palaeocurrents (Jackson et al., 1987).

Above the coarse-grained basal beds, a broad twofold facies-based subdivision of the Sly Creek Sandstone has been documented, although there is overlap in facies (Figure 3.7). The lower half of the formation is similar to the upper Yiyintyi Sandstone, comprising supermature, white, silicified fine- to medium-grained quartzarenite, with flat-bedding or low-angle planar cross-bedding, parting lineation and various ripple forms (Pietsch et al., 1991a) that typically occur in 20-100 cm thick cycles, divided by erosional scours (Jackson et al., 1987). Minor ferruginous-micaeous mudstone occurs as cm- to m-scale beds and as rip-up clasts in the sandstone. Herringbone cross-stratification has been recognised at several locations, but an overall easterly to southeasterly palaeocurrent population is present (Jackson et al., 1987; Pietsch et al., 1991a).
Figure 3.7 Summarised measured section of the Sly Creek and Rosie Creek Sandstones at the type section, Barren Range. Measured section 79/02, after Jackson et al. (1987). Legend in Appendix 2.
The upper half of the Sly Creek Sandstone is noticeably coarser-grained than the lower half, with m-scale trough cross-beds, broad shallow channels, mudclasts and local coarse-grained or pebbly conglomerate horizons with quartz and sandstone clasts (Pietsch et al., 1991a). Common 10-20 m thickening-upwards cycles are present in the northern BFZ (Rawlings et al., 1993). Thin (2-12 m) intervals of chert-cemented regolithic sandstone-breccia occur at several stratigraphic positions in the sequence, suggesting the presence of significant internal erosional breaks (Jackson et al., 1987). Variable to southerly-directed palaeocurrents were recorded by Jackson et al. (1987).

The Sly Creek Sandstone is typically supermature and is bimodally sorted in some areas, particularly in its upper part (Jackson et al., 1987). Rawlings et al. (1993) identified a distal felsic igneous provenance for detrital quartz and rock fragments. Possible detrital glaucony has been recognised locally in the upper Sly Creek Sandstone (Jackson et al., 1987).

In the central BFZ, a 10 m thick vesicular basalt unit occurs within the Sly Creek Sandstone ('Pdl', in Figure 3.3; Rawlings et al., 1993). It has a geochemical affinity with the Seigal Volcanics, suggesting it may represent distal continuation of Seigal volcanism (Haines et al., 1993).

The Sly Creek Sandstone has been interpreted as a moderately high-energy, nearshore shallow marine, tide- and wave-influenced sequence by most authors (Jackson et al., 1987; Pietsch et al., 1991a; Haines et al., 1993). This was based on the well rounded nature and unimodal or bimodal sorting of quartz grains, the presence of glaucony, planar cross-bedding, common symmetrical (wave) ripples and broad shallow channels, and an absence of tabular, matrix mud and imbricated conglomerate. Rawlings et al. (1993) interpreted 10 m scale thickening-upwards cycles as repetitious progradation and retrogradation of tidal channels across a shallow marine flat. In contrast, Rogers (1996) interpreted this unit as having a braided fluvial origin, based on comparison with documented fluvial deposits, such as the modern ephemeral Bijou Creek (Rust, 1972; Miall, 1977) and Carboniferous Ross Point Formation (Browne and Plint, 1994). Also cited as evidence was a lack of HCS, mudstone drapes on cross-bed foresets, and intermediary facies between basal fluvial units and the reportedly shallow marine units. The depositional setting is discussed further in section 3.3.

The Sly Creek Sandstone appears to thin northward within the BFZ from 770 m to 187 m over a distance of ~100 km. The existence and thickness of this unit elsewhere are unknown, as this stratigraphic level is not exposed. The overall geometry of the Sly Creek Sandstone is interpreted here to be a thick widespread sheet, thinning northward and eastward, with a possible depocentre near the Batten Range (Figure 3.3). Partial chronostratigraphic correlation (and interdigation) of the Sly Creek Sandstone and upper Seigal Volcanics (Murphy Inlier) is suggested here based on:

- the absence of Sly Creek Sandstone along the Murphy Inlier;
- the likely absence of upper Seigal Volcanics in the BFZ (Chapter 9), perhaps with the exception of a thin basalt unit (Pdl);
• a conformable-disconformable relationship between Seigal Volcanics and Rosie Creek Sandstone in the Murphy Inlier, and a similar relationship between Sly Creek Sandstone and Rosie Creek Sandstone in the BFZ;

• the preponderance of sandstone in the upper Seigal Volcanics in the Murphy Inlier;

• the possible presence of reworked celadonite, derived from Seigal Volcanics (Rawlings et al., 1993), in the upper Sly Creek Sandstone and Rosie Creek Sandstone.

In this scenario, the basal erosional surface of the Carolina Sandstone Member in the Murphy Inlier correlates with the base of the Sly Creek Sandstone in the BFZ as a regional tectonostratigraphic break ('Sly surface' in Figure 3.3). The Sly Creek Sandstone thus represents a siliciclastic apron, basinward of an active basaltic volcanic zone to the east. On the basis of lithostratigraphy, the Sly Creek Sandstone has been correlated with the >1000 m thick Dalumbu Sandstone on southern Groote Eylandt (Pietsch et al., 1994 & 1997; Figure 2.7 & 2.8) and the 250 m thick Gumarrimbang and Marlgowa Sandstones on the Arnhem Shelf (Sweet et al., 1999a&b).

3.2.5 Rosie Creek Sandstone Member

The Rosie Creek Sandstone Member is the upper ferruginous portion of the Sly Creek Sandstone, cropping out in the BFZ and Wearyan Shelf (Figure 3.1). The following description is based largely on the work of Jackson et al. (1987), Pietsch et al. (1991a) and Haines et al. (1993) in the BFZ, but it incorporates new data from the Wearyan Shelf, where this member is not currently differentiated from McDermott Formation. The Rosie Creek Sandstone lies conformably and gradationally between the Sly Creek Sandstone (below) and McDermott Formation (above) in the BFZ (Pietsch et al., 1991a), but rests disconformably on Seigal Volcanics on the Wearyan Shelf (Figure 3.3). Thickness varies from <10 m on the Wearyan Shelf to 210 m in the BFZ (Haines et al., 1993).

The Rosie Creek Sandstone is diverse in grainsize and composition, comprising cm- to m-scale coarsening-upwards cycles of fine- to coarse-grained, ferruginous and lithic sandstone, with thin interbeds of micaceous mudstone (Figure 3.8; Haines et al., 1993). Planar- and trough cross-bedding, channel scours and symmetrical to asymmetrical ripples vary in prominence. Herringbone cross-stratification, tool marks and desiccation cracks are also locally developed (Rawlings et al., 1993).

The most notable feature of the unit is the presence of rounded grains composed of green cryptocrystalline clay, thought to be glauconite, associated with coarse-grained bimodally-sorted sandstone (Pietsch et al., 1991a). Some grains resemble detrital celadonite, which Rawlings et al. (1993) argued may have been reworked from amygdales in the Seigal Volcanics. Accordingly, there is some doubt over the shallow marine origin implied by the presence of glauconite. Evaporite pseudomorphs, including 'cauliflower chert' after anhydrite and rare halite are recognised at several stratigraphic levels (Haines et al., 1993).

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Figure 3.8 Summary log for the Rosie Creek Sandstone, eastern Tawallah Range. Measured section MY90/14, after Haines et al. (1993). Legend in Appendix 2.
Data collected from the Wearyan Shelf (Piccaninny Creek; Figure 3.1) during the current study, show that the Rosie Creek Sandstone has a sharp erosional base and varies laterally in thickness and facies due to an irregular underlying palaeotopography of brecciated Seilal Volcanics. Ten metres of trough cross-bedded coarse-grained sandstone grades laterally over ~100 m into <2 m of medium-grained rippled sandstone with pink dolostone clasts and common evaporite pseudomorphs.

The depositional setting of the Rosie Creek Sandstone was interpreted by Haines et al. (1993) as shallow marine. Rawlings et al. (1993) suggested the coarsening-upwards cycles were produced by migration of tidal channels across a shallow mudflat, with localised evaporitic conditions prevailing in restricted lagoons or supratidal flats. In contrast, Rogers (1996) interpreted the unit in the central BFZ as a braid-delta system (cf. McPherson et al., 1987), transgressive between the braided fluvial Sly Creek Sandstone and the shallow marine McDermott Formation. This interpretation was based on the perceived transition it occupies and the presence of heavy mineral laminae, mudclasts and siltstone intervals.

On the basis of lithostratigraphy, the Rosie Creek Sandstone has been tentatively correlated with the 300 m thick McKay Sandstone of the Katherine River Group (Arnhem Shelf; Pietsch et al., 1994; Carson et al., 1999: Figure 2.7 & 2.8).

3.2.6 McDermott Formation

The McDermott Formation is a <500 m thick package of interbedded dolostone, chert, mudstone and sandstone (Jackson et al., 1987). It is exposed throughout the southern McArthur Basin, and includes outcrops formerly assigned by Pietsch et al. (1991a) and Haines et al. (1993) to Aquarium Formation in the BFZ. It also encompasses some of the outcrop assigned by Jackson (1982) to Wollongorang Formation in the northern BFZ. These lithostratigraphic re-interpretations are the result of regional assessment of erosional surfaces during the current study (Figure 3.3). However, the lithologic description below is based mostly on existing information from Jackson et al. (1987), Ahmad and Wygralak (1989), Pietsch et al. (1991a) and Haines et al. (1993).

The McDermott Formation conformably overlies Rosie Creek Sandstone and is generally disconformably overlain by Wumumantyala Sandstone, however, this contact is locally conformable or unconformable (Rawlings et al., 1993). Along the Murphy Inlier, the McDermott Formation is absent (Figure 3.3; Appendix 3.9), either due to erosion by the 'Wumumantyala surface' (Sweet et al., 1981) or onlap onto the Murphy Tecronic Ridge (Roberts et al., 1963). Thickness varies from ~500 m on the Wearyan Shelf (Jackson et al., 1987) to 120-300 m in the northern BFZ (conformable upper contact; Haines et al., 1993) and 150-200 m in the central BFZ (unconformable upper contact; Rogers, 1996).

Based on outcrops on the Wearyan Shelf, Jackson et al. (1987) divided the McDermott Formation into four broad units, which are also recognisable in DD91DC1 (Stegman and Palmer, 1993; Figure 3.9). The basal package (unit 1) comprises ~30 m of medium-grained cross-beded sandstone with thin mudstone intervals and halite casts. Unit 2 comprises 45-135 m of sandy dolarenite,
Figure 3.9 Summary drill-core log for middle-upper McDermott Formation in DD91DC1, Calvert Hills Station. Base of formation not intersected. Lithologies summarised from Stegman and Palmer (1993) and re-interpreted during the current study. Unit names assigned are equivalent to those of Jackson et al. (1987). Legend in Appendix 2.
fine-grained sandstone and mudstone with scattered stromatolites, chertified evaporites, intraclastic breccia, ooids and irregular authigenic quartz nodules. Unit 3 is a 45 m thick interval of strongly chertified and partly brecciated dolostone with relic intraclastic, peloidal, stromatolitic and ooidal textures, similar to textures in unit 2. Unit 4 consists of a diverse 300 m thick sequence of interbedded dolarenite, stromatolitic and evaporitic dolostone, mudstone, fine- to coarse-grained glauconitic sandstone and minor thin intervals of silicic (sufficeous?) mudstone. An alternative sequence stratigraphic subdivision of the McDermott Formation is into five cycles (Figure 3.9). The lower cycle is equivalent to unit 1 of Jackson et al. (1987). The upper four cycles (units 1, 2, & 3) are shallowing-upwards intervals, initiated with deep water shale and terminating in shallow water sandstone.

In the BFZ, the McDermott Formation is finer-grained, comprising thin-beded dolostone, red/brown to green shale and fine-grained glauconitic sandstone (Piet sch et al., 1991a). Coarsening-upwards cycles of shale and thick-beded sandstone are characterised by HCS and symmetrical ripples. In the measured reference section of Piet sch et al. (1991a), the McDermott Formation appears to contain condensed equivalents of all units recognised by Jackson et al. (1987). In the northern BFZ, the package becomes relatively carbonate-rich, dominated by stromatolitic and silty dolostone and shale (Haines et al., 1993).

