Geology and tectonic setting of the Tawallah Group, southern McArthur Basin, Northern Territory

by

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University of Tasmania, February 1996
Statement

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Abstract

The southern McArthur Basin comprises a Late Palaeoproterozoic to Mesoproterozoic sequence of clastic sediments, evaporitic carbonates, basaltic and rhyolitic volcanics and mafic intrusions that crop out between the Urapunga Tectonic Ridge and the Early Proterozoic Murphy Inlier. Within the NNW-trending Batten Fault Zone, the four recognised stratigraphic groups (Tawallah, McArthur, Nathan and Roper Groups) attain a maximum collective thickness of 12 km. The basal Tawallah Group unconformably overlies the Early Proterozoic Scrutton Volcanics, and comprises the lower 7 km of southern McArthur Basin stratigraphy. In the study region, a series of N- to NNW-trending fault blocks contain well-exposed sections of the Tawallah Group succession. Three main cycles of sedimentary deposition and igneous activity are recognised in the Tawallah Group, with each cycle marking major changes in the basin architecture and palaeo-environmental conditions.

The basal Tawallah Group Package represents a transgressive transition from alluvial braidplain (Yiyintyi Sandstone and Sly Creek Sandstone) through braid-delta (Rosie Creek Sandstone) to shallow subaqueous (Aquarium Formation) depositional environments. A period of widespread and largely subaerial mafic flood volcanism (Seigal Volcanics) separated Yiyintyi and Sly Creek Sandstone deposition. A second extension/subsidence depositional cycle and transgressive phase (middle Tawallah Group package) incorporates the Wunumnantyal Sandstone (braidplain) and Wollogorang Formation (shallow subaqueous). Mafic magmas intruded the lower and upper Wollogorang Formation lithologies during this cycle to form the Settlement Creek and Gold Creek Volcanics respectively. The depositional architecture of the middle Tawallah Group package was locally controlled by intrabasinal tectonic uplift of lower Tawallah Group and Scrutton Volcanics stratigraphy along the Tawallah Fault. The upper Tawallah Group package marks a regressive transition from nearshore (Warramana Sandstone) to braided river depositional environments (Nyanantu Formation), with local subaerial felsic volcanism (Tanumbirini Rhyolite). Elevation of the ambient geothermal gradient and the addition of mafic material to the crust by underplating and intrusion during extension are tentatively proposed as uplift mechanisms for this regressive transition.

The Seigal Volcanics, Settlement Creek Volcanics and Gold Creek Volcanics have sub-alkaline tholeitic geochemical compositions. Ti-Y-Nb-Zr relationships are consistent with genesis in a within-plate tectonic setting. A marked Nb-Ta trough on multi-element variation patterns supports a continental flood basalt affinity for the Tawallah Group mafic suite. Zr/Nb, Y/Nb and REE relationships indicate that the Settlement Creek and Gold Creek Volcanics were derived from a more enriched mantle source than the
Seigal Volcanics. Progressively lower degree partial melting of an asthenospheric mantle source in response to slower rates of tectonic extension is proposed to explain this trend towards more enriched compositions.

Deformation in the study region is characterised by complex brittle faulting along primary N-striking faults (Tawallah, Lorella and Bauhinia Faults). Fault zones in the Tawallah Group formations are typified by narrow deformation zones containing cataclasite, hydraulic breccia and wall rock alteration (silicification). Palaeostress analyses of fault-slip data led to the recognition of three main compressional deformation events. D$_1$ (E-W compression) occurred during the final stages of Aquarium Formation deposition and locally controlled later sedimentation patterns. A change in the rate of tectonic extension following D$_1$ caused lower degree partial melting of asthenospheric source regions, producing the 'enriched' geochemical compositions of the Settlement Creek and Gold Creek Volcanics. D$_2$ (NW-SE compression) involved sinistral strike-slip displacements along the Tawallah and Lorella Faults, and is correlated with syn-mineralisation deformation at the McArthur River Pb-Zn deposit. D$_3$ (NE-SW compression) post-dated Roper Group deposition, and is characterised by dextral strike-slip deformation adjacent to the Tawallah and Lorella Faults, and NE-directed reverse displacement on the Bauhinia Fault. Quartz-hosted fluid inclusions in D$_3$ hydraulic fault breccias contain moderate temperature (160 to 210°C), saline (8-13 eq wt.% NaCl) and oxidised fluids.

An intracontinental tectonic setting is proposed for the southern McArthur Basin. The basin architecture was characterised by WNW-trending rift compartments that were bound by NNW-striking transfer faults during the early stages of basin evolution (ie. deposition of the Tawallah Group). Termination of the initial rifting stage was followed by deposition of carbonate- and evaporite-dominated McArthur and Nathan Groups in a non-volcanic, sag-phase tectonic setting. Post-Roper D$_3$ compression marked the conclusion of Proterozoic sedimentation in the southern McArthur Basin.
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Chapter 1 - Introduction
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1.1 INTRODUCTION

Most of the world's non-renewable fuel resources and many important base metal deposits occur in sedimentary basins. Exploration for these resources requires an intimate knowledge of the local and regional characteristics of the host rocks, and an understanding of the principal controls on host rock depositional geometries. In intracratonic tectonic settings, regional variations in the sedimentary depositional architecture are primarily controlled by the initial structural geometry of the basin. Structural and geodynamic basin analysis in regions of complex, multi-phase deformation therefore relies heavily on stratigraphic data to establish the timing, kinematics and geometry of major deformational events.