Outcrops of unit 4 on the Wearyan Shelf were examined during the current study. The sandstones are universally fine-grained and exhibit HCS, load casts, tool marks, flute moulds and gutter casts. HCS is a distinctive form of cross-beding characterised by depositional domes and scoured depressions with randomly-oriented low-angle foresets, showing no evidence of bedform migration (Harms et al., 1975; Dott and Bourgeois, 1982; Hunter and Clifton, 1982). In unit 4, HCS is a complex amalgamation of concave-up lamination with 1-2 m wavelength and 0.1-0.2 m amplitude that truncate at angles <5°. Gutter casts are smooth erosional dm-scale furrows developed on the bed surfaces that are typically closely associated with HCS and other 'tempestite' features such as tool marks (Myrow and Southard, 1996). The upper 50 m of unit 4 is composed of dolostone with large domal and digitate stromatolitic bioherms and flat-pebble-breccia. It is consistently present on the Wearyan Shelf under the Wunnumantyala Sandstone.

Interpretation
The McDermott Formation is unusual in its intimate association of coarse-grained quartz sand-bearing carbonates and fine-grained siliciclastics. Jackson et al. (1987) interpreted the intraclastic, stromatolitic and evaporitic carbonate facies as peritidal (shallow subtidal to supratidal) in origin, based on comparisons with some units of the overlying McArthur Group. The depositional setting of the fine-grained siliciclastics was interpreted as a deeper-marine shelf. Jackson et al. (1987) suggested the palaeoshoreline was an arid, sabkha-like environment, with quartz sand supplied from nearby uplifts of Westmoreland Conglomerate and the Murphy Inlier. Provenance studies by Rawlings et al. (1993) indicate a distal felsic igneous source for most of the quartz and rock fragments, but these could equally have been recycled from basal clastic units of the Tawallah Group. According to Jackson et al. (1987), coarse-grained sand became entrapped by a fringe of carbonates in shallow intertidal or shoreline zones, while fine-grained sand was transported seaward.
into subtidal, storm-influenced zones. The abundance of carbonate intraclasts and peloids suggests differential uplift and reworking of the semi-lithified platform margin of McDermott Formation into the deeper basin. This is consistent with onlap relationships suggested by Roberts et al. (1963) and the apparent condensed sequence observed in the BFZ. The chertified and brecciated appearance of unit 3 and the prominence of sandstone at the base of unit 4 infers a widespread hiatus between these units and development of a Proterozoic duricrust (Jackson et al., 1987).

Sedimentological observations from the current study support the deeper-marine shelf model of Jackson et al. (1987) for the fine-grained siliciclastics. Glaucoclastic sandstone with HCS and gutter casts favours storm-dominated marine or restricted marine shelf setting (Whitaker, 1973; Myrow, 1992; Myrow and Southard, 1996). The close spatial and temporal juxtaposition of peloidal and subtidal facies recognised by Jackson et al. (1987), parallels the close association of braidplain and shallow marine shelf facies in the underlying Sly Creek and Rosie Creek Sandstones (section 3.3). This suggests rapid and repeated transgressive and regressive events, resulting from high-frequency eustatic cycles. Evidence for evaporitic conditions in deeper water facies (e.g., halite; Haines et al., 1993) suggests periodic restriction of the water body from the open ocean. Minor probably ruffaceous intervals suggest periods of distal volcanism and quiet sedimentation.

Jackson et al. (1987) correlated the 'duricrust' at the base of unit 4 with a similar chert breccia unit in the Sly Creek Sandstone in the BFZ, implying a diachronous relationship with the McDermott Formation. However, the McDermott Formation, with an intraformational chert breccia (unit 3), is now recognised in the BFZ (this study; Figure 3.3).

Correlation of the McDermott Formation and Gootoo Formation of the Katherine River Group (Arnhem Shelf) has been proposed by Pietsch et al. (1994). Common elements of these formations include ~500 m thickness, shallow marine shelf facies and large domal stromatolites that are tens of metres in diameter (Sweet et al., 1999b). Lateral equivalents are not recognised to the north, implying a northwest-southeast depocentre or shoreline. Assuming periodic restriction from the marine realm, this suggests a epeiric sea model.

3.2.7 WUNUNMANTYALA SANDSTONE

The Wununmantyla Sandstone is a widespread 200-500 m thick sheet of quartzarenite and lesser mudstone, exposed throughout the southern McArthur Basin. Outcrops mapped as Sly Creek Sandstone in the Calvert Hills (Ahmad and Wygralak, 1989) and Wallowhollow 1:250 000 mapsheet areas (Jackson et al., 1987) are now assigned to Wununmantyla Sandstone, based on revised correlations of erosional surfaces and lithostratigraphy in the current study (Figure 3.1 & 3.3). The following section summarises previous detailed studies of the central BFZ (Jackson et al., 1987; Rogers, 1996) and northern BFZ (Pietsch et al., 1991a; Haines et al., 1993). Fieldwork for the current study concentrated on exposures on the Wearryn Shelf and southern BFZ, and to a minor extent the central BFZ.

The Wununmantyla Sandstone conformably overlies McDermott Formation in the southern and northern BFZ (Haines et al., 1993; current study; Figure 3.10). However, in most
areas, this contact is a disconformity with minor erosional relief and is unconformable in the central BFZ (Rogers, 1996) and adjacent to the Murphy Inlier (Ahmad and Wygralak, 1989). In the Murphy Inlier, the basal unconformity progressively downcuts the underlying McDermott Formation and Seigal Volcanics toward the southwest (Figure 3.3; Appendix 3.9). In the central BFZ, the discordance between McDermott Formation and Wununmanntyala Sandstone is minor and the unconformity (‘Wununmanntyala surface’ in Figure 3.3) does not appear to truncate the McDermott Formation significantly on geological maps or aerial photographs (Appendix 3.10). It can only be assumed that the foci of the pre-Wununmanntyala uplift and unconformity proposed by Rogers (1996) was subsequently inverted and is now obscured by younger cover, or was removed by younger erosional events.

In the BFZ, the Wununmanntyala Sandstone incorporates a lower sandstone-dominated sequence (discussed here) and a conformably overlying mudstone-dominated sequence (Wuraliwnunya Member; section 3.2.8). In parts of the BFZ, the Wuraliwnunya Member is absent due to: (i) lateral facies variation in the upper Wununmanntyala Sandstone (Haines et al., 1993); (ii) intrusion of a Settlement Creek Volcanics dolerite sill below Wuraliwnunya Member (section 3.2.9) and; (iii) incision by the McArthur Group unconformity (Haines et al., 1993). The apparent absence of this member is also partly because it was not recognised during mapping by Jackson et al. (1987) or Pietsch et al. (1991a). As a result, there is considerable disparity in published thickness estimates. On the Wearyan Shelf, the Wununmanntyala Sandstone is conformably overlain by Aquarium Formation, a correlative of the Wuraliwnunya Member; these mudstone-dominated units are discussed collectively in section 3.2.8.

The distribution of Wununmanntyala Sandstone on the Wearyan Shelf was described by Ahmad and Wygralak (1989) as uniform and sheet-like, ranging between 200-400 m in thickness. In the BFZ, the thickness of the lower Wununmanntyala Sandstone is more variable, in the range of 100-500 m (Figure 3.3). However, cumulative thickness (lower Wununmanntyala Sandstone + Wuraliwnunya Member) is generally consistent with the Wearyan Shelf (Figure 3.11). Anomalous local thickness variations in the Wuraliwnunya Member, ranging from 0-300 m, have been interpreted as growth-fault-related facies variation (Rawlings et al., 1993). Thickening of the lower Wununmanntyala Sandstone to 500 m in the Batten Range and central Tawallah Range (Jackson et al., 1987; Haines et al., 1993) is due to thinning of the Wuraliwnunya Member by facies variation (Figure 3.1 & 3.3).

**Central-northern Batten Fault Zone**

Only one section has been measured in the central-northern BFZ during the current study (Scruton Range; Figure 3.11; Appendix 3.1) and the bulk of the following description is derived from previous studies. In general, vertical sections of the Wununmanntyala Sandstone are incomplete due to poor outcrop, with resistant sandstone benches divided by recessive intervals (Jackson et al., 1987; Haines et al., 1993). Sandstone is white or red/brown (sericinious), silicified, mature, fine- to medium-grained quartzarenite. Two lithofacies are recognised (Pietsch et al., 1991a; Rawlings et al., 1993): (i) thin- to medium-bedded sandstone...
Figure 3.11 Correlation diagram for the Wunanrujandjala Sandstone, Wunanrujandjala Member, Aqumanti Formation and Settlement Creek Volcanics. Logs generalised from those in Appendix.
with common symmetrical and rare asymmetrical ripples (linear and bifurcating), planar-lamination, flat-bedding and synaeresis cracks; and (ii) medium- to thick-bedded sandstone with planar and trough cross-beds, desiccation and synaeresis cracks and abundant mudclasts. Locally continuous sections up to 20 m thick are composed entirely of amalgamated symmetrical ripple pavements (Rawlings et al., 1993). However, the typical arrangement in the flat-bedded lithofacies is 10-20 cm cycles of planar cross-bedded, flat-laminated and ripple-laminated sandstone with local mudstone drapes (Appendix 3.1). Red/brown mudstone interbeds are prevalent in some areas, and may be grossly underestimated in other sections due to poor outcrop (Jackson et al., 1987; Pietsch et al., 1991a). Differences in sandstone to mudstone ratio in adjacent sections indicate rapid lateral facies variation. Minor components include glaucony, scattered rounded pebbles and cobbles, and evaporite pseudomorphs (Rawlings et al., 1993).

Coarse-grained immature sandstone occurs at the base of the formation in the central BFZ, and is rare higher up in the sequence (Jackson et al., 1987; Pietsch et al., 1991a). Pebble and cobble conglomerate is recognised locally at or near the base in the central BFZ (Pietsch et al., 1991a; Rogers, 1996). Clasts, rarely up to boulder-size, of silicified Sly Creek Sandstone, indicate local uplifts of underlying formations in the Batten and southern Tawallah Ranges (Figure 3.1 & 3.3; Rogers, 1996). Felsic igneous clasts, which locally make up a small proportion of the total clast population, are interpreted to have been derived from the underlying Scrutton Volcanics (Rogers, 1996).

Conformable basal sections in the northern BFZ (Haines et al., 1993), comprise a shallowing-upwards sequence of mudstone, stromatolitic dolostone, fine-grained HCS sandstone, and 'typical' Wunanuntanya Sandstone lithofacies as described above.

Southern Batten Fault Zone and Wearyan Shelf

Stratigraphic sections were constructed for the Wunanuntanya Sandstone at a number of localities during the current study (Figure 3.10 & 3.11; Appendix 3.2, 3.3, 3.4 & 3.5) and form the basis of the following description. From these sections a four-fold subdivision is evident that is outlined below (from base up). Not all subdivisions are present at any one location (Figure 3.11).

**Unit 1**

Lower shallowing-upwards sequence -10-15 m thick of mudstone, stromatolitic dolostone and fine-grained glauconitic sandstone with HCS (as described in McDermott Formation; section 3.2.6). Found at the base of sections with a conformable relationship with McDermott Formation, such as at Little Calvert River (Jackson et al., 1987; Figure 3.1) and Kiama Dome (Figure 3.10).

**Unit 2**

Approximately 5-25 m of trough cross-bedded, coarse-grained lithic sandstone with scattered granules and pebbles of quartz, dolostone, mudstone, chert or basalt (Plate 3.2A-B). Present in disconformable or erosional-basal sections at Bullet Creek, China Wall, Branch Creek, Kiama Dome and Calvert Hills Station (Figure 3.11).
Plate 3.2 Various sedimentary features of the Wununmpanyala Sandstone. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1. Arrow indicates way up.

A: McDermott Formation unconformably overlain by coarse pebbly sandstone of Wununmpanyala Sandstone unit 2. Calvert Hills Station locality 121.

B: Coarse pebbly-granular sandstone at base of Wununmpanyala Sandstone unit 2. Calvert Hills Station locality 121.

C: Long-wavelength symmetrical ripples in fine-grained sandstone of unit 3. Calvert Hills Station locality 121.

D: Soft-sediment faults in fine-grained sandstone of unit 3. Calvert Hills Station locality 121.


F-G: Continuous vertical sections through unit 4, showing medium-bedded, flat-bedded and rippled sandstone lithofacies. Calvert Hills Station locality 120.

H: Cross-sectional view of symmetrical ripples in unit 4. Calvert Hills Station locality 121.
Unit 3

About 20-45 m of dolomitic-glaucocratic-micaceous fine-grained sandstone and siltstone with large hopper and pagoda halite pseudomorphs, mudclasts, HCS, current lineation, soft-sediment faults and megaripples (Plate 3.2C-E). Present in most sections, including Buller Creek, Branch Creek, Kiana Dome and Calvert Hills Station (Figure 3.11).

Unit 4

Upper -150-250 m thick package of white (but locally ferruginous) fine- to medium-grained (coarse) quartzose sandstone, with 10 m-scale cycles of two distinct facies.

- **Flat-bedded rippled facies**: thin- to thick-bedded sandstone (Plate 3.2F-G) with symmetrical to slightly asymmetrical ripples (wavelength = 4-6 cm; linear, sinuous, chevron, bifurcating, lunate and interference types), and local adhesion ripples or warps, current lineation, tool marks, flute moulds, current crescents, soft-sediment faults, desiccation and syneresis cracks (Plate 3.2H & 3.3A-D). Ripples with bevelled tops and long-wavelength asymmetrical ripples are locally present. Flat-bedded and amalgamated ripple beds generally form dm-scale sets.

- **Cross-bedded facies**: very thick-bedded sandstone with amalgamated trough cross-beds (some high-angle with rare recumbent or overturned foresets; Plate 3.3E), planar cross-beds, mudclasts and sparse quartzo granule lags (Plate 3.3E). Cross-beds are generally medium-scale and lenticular over ~10 m.

Unit 4 is present in all sections, but there is significant vertical and lateral variability in the dominance and stacking pattern of the two facies. The Buller Creek and Calvert Hills sections (Figure 3.11; Appendix 3.3 & 3.4), for example, are dominated by flat-bedded rippled facies with only thin intervals of cross-bedded facies (Plate 3.2F-G). Other sections are dominated by stacked 0.1-5 m cycles of cross-bedded facies overlain by flat-bedded rippled facies. The base of unit 4 is locally scoured and minor gypsum pseudomorphs occur near the top (Plate 3.3G). A mid-sequence erosional surface and a thin horizon of intraformational conglomerate and breccia in the Calvert Hills section (Appendix 3.3; Plate 3.3H) may equate to a minor intraformational hiatus. There is potential for low-angle internal erosional surfaces similar to those described by Simpson and Eriksson (1991).

Provenance and depositional setting

Ahmad and Wygralak (1989) and Jackson et al. (1987) recorded polymodal or inconsistent palaeocurrents, and noted diverse orientations in wave ripples over very short intervals. Bull and Rogers (1996) recorded broad northerly- and southerly-directed palaeocurrent trends for the basal Wunnumntyala Sandstone around the Batten and southern Tawallah Ranges respectively (Figure 3.1). However, only 4 to 9 readings were made at three localities and there is significant (up to 180°) variation at each locality. Data have been corrected for tectonic dip, but not for fault block rotation and large-scale folding. When these data are corrected for folding, a consistent westerly palaeocurrent trend is evident.
Plate 3.3 Various sedimentary features of the Wununmatyala Sandstone. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1.

A: Linear-bifurcating symmetrical ripples in fine-grained quartzarenite of unit 4. Calvert Hills Station locality 122.

B: Chevron-crested symmetrical ripples with superimposed synaeresis cracks, unit 4. Calvert Hills Station locality 122.

C: Adhesion warts in medium-grained sandstone of unit 4. Calvert Hills Station locality 120.

D: Desiccation cracks in unit 4. Bullet Creek locality 212.

E: Overturned foresets on trough cross-beds in unit 4. Kiana Dome locality 113.


G: Gypsum rosettes in upper unit 4. Branch Creek locality 86.

Petrographic studies show most sandstone to be well sorted (in part bimodally sorted), with subangular to well rounded quartz and minor rock fragments with a felsic igneous provenance (Ahmad and Wygralak, 1989; Rawlings et al., 1993). In the central BFZ, a proximal felsic igneous provenance is evident in the lower part of the package (Rogers, 1996). Adjacent to the Murphy Inlier, metamorphic rock fragments and chert clasts are common. Reworked sedimentary quartz grains, with abraded authigenic quartz overgrowths, have not been identified in the current study or by Rawlings et al. (1993), but were recognised by Bull and Rogers (1996). They interpreted multiple quartz overgrowths as evidence of reworking of sand grains from lithified sandstones of the lowermost Tawallah Group. The common red/brown colour of the sandstone is due to ferruginous matrix or grain coatings (Pietsch et al., 1991a). Most sandstones are strongly quartz-cemented, in some cases prior to authigenic iron oxide.

The depositional environment of the Wunanmanyala Sandstone is interpreted by most workers to be nearshore peritidal, based on sheet-like geometry, polymodal palaeocurrent pattern, maturity of the sedimentary rocks, and presence of symmetrical ripples and desiccation cracks (Jackson et al., 1987; Ahmad and Wygralak, 1989; Haines et al., 1993). Rawlings et al. (1993) suggested that oxidised sediments were deposited in a water body that was isolated to some degree from oceanic influences, but still large enough to support a tidal regime, such as a large restricted or epeiric sea. In the southeast, the palaeoshoreline may have been the edge of the Murphy Tectonic Ridge (Ahmad and Wygralak, 1989). In contrast, Rogers (1996) interpreted the various facies of the Wunanmanyala Sandstone in the central BFZ as proximal to medial braidedplain, based on comparisons with modern analogues such as the Platte River (Miall, 1977).

The current study has identified a number of features in the lower Wunanmanyala Sandstone that may help resolve the palaeoenvironmental issue. On the Wearyan Shelf, units 1 and 3 contain a number of diagnostic shallow marine storm-generated sedimentary structures and lithologies (i.e., ‘tempestite’ facies; Myrow and Southard, 1996), including HCS, symmetrical ripples and glaucony. In addition, unit 3 shows evidence of subsequent infiltration of subsurface hypersaline brines and precipitation of evaporites (cf. Kendall and Harwood, 1996). The facies of units 1 and 3 are similar to those of the Wuraliwiwanta Member and Aquarium Formation (section 3.2.8), which were deposited in a shallow storm-affected marine setting, below fair-weather-wave-base. Unit 2 is poorly sorted with high-energy sedimentary structures, suggesting proximal braidedplain deposition (Miall, 1977). However, mineralogical maturity and a close association with subtidal marine sedimentary rocks of unit 1 and 3 are consistent with shallow marine reworking of coarse-grained fluvial detritus in a shoreface-foreshore setting (cf. Clifton et al., 1971).

Unit 4 is enigmatic, with sedimentary structures generally of equivocal origin (section 3.3). Cross-bedded and flat-bedded facies may equate with either a shallow intertidal or medial-distal braided fluvial origin, however, the preponderance of symmetrical ripples, tool marks, flute moulds, current crescents and synaeresis cracks in many sections favours an intertidal origin (de Raaf and Boersma, 1971). Local bimodal sorting and occurrence of desiccation features, adhesion ripples
or warts, and bevelled and long-wavelength asymmetrical ripples infer periods of emergence and aeolian reworking (Hunter, 1977). However, no large-scale aeolian bedforms were recognised, suggesting exposure periods were short. Local recumbent-folded cross-bed foresets are the result of current-generated shear stress acting on the upper surface of a bedform when its contained sediments were partly liquefied (Allen and Banks, 1972). These features have typically been described from, but are not diagnostic of fluvial settings (e.g., Blake et al., 1987). Locally-developed cycles of cross-bedded and flat-bedded sandstone resemble the peritidal parasequences of the upper Mount Guide Quartzite (Simpson and Eriksson, 1991). These cycles are thought to reflect flooding and establishment of a tidal shelf characterised by migrating dunes, shoaling upwards into intertidal and locally supratidal conditions.

The conglomeratic facies recognised by Rogers (1996) in the Batten and southern Tawallah Ranges are anomalous in a regional context. A proximal braidplain origin appears the best interpretation from a local perspective (Rogers, 1996). However, the associated mature quartzose sandstone facies are consistent with regional observations of shallow intertidal deposition (Jackson et al., 1987; Pietsch et al., 1991a; Haines et al., 1993). Conglomeratic facies may represent local fluvial deposition around uplifted blocks of lower Tawallah Group, flanked by a shallow tidal sea (cf. Cudzil and Driese, 1987) or, alternatively, they may be interpreted as foreshore (beach) reworking of conglomerates derived from nearby ranges (cf. Bourgeois, 1980; Leckie and Walker, 1982). Mature sandstone with planar cross-beds and symmetrical ripples, intermingled with crudely-stratified and generally non-imbricated conglomerate are consistent with significant wave reworking of detritus (Clifton et al., 1971). It is difficult to envisage a fluvial system, operating around the small perceived hinterland, reworking the coarse-grained locally-derived detritus to obtain the observed degree of textural and mineralogical maturity (cf. Pettijohn et al., 1987). Regardless, the important point is that there was substantial local palaeotopography (uplift) during deposition of the lower Wunnummantyla Sandstone (Rogers, 1996).

A more detailed and areally-extensive study of the Wunnummantyla Sandstone is required to properly resolve the depositional setting issue. However, based on the combined features of quartzarenite sheets in the lower Tawallah Group, a tentative depositional model is proposed in section 3.3.

Regional synthesis

The McDermott Formation-Wunnummantyla Sandstone contact represents a regional shallowing of depositional environments, and may have led to development of a local unconformity. Rogers (1996) proposed a large-scale intrabasinal uplift event in the central BFZ, in which fault blocks of basement volcanics were elevated >3000 m vertically to be incorporated into the basal Wunnummantyla Sandstone. Evidence presented for this model includes: polymict basal conglomerate with volcanic clasts; transverse palaeocurrent trends from the Tawallah Fault; detrital quartz overgrowths and; contrasting structural characteristics of the Sly Creek and Wunnummantyla Sandstones (Rogers, 1996). Evidence against such a model is:
the absence of a significant angular discordance or downcutting relationship with underlying stratigraphy (Appendix 3.10; Haines et al., 1993);

felsic igneous clasts have not been confirmed as basement-derived. These may instead have been locally-derived from contemporaneous igneous activity immediately preceding the Wunnummantyala Sandstone (cf. Pungalina Member, Chapter 6). Attempts to determine the provenance of these clasts using monazite dating failed. A U-Pb geochronological study of detrital zircon is required to resolve this issue.

The combined thickness of the Wunnummantyala Sandstone (including Wuraliwinuinya Member) and Aquarium Formation, is uniformly in the range of 300-500 m throughout the southern McArthur Basin (Figure 3.11). The preserved geometry is a flat-lying sheet, covering an area >60,000 km², deformed locally in the BFZ. Local fault control of facies led to the varied thickness of the Wuraliwinuinya Member (section 3.2.8). The Wunnummantyala Sandstone correlates with the Shadforth Sandstone on the Arnhem Shelf (Sweet et al., 1999b; Figure 2.7 & 2.8) and perhaps the Dhunganda Formation in the Walker Fault Zone and Gove Sandstone on the Caledon Shelf (Rawlings et al., 1997). This implies a quasi-contiguous sandstone sheet, covering an area >120,000 km². The contained facies and thickness of the depositional ‘basin’ are analogous with the lower Palaeozoic epicentric seaway of the USA (Sloss, 1963; Runkel et al., 1998).