The Proterozoic sedimentary basins of Northern Australia have been traditionally modelled in terms of 'layer-cake' depositional geometries (Plumb, 1979). However, with the ever-increasing application of modern basin analysis techniques to the understanding of basin dynamics, it is now generally accepted that the majority of sedimentary basins, regardless of tectonic setting, do not develop in a 'layer-cake' configuration (Miall, 1990). In contrast, the lithostratigraphic units of a given sedimentary basin are more typically diachronous or time-transgressive. During the initial phase of intracratonic rifting, complex vertical and lateral stratigraphic variations can develop in response to active faulting and the associated generation of differential topographic relief (horst and graben systems). In general, stratigraphic geometries developed in extensional rift basins are characterised by 'growth' wedges adjacent to basin-forming faults (Gibbs, 1984). Furthermore, the distribution of later "sag" basin phases and the arrangement of their sequences is largely controlled by the underlying structural template.

In an effort to provide further insight into the geometry and dynamics of intracratonic basin formation, this thesis presents a detailed study of the structural, sedimentological and geochemical evolution of the Tawallah Group, the basal sedimentary package of the southern McArthur Basin. Particular attention is paid to the structural controls on intrabasinal sediment patterns during both the extensional and compressional phases of basin formation.
1.2 SCOPE OF RESEARCH

This study formed part of the basin analysis module of AMIRA/ARC project P384, a multi-disciplinary research project aimed to define exploration criteria and genetic models for Proterozoic sediment-hosted base metal deposits (Large et al., 1995). Field-based research formed a large component of the basin analysis module, with most field investigations concentrated in the southern McArthur Basin.

The southern McArthur Basin comprises a well-exposed sequence of intracratonic clastic, evaporitic carbonate and volcanic rocks that have experienced only minor ductile deformation and metamorphism relative to other Proterozoic terranes of the North Australian Craton. Consequently, it provides an exceptional opportunity for the study of Proterozoic tectonics in Northern Australia. Understanding the tectonic evolution of the southern McArthur Basin is also of considerable interest for exploration, because the basin contains the world class, 200 Mt HYC Pb-Zn deposit (Plumb et al., 1990).

The principal objective of this thesis has been to constrain the early tectonic development of the southern McArthur Basin, by investigating structural, sedimentological, volcanological and geochemical aspects of the basal sedimentary package (Tawallah Group). The Tawallah Group was targeted for three main reasons: 1) it is characterised by thick, resistant sandstone formations and is therefore well-exposed throughout the southern McArthur Basin (Fig. 1.1); 2) it is the oldest stratigraphic package in the basin, and is therefore likely to have preserved evidence for all major deformation events; and 3) compared to the younger McArthur Basin stratigraphy, surface exposure of brittle deformational features in the Tawallah Group is exceptional. Specific aims of this study were to:

• describe and provide palaeo-environmental interpretations for the individual formations in the Tawallah Group, establish an event stratigraphy and reconstruct the local Tawallah Group depositional architecture.

• evaluate the setting and dynamics of tectonism during deposition of the Tawallah Group by examining major and trace element compositions of the Seigal Volcanics, Settlement Creek Volcanics, Gold Creek Volcanics and Tanumbirini Rhyolite.

• characterise the brittle deformation features in the study region.

• establish a local deformation event hierarchy and define the geometric and kinematic characteristics of each event.

• investigate the dynamics of fluid flow in a major strike-slip fault system.

• construct a tectono-stratigraphic model for the southern McArthur Basin.
Fig. 1.1 Distribution of Tawallah Group exposures in the southern McArthur Basin showing location of the western McArthur River Region (after Jackson et al., 1987).
1.3 PREVIOUS WORK

Geological investigations in the southern McArthur Basin date back to the initial discovery of galena near McArthur River station by pastoralist Tom Lynott in 1887 (Pietsch et al., 1991a). Excluding the numerous (> 600) unpublished company reports, the first regional geological mapping incorporating the study region was conducted by the Bureau of Mineral Resources for production of the BAUHINIA DOWNS 1:250 000 map sheet (Smith, 1964). Subsequent geological investigations were conducted by the Northern Territory Geological Survey for production of the McArthur River 1:100 000 and second edition Bauhinia Downs 1:250 000 geological map sheets (Pietsch et al., 1991a; 1991b). Comprehensive descriptions of the southern McArthur Basin stratigraphy are provided by Jackson et al. (1987), Rawlings et al. (1993) and Haines et al. (1993). Regional variations in the sedimentary facies and depositional architecture of the Wollogorang Formation were outlined by Jackson (1982). Volcanological studies of the Gold Creek Volcanics have been conducted by Rawlings (1993).