3.2.8 Aquarium Formation and Wuraliwinuinya Member (of the Wunnummantyala Sandstone)

These two units are discussed collectively because they are contemporaries and exhibit similar facies characteristics (Figure 3.2), however, they are not contiguous and cannot be rationalized to one formation based on present data. The Aquarium Formation crops out throughout the Wearyan Shelf, where it is between 120 and >150 m thick (Figure 3.11). The Wuraliwinuinya Member is currently only mapped in the northern BFZ (Haines et al., 1993), where 0-300 m is exposed. However, during the current study this unit was also identified in the Scruton Range, Mallapunyah and Klana Domes (Figure 3.1), areas in which it was not reported by Jackson et al. (1987), Pietsch et al. (1991a) and Rogers (1996). The apparent absence in some areas is also due to lateral facies variation and incision by the McArthur unconformity (Figure 3.3). The following description is based largely on new information from the Wearyan Shelf, and to a lesser extent the central-southern BFZ (Appendix 3.2, 3.4, 3.6 & 3.7).

The Aquarium Formation conformably overlies Wunnummantyala Sandstone with a gradational contact. Similarly, the Wuraliwinuinya Member conformably overlies the Wunnummantyala Sandstone, but is also a lateral facies variant of the upper part of this formation (Figure 3.3). The conformity marks a transition from medium-grained to fine-grained sandstone and is associated with a distinctive change in bedforms. The Wuraliwinuinya Member and Aquarium Formation are ‘overlain’ by dolerite of the Settlement Creek Volcanics. Collectively, these units generally form an upward-finings sequence that incorporates a lower fine-grained sandstone facies and an upper dolomitic mudstone facies (Figure 3.10, 3.11 & 3.12). In contrast, the Wuraliwinuinya Member in northeastern Tawallah Range (Figure 3.1) is a thickening-upwards sequence of mudstone and fine- to medium-grained glauconitic sandstone; dolostone is absent (Haines et al., 1993).
Aquarium Formation section - Calvert Hills Station

- Settlement Creek Volcanics:
  - dolerite sill.

- redbrown mudstone breccia (hematitic) with distorted halite casts.

- upper Aquarium Formation: upward-fining sequence of green to redbrown ferruginous, litic, glauconitic, dolomitic micaceous fine-grained sandstone and mudstone. Thin to medium bedded, sandy cross- and parallel-laminated with small brown to moderate-angle trough cross-casts. FCS and interference ripples. Common tool marks, flute marks, normal crests and load casts (ex. fluvial debrise). Minor level dolomite beds and medium-grained quartz sandstone with FCS and rare mud beds. Pseudomorphs after halite and Talcylite common toward top.

- fine sandstone as per base of formation.

- recrystallized interval with sparse outcrop of fine-grained glauconitic-ferruginous sandstone and siltstone with FCS, convolute bedding and small trough cross-beds.

- fine-grained (intermediate) maroon to white quartz sandstone, locally glauconitic, ferruginous and mottled, thick-beded with trough cross-beds and probable FCS. Basal concordant, thinner bedded and more convolute upwards.

- sharp conformable contact, facies interface.

- Wunnumattulla Sandstone: medium-grained quartz sandstone.

upper Aquarium Formation measured section - Bullet Ck

- Settlement Creek Volcanics: fine- to coarse-grained fresh dolerite sill.

- redbrown to yellow hematitic mudstone, locally brecciated.

- redbrown dolomitic siltstone with common halite marks.

- per-scale beds of cross-laminated tuff,
  - dolomite and fine-grained dolomite,
  - interbedded with dolomitic siltstone.

- dolomitic glauconitic siltstone and dolomite,
  - small round fibrous evaporite pseudomorphs (solar evaporites).

- dolomitic glauconitic siltstone, flakey to folly.

- siltstone and dolomitic siltstone; sedimentary structures and lithologic features as below.

- flaky, fine-grained, thin dolomitic micaceous, locally glauconitic sandstone, MCS, normal crests, tool marks, ripples, current bioturbation, fossil casts.

- top of slope of fine-grained medium-beded sandstone lower Aquarium Formation.

Figure 3.12 Logs for the Aquarium Formation (Calvert Hills Station) and upper Aquarium Formation (Bullet Creek measured section). Note that scales are different. Legend in Appendix 2.
In most areas, the lower facies is uniformly fine-grained, with thick beds of diffuse trough and hummocky cross-beded maroon sandstone, with local mudclasts, syneresis cracks, linear and interference megaripples, current lineation, flute casts, runzel and tool marks, glaucony and stratified sediment-incorporative gypsum pseudomorphs (Figure 3.12; Plate 3.4A-E). Coarsening-upwards cycles and various soft-sediment deformation features, such as slumps, convolute bedding and load casts, are present in northeastern Tawallah Range (Figure 3.1; Rawlings et al., 1993). In thin-section, the sandstone comprises subrounded quartz, felsic igneous rock fragments, muscovite and glaucony (Plate 3.4E), with thin oxide grain coatings overgrown by authigenic quartz. Glaucony forms concentric laminae around a detrital quartz nucleus (i.e., 'accretionary').

The upper facies is composed of dolomitic, glauconitic, micaceous and ferruginous mudstone and fine-grained sandstone, with scattered intervals of dolomitite and dolarenite (Figure 3.12; Plate 3.4F-H). Carbonate units are invariably dolomitic, rather than calcareous (Appendix 3.11). Common features in the lower part are cross-lamination and small cross-beds (Plate 3.4H), current lineation, flute and runzel marks, load casts and local HCS. Spectacular multidirectional tool marks, as described from the northern McArthur Basin by Haines (1998), are common (Plate 3.5A-B). The overall grain size, concentration of glaucony and amount of tracial bedforms decrease upwards, and the uppermost beds are characterised by fine parallel-laminated red/brown (oxic) mudstone that is massive to locally disrupted. Displacerine and sediment-incorporative halite and anhydrite pseudomorphs are prolific in this part of the sequence (Plate 3.5C), and large skeletal (pagoda) halite pseudomorphs, up to 15 cm across, are present locally (Plate 3.5D). Mudstone in the uppermost 1-10 m is 'baked' and locally brecciated adjacent to the Settlement Creek Volcanics (Plate 3.5E-G), and distorted barite-filled halite casts are common (Plate 3.5H; see section 3.2.9 for description of contact).

The two facies of the Aquarium Formation and Wuraliwnunya Member are gradational both vertically and laterally and are distinguished on the basis of grain size trends and influence of wave or current tractive mechanisms. The lower fine-grained sandstone facies contains evidence for storm-dominated marine shelf deposition, such as glaucony and various 'tempestite' features (e.g., flute casts, tool marks and HCS; Myrow and Southard, 1996). Runzel marks (Teichert, 1970; or 'Kinneya' of Seilacher, 1984) are closely associated with HCS, and are interpreted as microbially-mediated structures formed in a subtidal siliciclastic setting (Hagadorn and Bottjer, 1997). These are characteristic of storm beds in the McArthur Basin. Many of the linear tool marks or drag marks (Plate 3.5A-B) are interpreted to have been produced by strands or colonies of drifting algae dragging across the sea floor during turbulent storm events (Haines, 1997). Others may have formed by bouncing of mud clasts onto the substrate (Conybeare and Crook, 1982). The presence of stratified intraclastina gypsum pseudomorphs indicates percolation of hypersaline groundwater through the sediment pile during or soon after deposition (Kendall and Harwood, 1996).
Plate 3.4 Various sedimentary features of the Aquarium Formation and Wuraliwuntya Member of the Wunaamantyala Sandstone. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1. Arrow indicates way up.

A: flute casts in fine-grained sandstone of lower Aquarium Formation. These may have been accentuated by loading. Bullet Creek locality 214.

B: Plan view of large elliptical mudclast impressions in fine sandstone of lower Wuraliwuntya Member. Kiana Dome locality 106.

C: Runzel marks in fine-grained sandstone of lower Aquarium Formation. Bullet Creek locality 214.

D: Discoidal gypsum pseudomorphs in fine-grained sandstone of lower Aquarium Formation. Kiana Dome locality 106.

E: Photomicrograph of accretionary glaucony coatings on detrital quartz grains in the lower Aquarium Formation. Thin-section 214A (Bullet Creek). Plain-polarised light.

F: Outcrop habit of mudstone and lesser fine-grained sandstone of upper Wuraliwuntya Member at Mallapunyah Dome locality 36.

G: Outcrop habit of mudstone and lesser dolostone of upper Aquarium Formation at Bullet Creek locality 348.

H: Small (dm-scale) cross-bed in fine-grained dolomitic sandstone of upper Aquarium Formation at Bullet Creek locality 348.
Plate 3.5 Various sedimentary features of the Aquarium Formation and Wuraliuntya Member of the Wununiwanyala Sandstone. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1. Arrow indicates way up.

A-B: Multidirectional tool/scrap marks in plan view from upper Aquarium Formation. Calvert Hills Station locality 125.

C: Fibrous chert nodules after anhydrite in mudstone, upper Aquarium Formation. Calvert Hills Station locality 125.

D: Large skeletal (pagoda) halite pseudomorph in plan. Upper Wuraliuntya Member, Mallapunyah Dome locality 37.

E: Brecciated mudstone hornfels from upper Wuraliuntya Member adjacent to Settlement Creek Volcanics. Note the partial articulation of clasts. Kiana Dome locality 108.

F: Brecciated mudstone hornfels from upper Wuraliuntya Member. Breccia clasts show a high degree of jigsaw-fit. Sample 38C (Mallapunyah Dome).

G: Brecciated mudstone hornfels from upper Aquarium Formation. Calvert Hills Station locality 125.

H: Distorted halite cast from near contact between Aquarium Formation and Settlement Creek Volcanics. Sample 125C (Calvert Hills Station).
The overlying mudstone and fine-grained sandstone facies shows a decreasing influence of traction or agitation, consistent with either: (i) deepening into a sub-storm wave-base setting or; (ii) shallowing into a marginal marine or lacustrine salina/mudflat setting. The prevalence of oxic mudstones and evaporites at the top of the package favours the latter shallow water hypersaline setting. This is consistent with the evaporitic (lacustrine) mudflat interpretation for desiccated halite-rich mudrocks of the lowermost Wollogorang Formation (Jackson, 1982 & 1985; Donnelly and Jackson, 1988), which was contiguous with these two units prior to intrusion of the Settlement Creek Volcanics sills (section 3.2.9). A shallowing-upwards trend is also evident in the northeastern Tawallah Range (Haines et al., 1993).

In the upper Aquarium Formation and Wuraliwniynya Member, halite and anhydrite pseudomorphs are generally associated with disrupted fine lamination. These probably grew displacively or incorporation into un lithified sediments within the phreatic and capillary zones (Gornitz and Schreiber, 1981; Handford, 1991), although pagoda halite is probably bottom-precipitated (Southgate, 1982). The absence of definitive evidence of desiccation suggests shallow subaqueous conditions prevailed, and hyperconcentration of seawater took place by restriction of access to the sea (i.e., saltern; Warren, 1989). Thin isolated beds of cross-stratified sandstone and dolarenite within the mudstone may reflect migration of tidal channels across a supratidal to intertidal (marine) mudflat, although Jackson (1982) interprets a similar facies association in the upper Wollogorang Formation as fluvial channels cutting a lacustrine mudflat. A marginal marine, rather than lacustrine setting is favoured for the uppermost Aquarium Formation and Wuraliwniynya Member, and lowermost Wollogorang Formation, on the basis of close spatial and temporal association with underlying marine shelf sedimentary rocks, and the absence of definitive continental evaporites (e.g., trona).

The sharp change from medium-grained trough cross-bedded Wunumantya Sandstone into fine-grained ‘tempestite facies’ Aquarium Formation is interpreted to reflect a transgression from a mixed braidplain-inner shelf setting to a storm-dominated restricted marine shelf (cf. Harms et al., 1982; Aigner and Reineck, 1982). The presence of cross-beds, rather than HCS, in the upper Wunumantya Sandstone is probably because megaripples and sandwaves are the stable bedforms in medium- to coarse-grained sand in storm shelf settings (Nottridge and Kreisa, 1987; Leckie, 1988). A subsequent regression led to deposition of the upper Aquarium Formation and lower Wollogorang Formation in a marginal marine salina setting.

Correlatives of the Aquarium Formation and Wuraliwniynya Member, comprising equivalent facies, are widespread in both the southern and northern McArthur Basin, suggesting the existence of an extensive shoaling marginal-marine shelf or epeiric sea. Examples include the Bonanza Creek and lower McCaw Formations on the Arnhem Shelf (Figure 2.7 & 2.8; Sweet et al., 1999b), upper Dhunganda Formation in the Walker Fault Zone and Yuduyndu Formation on the Caledon Shelf (Rawlings et al., 1997). Ancient restricted marine evaporite platforms, with evidence of variable water depths and subaerial exposure, are commonly much wider (>1000 km) and with lower gradients than modern counterparts (Warren, 1991).
Lateral facies and thickness variations in the Wuraliwinunya Member in the BFZ have been interpreted as related to localised zones of increased subsidence, associated with growth faulting (Rawlings et al., 1993). In contrast, facies and thickness are consistent on the Wearyan Shelf inferring increased synsedimentary tectonism along the adjacent BFZ at this time.

3.2.9 Settlement Creek Volcanics

The Settlement Creek Volcanics comprise a single or composite set of dolerite sheets that lie between the Aquarium Formation/Wuraliwinunya Member and the overlying Wollogorang Formation (Figure 3.2, 3.10 & 3.11). Some sheets are also present higher in the middle Wollogorang Formation (Figure 3.3), such as the coherent mafic rocks incorrectly assigned to the Gold Creek Volcanics in Mallapunya Dome (Australian Geophysical, 1968; Jackson et al., 1987; Wright, 1994; Figure 3.1), and the 90 m dolerite intersection in DD91CCK1 (Camel Creek; Appendix 5.9). The Settlement Creek Volcanics are recognised throughout the southern McArthur Basin and are generally in the order of 20-200 m thick. The following description is based on new field data from the Wearyan Shelf, southern BFZ and Tanumbarini Inlier (Figure 3.1).

Dolerite and basalts

The main rock-type of the Settlement Creek Volcanics is fine- to medium-grained, grey to green/black aphyric dolerite, comprising plagioclase, pyroxene and opaque oxides. The upper 1-5 m of individual sheets is generally finer-grained basalt, part of which may have been originally glass. This zone is weakly to moderately vesicular or vuggy, with infills of quartz, carbonate, chlorite and celadonite. Vesicles typically occur as a series of trails. The cores of most sheets are medium- to coarse-grained and locally porphyritic, with ophitic and subophitic textures (Plate 3.6A). Irregular or polygonal jointing is common.

Alteration and hydraulic breccia

Dolerite is incipiently altered in most areas and assumes a green or pink/brown colour. Secondary chlorite-K-feldspar-actinolite-haematite assemblages are present in various quantities (Plate 3.6B). In fault zones and adjacent to many veins (e.g., parts of Mallapunya Dome, Foelsche Inlier and Masterton Horst; Figure 3.1), alteration is intense, with the development of red/orange coloured ‘redrock’, dominated by secondary K-feldspar and haematite (Plate 3.6C). Hydraulic breccia, with a high degree of jigsaw-fit, is common within the fault zones and is infilled by quartz, carbonate, barite, chlorite, haematite and K-feldspar. Breccia clasts are typically altered or have alteration selvages (Plate 3.6D), presumably because of enhanced permeability and water-rock interaction. Regional-scale potassium metasomatism was first suggested by Jackson et al. (1987) to explain ‘redrock’ alteration. Haines et al. (1993) used geochemical data to show that alteration took place during the late-stage passage of oxidised alkaline fluids, which they interpreted as magmatic in origin. Cooke et al. (1998) have since shown by isotopic and fluid inclusion studies that these fluids were low temperature saline basinal brines.
Plate 3.6 Various features of the Settlement Creek Volcanics. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1.


B: Photomicrograph of pervasively-altered medium-grained dolerite, with laths of plagioclase replaced by K-feldspar and haematite, and intergranular pyroxene replaced by chlorite. Interstitial quartz has infilled corroded void space. Thin-section 20B (Mallapunyah Dome). Plain-polarised light.

C: Pervasive 'redrock' alteration and partial brecciation of dolerite within a fault zone in Foelsche Inlier (locality 181). Note the thin quartz-K-feldspar veins.

D: Fracture-controlled 'redrock' alteration in dolerite hydraulic breccia. Fractures contain quartz, K-feldspar, chlorite and carbonate. Sample 248A from DD95GC001 (CRAE drill hole, Pungalina).

E: Subhorizontal mildly-sinusuous contact between green dolerite of the Settlement Creek Volcanics (S) and brown flaggy mudstone of the Wollogorang Formation (W). Contact is marked by arrow. This is the upper margin of a sill in the Mallapunyah Dome (locality 12). Note that only a few centimetres of mudstone is metamorphosed adjacent to the sill.

F: Serrated upper contact between microdolerite sill of the Settlement Creek Volcanics (S) and diffusely-laminated 'baked' mudstone of the Wollogorang Formation (W), Sample 26A (Mallapunyah Dome).

G: Lobate protrusion of microdolerite of the Settlement Creek Volcanics (S) within 'baked' and brecciated mudstone of the Wollogorang Formation (W). Mallapunyah Dome locality 26.
Upper and lower contacts between dolerite sheets and hostrock

With few exceptions, the Settlement Creek Volcanics occur at the same stratigraphic level over the entire southern McArthur Basin. The unit generally divides halite-bearing oxic mudstones of the Aquarium Formation and Wuraliwuny Member from similar mudstones of the Wologorang Formation (Figure 3.10). The upper and lower surfaces of sheets are typically smooth, planar or mildly sinuous on a 10 m scale (Plate 3.6E; Figure 3.13A), and are generally concordant with the overlying and underlying formations on a kilometre scale. There are rare examples of small (dm to m scale) bulbous masses of quenched basalt that protrude up into hornfelsed mudstone (Plate 3.6F-G; Figure 3.13A). In the Robinson Dome, -5 m diameter 'pimples' of basalt breccia protrude 1 m upwards into the overlying sediments. Grossly irregular discordant contacts are recognised at several localities, and in some cases, dolerite bodies are contiguous up into the middle Wologorang Formation (e.g., parts of Mallapunyah Dome, Foelsche Inlier, Camp Creek and Camel Creek; Figure 3.1). The lower boundary of the Settlement Creek Volcanics is also generally planar and concordant, but in some areas (e.g., parts of Mallapunyah Dome and Foelsche Inlier), it is a complicated amalgamation of breccias and coalescing concordant and discordant dolerite bodies (Figure 3.13B).

Ropy surfaces

Unusual and diagnostic wrinkles and bulbous lobes are locally recognised on the planar upper surface of the Settlement Creek Volcanics or, less commonly, as successive horizons in the upper 1 m of the dolerite sheet (Plate 3.7A-E). In rare cases, they occur at the interface between the coherent dolerite sheet and its marginal breccia. These wrinkles resemble the pahoehoe or 'ropy' top of many modern basaltic lava flows (MacDonald, 1953; Fink and Fletcher, 1978). Vesicles immediately below the basalt-sediment interface are large and unidimensionally stretched (Plate 3.7D), whereas lower down they are small and spherical but more concentrated.

Marginal dolerite breccia

The marginal dolerite of some sheets is strongly brecciated, with textures ranging from in situ jigsaw-fit (Plate 3.7F) to autoelastic and autorotated (Plate 3.7G). Autorotated breccia is monomict to polymict, with angular to subrounded, vesicular and/or massive dolerite clasts. In some cases, significant interaction and partial assimilation of the host sedimentary rocks has taken place, and dolerite has undergone 'redrock' alteration while the sedimentary rocks have been silicified. At Kilgour Waterhole (western Mallapunyah Dome; Figure 3.1), clasts of mildly vesicular basalt and wallrock mudstone are suspended in a matrix of coherent basalt, suggesting multiple emplacement or, more likely, lateral or vertical propagation of the interface between the dolerite sheet and wallrock.
Figure 3.13 Geometrical relationships of the Settlement Creek Volcanics (SCV).

A. planar in situ SCV-Wollogorang Fm contact, with small localised sills & dykes, Mallapunyah Dome.
B. complex irregular SCV-Wuralivunyta Mbr contact, with thick hornfels breccia zone, Mallapunyah Dome.
C. lateral variation in SCV-Wollogorang Fm contact relations, 12 Mile Creek; see text for description of zones (i) to (v).
D. dolerite apophysis at Eagle Hawk Neck, showing the conical cross-section and EW-elongate aspect.
E. fault-bounded geometry of SCV-Wollogorang Fm contact, Mallapunyah Dome.

Note that vertical and horizontal scales are different.
Plate 3.7 Various features of the Settlement Creek Volcanics. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1. Arrow indicates way up.

A-B: Pahoehoe-like 'ropy' upper surface of the Settlement Creek Volcanics sill in the Mallapunyah Dome (locality 11B).

C: Bulbous and 'glassy' upper surface of the Settlement Creek Volcanics sill near Calvert Hills Station (locality 126). Note the stretched vesicles.

D: Upper 50 cm of the Settlement Creek Volcanics sill near Calvert Hills Station (locality 126). Note the high concentration of small spherical vesicles at the base of the exposure and the low concentration of large stretched vesicles at the top. Outcrop is stained by green celadonite.

E: Pahoehoe-like 'ropy' surface in the upper 1 m of the Settlement Creek Volcanics sill in the Mallapunyah Dome (locality 32). Note that this surface does not coincide with the Settlement Creek Volcanics-Wollogorang Formation contact.

F: Monomict clast-supported in situ breccia in the upper part of the Settlement Creek Volcanics. Mallapunyah Dome locality 38.

G: Monomict matrix-supported auto-rotated breccia in the Settlement Creek Volcanics. Eastern Creek (northern Scrutton Range) locality 117.
Marginal and internal hornfels and hornfels breccia

Finely-laminated green, red/brown, yellow and purple mudstone hornfels is developed at the lower and upper contacts of the Settlement Creek Volcanics with the Aquarium Formation/Wuraldawinta Member and Wollogorang Formation respectively, and as local rafts within the dolerite sheets. The upper hornfelsed margin ranges from 3 cm to 10 m thick, and is thinnest where the upper sheet surface is planar and dolerite is coherent. At some localities, contact metamorphic effects are limited to a few centimetres and the overlying mudstone of the Wollogorang Formation is gently warped (Plate 3.6E). Well-preserved halite casts, recrystallised dolomite, and rare metamorphic amphibole and metasomatic K-feldspar 'phenocrysts' occur in the hornfels immediately adjacent to the contact. The grade of metamorphism is otherwise too low for the growth of other secondary minerals. A thick carapace of hornfels breccia is developed where the Settlement Creek Volcanics is internally brecciated, and where small protrusions diverge from the main sheet (e.g., Plate 3.6G). Brittle and ductile deformation features are noted in the breccia and in some cases, the hornfels is comprised of articulated cm-scale clasts that define folds (Plate 3.5E). These features suggest the mudstone was semi-lithified when the dolerite was emplaced.

The lower hornfelsed margin is generally much thicker (up to 20 m) and more complicated than the upper margin, in many cases because there are numerous subsidiary 'break-outs' of dolerite (Figure 3.13B). Horizons of hornfels breccia (Plate 3.5E-G) and dolerite breccia are common, and in some cases are divided by intervals of polymictic (dolerite-hornfels) automictic breccia. Discordant barite- and quartz-filled halite casts (Plate 3.5H) are common. The hornfels zone in DD95GC001, drilled by CRAE in the Pungalina area (Figure 3.1), comprises grey/black (reduced) and brecciated dolomitic mudstone.

Large concordant and discordant rafts of mudstone hornfels lie within the Settlement Creek Volcanics locally, and are associated with extensive 'redrock' metasomatism of the adjacent dolerite. Thick intervals of mudstone, carbonate and hornfels intervene between multiple sheets of Settlement Creek Volcanics in the Foelsche Inlier and Kiana Dome (Figure 3.1), and were originally interpreted to indicate sedimentation during interflow hiatuses (Yates, 1963).

Hornfels breccias were first thought to have formed by solution collapse (Jackson et al., 1987) but were subsequently interpreted by Pietsch et al. (1991a), Bull (1993), Haines et al. (1993) and Rawlings et al. (1993) as flow-banded autobrecciated rhyolite. Rogers (1996), from drill core evidence, suggested that they are hornfelsed dolomitic and muddy wallrocks. This interpretation is supported by considerable additional evidence collected during the current study.

Upper contact geometry at 12 Mile Creek

At 12 Mile Creek (Figure 3.1), a variety of upper contact relations with the Wollogorang Formation are exposed over a strike length of 2 km (Figure 3.13C).

(i): **coherent contact** between chilled vesicular basalt and mudstone hornfels (Plate 3.8A). The upper 5 cm of the dolerite sheet is a green non-vesicular chilled margin, underlain by a 1 m vesicular zone. Uppermost vesicles are elliptical and stretched parallel to the contact;
Plate 3.8 Various features of the Settlement Creek Volcanics. Outcrop areas for photos, samples and thin-sections shown in Figure 3.1. Arrow indicates way up.

A: Sebhorizontal planar contact between vesicular basalt/microdolerite of the Settlement Creek Volcanics (S) and hornfelsed mudstone of the Wollogorang Formation (W). This represents the upper margin of a sill along 12 Mile Creek (locality 203). Note that the mudstone is metamorphosed for several metres above the contact with the sill.

B: 'Knobbly' texture in hornfelsed dolomitic mudstone of the Wollogorang Formation immediately above the contact with Settlement Creek Volcanics. 12 Mile Creek locality 203.

C: Geomorphology of the northern edge of Camp Creek near Eagle Hawk Neck (locality 217), illustrating the general concordance of the contact between Settlement Creek Volcanics (S) and Wollogorang Formation (W). Note, however, on the left side of frame that a dark conical mass of dolerite (P) protrudes up into the lower Wollogorang Formation. This protrusion probably connected laterally with the plug at Eagle Hawk Neck prior to modern erosion.

D: Monomict matrix-supported breccia, comprising angular to jigsaw-fit clasts of basalt in a chloritic mud matrix. Settlement Creek Volcanics at Eagle Hawk Neck (locality 217).

E: Mosaemic clast-supported breccia, comprising angular to rounded, rotated clasts of chlorite-altered dolostone in a chloritic mud matrix. Although this breccia is largely stratigraphy-preserving, it contains sporadic round pillows of basalt. Settlement Creek Volcanics at Eagle Hawk Neck (locality 217).

F: Polymict matrix-supported breccia, comprising angular to rounded, rotated clasts of variably-altered dolostone, mudstone and dolerite in a chloritic mud matrix. In thin-section, some mudstone clasts merge with the matrix and were un lithified when the breccia formed. Eagle Hawk Neck, sample 217B.

G: Subvertical stria on the faulted surface of an uplifted block of Settlement Creek Volcanics in the Mallapunyah Dome (locality 29). These striae are consistent with slightly oblique dip-slip movement.
below this they are spherical. The lower 10 cm of pink mudstone is hornfelsed, and is overlain by a 30 cm interval of pink ‘knobbly’ dolomitic mudstone. Overlying mudstones are finely-laminated with halite casts.

(ii): brecciated mudstone against coherent basalt. The same chilled and vesicular basalt zones as per (i), but the upper surface is wrinkled and lobate. The surface is concordant, planar to undulose, and is locally controlled by small faults. Overlying hornfels, mudstone and carbonates are extensively brecciated, contorted and convoluted, with brittle to semi-ductile features. The ‘knobbly’ horizon is considerably thicker (Plate 3.8B).

(iii): brecciated basalt against coherent mudstone. The upper 10-30 cm of basalt is brecciated, but the contact is essentially concordant. Vesicles occur in the upper two metres.

(iv): complex contact between multiply-breciated basalt and coherent hornfels. Several generations of superimposed breccia and vesicle zones in the upper two metres of basalt provide evidence of multiple stages of dolerite emplacement.

(v): irregular lobate contact between small (0.5 m wide and <10 m long) basalt protrusions and semi-coherent hornfels. Lobes are vesicular and internally autobrecciated. Adjacent hornfels is locally folded and contorted.

Upper contact geometry at Camp Creek/Eagle Hawk Neck

The general concordant nature of the Settlement Creek Volcanics—Wollogorang Formation contact is interrupted at Eagle Hawk Neck (Figure 3.1) by an elongate subhorizontal EW-oriented apophysis of dolerite, which occurs ~50 m higher than normal, within the ‘nodule beds’ of the middle Wollogorang Formation (Rod, 1978). The dolerite body is conical in cross-section and is several kilometres long, taking on the shape of a railway H-section (Plate 3.8C; Figure 3.13D). Coherent basalt and dolerite are strongly jointed and are generally fresh and unaltered. Intense brecciation of the mudstone and carbonate hostrocks, and alteration of the breccia matrix is associated with this body. Various breccia types are present, most of which are monomict.

(i): dolerite/basalt breccia. Clast- to lesser matrix-supported, with angular cobble- to boulder-sized clasts in a chloritic mud matrix (Plate 3.8D). Clasts range from jigsaw-fit to rotated, and most show evidence of mechanical or hydraulic (not hydroclast) fracturing.

(ii): dolostone+ mudstone breccia. Mostly clast-supported with semi-ductile and brittle deformed cobbles in a chloritic mud matrix (Plate 3.8E). The breccia sequence is unstratified and unsorted, and shows a high degree of stratigraphy preservation, suggesting it is largely in situ. Clasts typically show evidence of alteration and/or ‘baking’, which culminates locally as amphibole hornfels.

(iii): polymict breccia. Clast- to matrix-supported with red/brown mudstone, dolostone, laminated dolomudite and dolerite/basalt in a chloritic mud matrix (Plate 3.8F). Some spherical- to elliptical-shaped basal clasts may by chilled ‘pillows’. In thin-section, irregular vesicular ‘cognate’ basalt clasts are evident, indicating that breccia formation was accompanied by emplacement of magma.
Green chloritic alteration is generally restricted to the breccia matrix, which was probably unconsolidated mud and decarbonised dolostone, but is locally pervasive. In some cases, clasts of red oxic mudstone from the lowermost Wollogorang Formation are chloritised, and diagenetic dolomite nodules from the 'nodule beds' are strongly recrystallised and are largely devoid of their original organic matter. Chloritic alteration is interpreted to relate to the passage of reduced fluids through the breccia pile. This fluid may have been derived directly from the dolerite, from ambient pore-waters in the carbonates, or by thermal maturation of organic matter in the 'nodule beds'. In the Redbank and Running Creek areas, similar alteration is related to the passage of locally-derived hydrocarbon-bearing fluids (Morris, 1996).

The timing of dolerite emplacement and brecciation is synchronous with lithification of the Wollogorang Formation, constrained by the presence of lithified hostrocks (nodular dolostone class), ductile to fluidised hostrocks (mudstone matrix) and 'cognate' basalt clasts.

**Fault-segmented geometry in Mallapunyah Dome**

The geometry of the Settlement Creek Volcanics in Mallapunyah Dome (Figure 3.1) is a broad saucer-shaped body (i.e., laccolith), segmented into upthrown and downthrown blocks by km-spaced north-trending faults, apparently developed during emplacement (Figure 3.13E; see also Figure 5.5). Upthrown blocks crop out as 20-200 m wide, 5-10 km long strike-ridges of resistant dolerite, with intense alteration, silicification, brecciation and quartz veining. Hornfels zones above and adjacent to the dolerite are 10s of metres thick, typically brecciated and intensely 'redrock'-altered. Dip-slip movement is indicated by fault fibres bounding upthrown blocks (Plate 3.8G). Resistant strike-ridges are separated by 1-2 km of recessive lower Wollogorang Formation, with a thin coherent hornfels zone (Figure 3.13A).

**Interpretation and discussion of dolerite sheets**

Initial interpretations of the Settlement Creek Volcanics suggested they were largely extrusive (Roberts et al., 1963; Ahmad and Wygralak, 1989; Jackson et al., 1987; Pietsch et al., 1991a; Haines et al., 1993), although several authors documented examples of sills. The main evidence cited was the 'ropy' pahoehoe-like upper surface, marginal volcanic breccia (agglomerate or autobreccia) and locally intermingled muddy and tuffaceous sedimentary rocks. Bull (1993) and Rogers (1996) suggested an intrusive origin for dolerite in the Mallapunyah Dome, based on the presence of a localised hornfelsed zone and brecciated sheet margins. Sedimentary 'interbeds' were interpreted as rafts of Wollogorang Formation, segmented during emplacement of multiple sills.

Contact relationships and features observed during the current study provide a clearer picture of the origin of the Settlement Creek Volcanics. Features that support an extrusive origin include:

- the occurrence of the dolerite sheet at essentially the same stratigraphic level throughout the region;
- the upper surface is typically smooth and planar or sinuous on a 10m scale and;
- 'ropy' or pahoehoe-like upper surface features.
Features that support an intrusive origin include:

- lack of an upper erosional surface;
- locally discordant nature of the unit;
- sheets and protrusions of dolerite extend up to 130 m into the overlying succession (middle Wollogorang Formation), forming contiguous irregular shapes that could not have been gravitationally stable if interpreted as lava field topography (e.g., Figure 3.13);
- local fault control of upper surface;
- coarse grain size of dolerite;
- scarcity of vesicles in upper part of unit when compared to conventional (pahoehoe) lava flows (Self et al., 1997);
- presence of a hornfelsed zone immediately above and below the unit, including the rare growth of secondary amphibole and K-feldspar and the recrystallisation of dolomite;
- locally brecciated hangingwall host rocks, sometimes containing bulbous 'cogonite' basalt clasts;
- local presence of sedimentary host rock clasts suspended in coherent basalt at the top of unit and;
- geochemical and temporal correlation of the Settlement Creek Volcanics with upper 'flow' units of the Gold Creek Volcanics, 300 m stratigraphically higher in the Tawallah Group (Chapter 9). This correlation implies that the Settlement Creek Volcanics were emplaced as a sill at a level 300 m below the palaeosurface of the Tawallah Group at ~1725 Ma. Some magma continued upwards through the rock package to be erupted at the palaeosurface as the upper Gold Creek Volcanics.

Although 'ropy' pahoehoe-like surfaces at or near the top of the Settlement Creek Volcanics would appear to provide indisputable proof of an extrusive origin (Self et al., 1998), I believe that most other features are difficult or impossible to accommodate in an extrusive model. Consequently, I favour the view that the Settlement Creek Volcanics are a regional-scale dolerite sill or set of sills. Further work is required to completely resolve this issue. The significance of the 'ropy' upper margin is enigmatic, as no comparable feature has previously been documented from sills. Hypothetically, the wrinkles could formed as a result of delamination of the sediment-magma interface in response to fluid or gas overpressure during emplacement. This would have allowed essentially frictionless viscous flow of the magma. They may also be due to the lubricative effects of halite at the contact zone.

An intrusive origin for the Settlement Creek Volcanics implies emplacement of a mafic sheet at essentially the same stratigraphic level over a vast area. Correlatives are recognised on the western Arnhem Shelf (McCaw Formation; Sweet et al., 1999b; Figure 2.7 & 2.8) and lower in the stratigraphy on the northern Arnhem Shelf (Oenpelli Dolerite; K. Kyser, unpubl. data). The reason for the vast areal extent is unknown. Halite-bearing mudstones dividing the Aquarium and Wollogorang Formations may have provided an effective seal or viscosity contrast in the host sediment pile. Sills may have otherwise been emplaced at the point of neutral buoyancy. Feeders for the Settlement Creek Volcanics have not yet been established, but red orthoclase-altered aphyric basalt and microdolerite dykes that crosscut the Seigal Volcanics adjacent to the Murphy Inlier (Sweet et al., 1981) are possible candidates. As mentioned above, geochemical studies
(Chapter 9) suggest that the Settlement Creek Volcanics are a deeper-level intrusive equivalent of the uppermost Gold Creek Volcanics, which were emplaced as volcanics and synsedimentary intrusives. Importantly, the recognition of an intrusive origin for the entire Settlement Creek Volcanics requires that the Aquarium Formation and Wollogorang Formation were sedimentologically contiguous prior to sill emplacement. This is supported by the sedimentary facies of the two units, which are essentially identical.

The presence of upward-intruding dolerite apophyses with linear surface distribution suggests the Settlement Creek Volcanics were emplaced synchronous with faulting of the country rocks. The persistence of large apophyses elsewhere in the region is difficult to establish due to poor outcrop, but intersections of dolerite within the upper-middle Wollogorang Formation in several drill holes suggest they are widespread. The close spatial association of weak hornfelsing, alteration and brecciation with apophyses at several localities may provide a link between sill emplacement, breccia pipe formation and regional base metal mineralisation.

3.3 QUARTZARENITE DEPOSITIONAL MODEL

Thick and widespread sheets of supernormal quartzose sandstone, typically devoid of mudstone, are essentially restricted to the Precambrian and lower Palaeozoic (Pettijohn et al., 1973; Eriksson et al., 1998). They comprise well-rounded and -sorted quartz sand and are typically interstratified with shallow marine carbonates (the 'orthoquartzite-carbonate association' of Pettijohn, 1957). Cross-beds and ripple marks are characteristic sedimentary structures. Many quartzarenite sheets are located in (and sometimes encompass) cratonic interiors (e.g., the 'unconformity-bounded sequences' of Sloss, 1963) that were stable and of low topographic relief (Chandler, 1988). In many cases, sandstones lack diagnostic sedimentary structures and a fossil record, and thus cannot be easily ascribed to either fluvial or shallow marine processes with any certainty. Modern analogues do not exist and there is doubt about the application of uniformitarianism to Precambrian sedimentary basins (e.g., Els, 1998). The non-vegetated Precambrian is envisaged to have been characterised by extensive sand-rich continental areas that were far more vulnerable to extensive alluvial and aeolian reworking than modern continental environments (Chandler, 1988). Depositional processes would have differed substantially from the Phanerozoic due to secular changes in biologic, astrologic, climatic and tectonic processes (see review in Eriksson et al., 1998). Marine shelves, for example, may have had a higher-energy hydraulic regime due to greater moon-tide pull (Visser, 1974) and wider shallower bathymetry (Klein and Rye, 1978).

The Yiyintyi, Sly Creek and Wumunmartyala Sandstones exhibit the scale and sedimentary features of this enigmatic sedimentary facies. While definitive fluvial and shallow marine facies occur in the Tawallah Group (e.g., Aquarium Formation), they are generally not in close spatial and temporal association with these quartzarenite units. Various internal features of the quartzarenite units imply both shallow marine and fluvial attributes, and are listed in Table 3.1 and discussed in Appendix 3.8. A model is presented below to encompass these mixed attributes and resolve the conflicting interpretations of Rogers (1996), Jackson et al. (1987), Haines et al. (1993) and others.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Character in lower Tawallah Group quartzarenite units</th>
<th>Character favours shallow marine</th>
<th>Character favours braidplain</th>
<th>Character favours ‘mixed’ setting</th>
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</thead>
<tbody>
<tr>
<td>grain size</td>
<td>fine to coarse</td>
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<td>√</td>
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<td>sorting</td>
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<td>x</td>
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<tr>
<td>rounding</td>
<td>good</td>
<td>√</td>
<td></td>
<td>x</td>
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<td></td>
<td>x</td>
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<tr>
<td>glauconite</td>
<td>rare</td>
<td>x</td>
<td></td>
<td>√</td>
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<td>heavy mineral laminae</td>
<td>rare</td>
<td>x</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>mudstone</td>
<td>generally minor, but difficult to assess in</td>
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<td></td>
<td>√</td>
</tr>
<tr>
<td></td>
<td>discontinuous outcrop</td>
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<td></td>
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<tr>
<td>mudclasts</td>
<td>present locally</td>
<td>√</td>
<td></td>
<td>√</td>
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<td>conglomerate</td>
<td>local; generally not imbricated</td>
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<td>cross-bedding</td>
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<td>large-scale dunes</td>
<td>rarely preserved (where active dune has been</td>
<td>√</td>
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<td>x</td>
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<td>covered by basalts; Groote Eyland)</td>
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<td>flat bedding</td>
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<td>√</td>
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<td>√</td>
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<tr>
<td>ripples</td>
<td>common and laterally continuous in some units</td>
<td>√</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>symmetrical and lesser asymmetrical</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>parting limestone</td>
<td>common locally</td>
<td>√</td>
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<td>√</td>
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<td>hummocky cross-stratification (HCS)</td>
<td>absent, but may be indirectly associated</td>
<td>x</td>
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<td>desiccation cracks</td>
<td>common locally</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
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<td>adhesion ripples</td>
<td>scarce</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>coarsening- and thickening-upwards cycles</td>
<td>common locally</td>
<td>√</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>channels</td>
<td>scarce; broad &amp; shallow</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>overall formation geometry</td>
<td>sheet-like, extensive, craton-scale in some cases</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>intermediary facies between fluvial and shallow marine (e.g. lagoon or barrier island)</td>
<td>not obvious</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>palaeocurrents</td>
<td>unimodal to lesser bimodal and polymodal</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Features relevant to discrimination of braidplain from high-energy tide-dominated shallow marine setting in quartzarenite units of the lower Tawallah Group.
3.3.1 Epeiric Platform Model for Lower Tawallah Group Sandstone Sheets

The balance of evidence presented in Appendix 3.8 and Table 3.1 favours (but does not unequivocally demonstrate) a shallow marine origin for most of the quartzarenite units of the lower Tawallah Group. Many elements of the descriptions are common to other Proterozoic and lower Palaeozoic sheet sandstones (Banks, 1973b; Johnson, 1977; Levell, 1980a&b; Soegaard and Eriksson, 1985; Tirsgaard, 1993). However, other elements such as bedforms and geometry are distinct, and require a unique evolutionary model. A hybrid shallow marine-fluvial model is outlined below in terms of its sedimentological and basal attributes. This model incorporates local conglomeratic facies in the central BFZ that may be of alluvial fan-proximal braided plain origin (Roget, 1996).

Sedimentological attributes

The majority of quartzarenite facies in the Tawallah Group are thought to have been deposited on a low-gradient shallow marine shelf influenced by strong tides, storms and waves (Figure 3.14). This depositional model involves interaction of braided fluvial, foreshore, shoreface and inner shelf processes. Initially, some sand was supplied to the foreshore and shoreface from braided streams, but most probably represents relict braidedplain and aeolian deposits captured during landward migration of the transgressive shoreline. In the shoreface-foreshore, sand was efficiently reworked by tides, waves, periodic storms and minor coastal aeolian processes. Storm surges eroded the foreshore and transported sand onto the inner shelf, where sandwaves and sand-ridges migrated under the influence of storm-enhanced unidirectional tidal currents. Some finer-grained sand was carried onto the proximal outer shelf where it was reworked by storm waves. During quiet times, larger bedforms were essentially inactive and failed to record the reversal of tidal currents. Wave-propagated ripples formed on the shoreface and inner shelf. Bedform migration only occurred during storms, when tidal currents were reinforced by storm surge, resulting in unimodal palaeocurrents (e.g., Banks, 1973b; Johnson, 1977; Appendix 3.8).

The type of sequence deposited (transgressive or regressive) is determined by the interplay of subsidence and global sealevel (i.e., accommodation space; Posamentier and Vail, 1988). This is difficult to assess for most of the Tawallah Group, due to a lack of diagnostic facies and the broad scale of the current study. However, it is envisaged that progradation of the shoreline during regressions formed shoaling-upwards cycles in some parts of the sand sheet, with offshore sandwave deposits overlain by shoreface (intertidal) and foreshore (supratidal) deposits. Aggradational parts of the sand sheet experienced less fluctuation in relative sealevel and deposited stacked cycles of intertidal channel facies overlain by supratidal flat facies. Transgressive deposits may constitute the more homogeneous parts of the sand sheet, where storms and tides developed a laterally-extensive shoreface-offshore sand-ridge system during shoreline retreat (cf. Swift and Field, 1981). Undoubtedly, braided fluvial and aeolian deposits were preserved within the sand sheets, but are difficult to distinguish from the inferred marine deposits (cf. Dott et al., 1986).
Figure 3.14 Schematic depositional model for quartzarenite and immature sandstone/mudstone units of the lower Tawallah Group. A braided stream-dominated coastal plain passes basinward into a high-energy shoreline, thence into a tide- and storm-influenced shallow shelf. Note that this diagram depicts a semi-stationary shoreline configuration of the highstand systems tract, so as to illustrate the envisaged depositional environments. The basin-scale depositional model discussed in the text employs a transient shoreline that translates laterally over large distances as a result of rapid and high-frequency sea level fluctuations and a low-gradient shelf. Due to the low envisaged gradient, the horizontal scale is in the order of 100 km, however, the dimensions of individual environments is schematic. Adapted from Levell (1980b) and Johnson and Baldwin (1996).
Basinal attributes

The basinal model envisaged is similar to that of Runkel et al. (1998) for the Western Interior Basins of North America, in which deposition took place on a tectonically-stable craton interior, distal to an active margin centred on the Appalachians. Based on petrographic information and limited palaeocurrent data and thickness variations, the source of detritus for the Tawallah Group appears to have been a distal uplifted cratonic hinterland to the north or northeast. However, intrabasinal uplifts such as the Murphy Inlier and the Batten and Tawallah Ranges area along the Tawallah Fault may have had a local influence on provenance. In this scenario, the lower Tawallah Group may have been the northern ramp of an EW-oriented intracratonic (epeiric) sea, or a broad gently southward-tilted continent shelf (toward an active or passive margin). Deposition on this ramp or shelf was initially subaerial, with sediments dispersed on a broad braided plain with indistinct channels (e.g., lower Yiinty Sandstone). Local aeolian sediment transport may have taken place where the stream system was temporarily inactive.

The low-gradient ramp was subsequently influenced by large-amplitude and high-frequency eustatic cycles. Shelf bathymetry may have enhanced tidal height and currents. Because the depositional surface had a low topographic or bathymetric gradient, even small changes in relative sealevel grossly affected the distribution of terrestrial and marine influences. Repeated sealevel changes led to rapid progradation and retrogradation of the shoreface across the shelf and deposition of cyclic sand packages. According to Posamentier et al. (1992), a slowly-subsiding low-gradient shelf or epeiric basin that is supplied constantly and rapidly with sand will tend to develop a widespread progradational sand sheet of uniform thickness. The basinward extent of this sand sheet will be necessarily large, because the very low shelf gradient will result in a large lateral translation of the shoreline relative to vertical drop in sealevel (Runkel et al., 1998).

The sand sheet was fed by broad braidplains during lowstands and was periodically inundated and reworked along a laterally-migrating non-barred shoreline during transgressions and highstands (Figure 3.14). The exact morphology of this shoreline is difficult to determine, but due to the shallow dip of the shelf it was probably characterised by numerous transient sand islands and embayments. Slow subsidence and accommodation rates, overprinted by successive periods of sealevel rise and fall, allow for efficient aggradational reworking of sands in the shoreface-foreshore and facilitated the generally high degree of textural and mineralogical maturity. At any one instant, fluvial, aeolian, shoreface and offshore processes dominated different parts of the sand sheet, only to be replaced during lateral migration of the shoreline.

The interpreted preferential preservation of tide- and storm-influenced shallow marine lithofacies in the various quartzarenite units may be due to the broad and energetic nature of the shoreface and the low angle of the shelf, or may reflect the active filling of accommodation space during transgressions. Subtidal 'tempestite' facies were reworked and winnowed in the intertidal
zone during lowstands, while fluvial facies were inevitably replaced by inner shelf and shoreface facies during highstands (cf. Runkel et al., 1998). Sustained periods of increased accommodation space are marked by the widespread deposition and preservation of deeper storm-influenced facies on the lower shelf, such as Wununmantyala Sandstone units 1 and 3.

The model outlined here differs from that of Dott et al. (1986), who interpreted the widespread sand sheet distribution of the lower Palaeozoic of eastern USA to be the result of fluvial and aeolian processes, with partial reworking in a shallow marine setting. They envisaged a single transgression for each fluvial-aeolian sand blanket (e.g., St Peters Sandstone), with reworking of the only the upper part of the sheet. Their model may be acceptable for a 40 m thick sand sheet, but cannot be applied to Tawallah Group quartzarenite sheets of >300 m thickness, nor the stacked marine cycles within the Tawallah sand sheets. The model of Runkel et al. (1998), with substantial marine transport and reworking, is considered a better analogue, because it provides a realistic mechanism for maturation of the sediments and development of cycles. Modern studies of shelf-shoreface systems (e.g., Swift and Field, 1981; Swift and Thorne, 1991) indicate that marine sediment transport is a viable mechanism for widespread sand distribution.

It is thought that quartz sand dominated during deposition of Tawallah Group quartzarenite units due to mud-bypass mechanisms, the relatively energetic coastal processes and the efficient reworking of sediments. Higher-order controls on sand composition are interpreted to have been climate (humid and hot), basinal (broad epeiric platform or low-gradient shelf) and tectonic (post-supercontinent breakup). Internal cyclicity within the quartzarenite units is attributable to allocyclic and autocyclic processes. Allocyclic processes may be genetically linked to broad domal uplift (arching) of the distal craton interior and/or magmatic arc and orogenic activity at the plate margin. In this respect, they resemble the Palaeozoic unconformity bounded sequences of North America (Sloss, 1963), which record evolution of the Cordilleran and Appalachian Orogens.

It is speculated that a gradual marine transgression and development of a low-gradient widely-dispersed sand sheet in lower Tawallah Group times was due to a first-order sea level rise and a reduction in continental freeboard (cf. Eriksson, 1999), perhaps associated with disintegration of a supercontinent (cf. Klein and Hsu, 1987) or due to regional tectonic processes (Leighton, 1996). This hypothesis is examined further in Chapter 10.

3.4 DEPOSITIONAL-VOLCANOLOGICAL MODEL

The lower Tawallah Group is characterised by widespread sheets of sandstone and lesser conglomerate, carbonates and mafic volcanics. The base of the Tawallah Group is composed of pebbly sandstone in most parts of the basin (lower Yiyintyi Sandstone) and was deposited in a proximal-medial braided fluvial environment. This is overlain by a >2000 m thick supermature quartzarenite sheet (upper Yiyintyi Sandstone) of medial-distal braided plain or shallow marine origin. In contrast, 1500 m of alluvial conglomerate (Westmoreland Conglomerate) marks the
base of the Tawallah Group at the basin margin near the Murphy Inlier. Both the basinal and basin-margin facies are characterised by 100-1000 m-scale internal cyclicity that probably relates to tectonism in the hinterland. During this interval, palaeocurrents range from unimodal and southwesterly-directed to locally bimodal and northeast-southeast-trending. Initial sedimentation was possibly accommodated by local north-tilted growth wedges, but little else is known about basin architecture at this time.

Sedimentation was interrupted by a large-scale mafic volcanic event, in which a series of stacked basalt lavas were emplaced onto a gently southward- and eastward-dipping landscape (Seigal Volcanics). Emplacement rates were rapid and intraformational sedimentation was negligible, particularly in the early stages of volcanism, where lavas were emplaced by vertical inflation. Emplacement rates diminished with time resulting in erosional hiatuses and periodic sedimentation interspersed with volcanism. The Carolina Sandstone Member represents the largest hiatus, during which significant incision of the lower Seigal Volcanics took place. Lavas of the upper Seigal Volcanics were subsequently emplaced as invasive shallow sills into the wet sediments producing the characteristic peperitic margins. By this time, volcanism was restricted to the peripheral Murphy Tectonic Ridge and a 500 m thick quartzarenite sheet (Sly Creek Sandstone) was concurrently deposited in the adjacent BPZ. Palaeocurrents at the base of the Sly Creek Sandstone are southeasterly-directed, but shift toward variable to southerly in the bulk of the unit, consistent with the preserved thickening to the south and west. The sandstone therefore appears to have been deposited as a shallow marine ramp interdigitating the main volcanic accumulations adjacent to the Murphy Tectonic Ridge.

Following a brief hiatus, sedimentation resumed with deposition of a west-thickening ferruginous and evaporitic heterolithic clastic sequence (Rosie Creek Sandstone). The perceived high-energy peritidal setting was transgressed by shallow marine shelf conditions, in which mudstones and carbonates were deposited (McDermott Formation). This vast platform sequence has been divided into four subunits that exhibit uniform thickness and facies characteristics, but may have onlapped the Murphy Tectonic Ridge. Alternating subtidal-peritidal deposition resulted from high-frequency eustatic cycles, akin to those that influenced the quartzarenite sheets (see below), and a coastal sabkha fringe. In terms of palaeogeography and facies, this best fits an epeiric sea model, in which the water body was periodically restricted from the marine realm. Contiguity with similar facies in the northwestern McArthur Basin suggests this sea extended in a northwest-southeast direction, but its total dimensions and shape are unknown.

An episode of regional uplift or sea level fall led to a regression and local erosion of the underlying carbonates. The conformably to disconformably overlying sandstone sheet (Wunnumantyala Sandstone) is uniform in thickness (300 m) and facies over most of the basin. Localised basal conglomerate and thickening of the overlying Wuraliwuntja Member in the central BPZ may relate to local synsedimentary deformation. Elsewhere, thin but laterally-persistent marine shelf sandstone and siltstone were deposited alternately alongshoreface quartzarenite in the lower part of the formation, and were succeeded by the main quartzarenite sheet of mostly high-energy shallow marine origin.
Lateral correlations, polymodal palaeocurrents and ubiquitous haematite grain-coatings suggest a restricted shallow marine embayment or epeiric sea setting of similar dimension to the McDermott Formation. The Murphy Tectonic Ridge was apparently the southeasterly shoreline.

Restriction and perhaps deepening of the water body led to deposition of a widespread (but locally growth-fault-confined) fine-grained sand blanket in a storm-dominated shelf environment (lower Aquarium Formation and Wuraliwenya Member). Continued restriction and shallowing of the water body instigated widespread evaporitic redbed deposition in a low-energy partly-emergent setting (marginal marine saline or salt-en). This basin appears to have extended further northward than the earlier seaways, but was more restricted from the main water body or ocean, which may have existed to the south.

Renewed intertidal carbonate deposition (Wollagorang Formation) was facilitated by re-establishment of marine links. Sustained carbonate-siliciclastic deposition was terminated by intrusion of dolerite sills (Settlement Creek Volcanics) into the redbed sequence, principally at the main evaporitic horizon. Hostrocks were metamorphosed and brecciated during emplacement and plugs and elongate fault-controlled breccia lenses were formed. A genetic connection with at least some of the enigmatic Cu-bearing breccia pipes on the Wearyan Shelf (Knutson et al., 1979) is likely, but the exact relationship with base metal mineralisation is unknown.

The depositional setting of quartzarenite units in the lower Tawallah Group cannot be determined unequivocally. Analysis of contained features suggests deposition on an extensive and low-gradient platform that was initially dominated by fluvial and aeolian processes. The platform was subsequently transgressed to form a shallow marine shelf or epeiric ramp that was influenced by an energetic tidal regime with superimposed storm and wave processes. Sand maturity was facilitated by high-frequency eustatic cycles, in which the shoreline repeatedly transgressed and regressed across the sand sheet. The resulting deposits contain features attributable to both shallow marine and fluvial deposition, with a subordinate aeolian influence. A close balance of sediment supply, sediment dispersal and subsidence is envisaged, implying a stable intracratonic setting with slow accommodation rates. Internal cyclicity is thought to relate to allocyclic and autocyclic processes, the former possibly emanating from uplift of the distal craton interior and/or active margin. In this respect, they resemble the ‘unconformity bounded sequences’ of Sloss (1963). Intrabasinal uplifts provided only minor influence on provenance and deposition. Gross accommodation space may have been provided by global sealevel rise or craton-scale subsidence in response to a period of supercontinent breakup or due to regional tectonic processes (Chapter 10).

3.5 KEY OUTCOMES

1) A review of data from the Westmoreland Conglomerate and Yiyintyi Sandstone has identified correlative internal cyclicity that may coincide with basin-margin tectonic events. Possible north-dipping growth wedges may be implied from thickness variations in the northern BFZ; otherwise a sheet morphology is apparent. Palaeocurrents change upsequence from unimodal and southwesterly-directed to bimodal with northeast-southeast trends. Alluvial deposition dominates the base, but the bulk of this succession is of enigmatic origin (see 9).
2) Volcanological studies near the Murphy Inlier indicate that the Seigal Volcanics are composed of two distinct units, divided by a sharp erosional surface and thin sandstone lens (Carolina Sandstone Member) that thickens and downcuts to the southwest. Sedimentary units and erosional hiatuses between basalt sheets are generally lacking in the lower unit, indicating that most lavas were emplaced by endogenous growth. Lavas in the upper Seigal Volcanics are characterised by peperitic margins, formerly interpreted as agglomerate or sedimentary infill of irregular autobreccia flow tops. These basalt sheets were emplaced as invasive flows or shallow sills. Only the lower Seigal Volcanics are present in the BFZ, and the Sly Creek Sandstone in this area appears to at least partly correlate with the upper Seigal Volcanics in the Murphy Inlier. In the BFZ, the thickness of the Seigal Volcanics was found to increase gradually to the south.

3) Regional studies demonstrate that the Sly Creek Sandstone is absent on the eastern Wearyan Shelf. The unit formerly mapped as Sly Creek Sandstone on the Wearyan Shelf is now recognised as the Wunnumantyala Sandstone. Thickness variations suggest the Sly Creek Sandstone thins gradually northward and eastward from the central BFZ, but is essentially sheet-like in form. Palaeocurrents change upsequence from northeasterly to southerly-directed and the depositional setting is equivocal (see 9).

4) A thin (~10 m) interval of Rosie Creek Sandstone was identified on the eastern Wearyan Shelf, where it disconformably overlies Seigal Volcanics. From this locality it thickens to 200 m in the BFZ.

5) Outcrops currently mapped as Aquarium Formation in the BFZ are reassigned to the McDermott Formation. This unit has uniform distribution and thickness throughout the basin, but is marginally attenuated in the BFZ and immediately adjacent to the Murphy Inlier. Facies associations suggest subtidal-peritidal deposition in a shallow sea during rapid and repeated transgressions and regressions.

6) Regional stratigraphic sections and a fence diagram for the Wunnumantyala Sandstone delineate four subunits. The Wunnumantyala Sandstone has a conformable to disconformable base that locally downcuts the McDermott Formation, but only along the Murphy Inlier does it cut down onto the Seigal Volcanics. The local basal disconformity and conglomerates reflect an uplift event, however, map patterns and field relationships provide no support for models invoking significant basin inversion and incision of basement volcanics (Rogers, 1996). Conformable basal relationships involve a transition from subtidal and intertidal Stromatolitic dolostone to glauconitic sandstone of marine shelf affinity. Overlying quartz arenite is consistent in thickness and facies over a vast area and is of enigmatic origin (see 9).

7) Wuraliwuinya Member of the Wunnumantyala Sandstone and Aquarium Formation are correlated across the basin. Local facies variation in the BFZ appears to be controlled by growth faults (Rawlings et al., 1993). The depositional setting evolved from storm-dominated restricted marine shelf to a marginal marine salina through time.
8) The Settlement Creek Volcanics appear to be intrusive across their entire extent, indicating vertical contiguity of Wuraliwnyntja Member/Aquarium Formation with the lower Wollogorang Formation prior to intrusion. A variety of unique sill-margin features and relationships are described. Locally, the sill propagates up into the upper Wollogorang Formation where it is generically associated with plug-shaped mineralised breccia bodies (?breccia pipes) and linear fault-bounded outcrop belts.

9) Quartzarenite units in the lower Tawallah Group (Yiyintyi, Sly Creek and Wununnmantya Sandstones) have a collage of shallow marine and fluvial features, best explained by deposition on a low-gradient shelf or epeiric ramp. The depositional model also incorporates a hot humid climate, slow subsidence, energetic shoreline and high-frequency eustatic sealevel oscillations. Possible tectonic connotations are the existence of: (i) a distal active margin, orogen and/or intracontinental arch and; (ii) a supercontinent breakup event preceding deposition of craton-scale quartzarenite sheets.

10) The analysis of facies, thickness and distribution suggests that shelf carbonates and fine-grained siliciclastics accumulated in shallow epeiric seas that were at times restricted from marine influences. Northwest-southeast depoaxial or palaeoshoreline trends are implied.