Plumb and co-workers (Plumb, 1979; Plumb et al., 1980; Plumb et al., 1981; Plumb and Wellman, 1987, Plumb et al., 1990; Plumb, 1994) and Etheridge and Wall (1994) have proposed models for the tectonic and structural evolution of the southern McArthur Basin, based on regional geological and geophysical map patterns. However, the only detailed study that has documented syn-depositional structural control on local sedimentation patterns in the BAUHINIA DOWNS region was conducted by Hinman (1995), for the Barney Creek Formation at the McArthur River Pb-Zn deposit.

The economic potential of the southern McArthur Basin was realised in 1955 with the discovery of siliceous gossans at the Reward and HYC prospects (Buchanan, 1984). Active mineral exploration has gradually intensified since this time, with approximately 58 reported mineral occurrences in the BAUHINIA DOWNS region alone (Pietsch et al., 1991b). The AMIRA/ARC project P384 combined regional geological, geophysical, geochemical and structural studies in the southern McArthur Basin to evaluate the controls on the location and timing of base metal deposits in sedimentary basins. The major research findings of this project are outlined by Large et al., (1995).

1.4 LOCATION AND PHYSIOGRAPHY

1.4.1 Location of the study region

The western McArthur River region is located in the central part of the southern McArthur Basin (Batten Fault Zone), approximately 35 km west of the McArthur River Pb-Zn deposit in the Northern Territory of Australia (Fig. 1.1).
study region covers approximately 1925 km² of Tawallah Group and lower McArthur Group lithologies that crop out between the Tawallah Fault, the western Scrutton Range margin, the southern termination of the Batten Range and the MOUNT YOUNGIBAUHINIA DOWNS 1:250 000 map sheet boundary (Fig. 1.2). Existing geological maps that contain the study area include the MCARTHUR RIVER 1:100 000 and the BAUHINIA DOWNS 1:250 000 scale map sheets (Pietsch et al., 1991a; 1991b).

1.4.2 Physiography and access

Climatic conditions in the southern McArthur Basin are monsoonal, with a warm, dry season from May to October, and a hot, wet season from November to April. Total rainfall during the 'dry season' averages 37 mm per year with an average maximum temperature of 32°C, whereas the 'wet season' has a total rainfall averaging 753 mm per year and a mean maximum daily temperature of 35°C (Australian Bureau of Meteorology, 1988).

The geomorphology of the study region is characterised by dissected linear sandstone ridges and escarpments separated by flat Cainozoic alluvium- and lateritic soil-covered plains. The sandstone ridges only locally exceed 250 m above sea level, with topographic elevation of the inter-ridge plains typically less than 50 m. The local topographic variability is largely controlled by differential erosion of the sandstone and less competent carbonate and volcanic formations of the Tawallah and lower McArthur Groups. Vegetation in the region consists of low to moderate density, sub-tropical savannah that is well-established adjacent to perennial waterholes, ephemeral waterways and groundwater springs.

Cape Crawford roadhouse is located 20 km south of the study region, at the junction of the Tablelands and Carpentaria Highways (Fig. 1.2). Formed gravel roads that extend from Cape Crawford to Borroloola and north to Roper River provide the main access to the Batten, Scrutton and Tawallah Ranges (Fig. 1.2). Off-road access is limited to periodically maintained station and exploration tracks which provide four-wheel-drive access to most parts of the study region during the dry season.

1.4.3 Field program

All detailed structural mapping for this project was completed during twelve months of intensive fieldwork over three successive field seasons from 1992 to 1994. To investigate the main structural relationships within the study region, five separate areas were selected and mapped at 1: 25 000 scale using a topographic base of colour aerial photographs. In 1992, detailed mapping of the Batten Range was completed. The Scrutton Range and two areas in south-western Tawallah Range were covered in 1993.
Fig. 1.2 Main access routes and settlements in the BAUHINIA DOWNS region. Locations of the study region (pink) and the McARTHUR RIVER region (green) are also shown.
Detailed mapping of a third area in the south-western Tawallah Range was completed during the 1994 field season. At each field locality, the sedimentary lithologies and local structural features were described, and where possible, the orientation and kinematics of brittle fault zones determined.

To evaluate the local palaeo-environmental architecture of the Tawallah Group, detailed facies logs for each formation were measured during the 1994 field season. Where possible, sedimentary sections were measured at various locations throughout that study region to investigate local facies variations and to complement the regional structural mapping (Appendix 1). Representative samples of each Tawallah Group formation were collected from these sections. The Seigal Volcanics, Settlement Creek Volcanics, Gold Creek Volcanics and Tanumbirini Rhyolite were sampled for geochemical analysis, and hydraulic fault breccias from the Sly Creek Sandstone were sampled for fluid inclusion studies. Specific details of the geochemical and fluid inclusion sampling programs are outlined in sections 4.1 and 7.2 respectively.

1.5 THESIS ORGANISATION

This thesis is subdivided into three sections. The first section (Chapters 1 and 2) is introductory, and provides a summary of the regional geology and tectonic setting of the southern McArthur Basin. The second section (Chapters 3 to 7) forms the main body of the thesis, and comprises detailed descriptions and interpretations of the local Tawallah Group geology and geochemistry. In the third section (Chapters 8 and 9), the preferred model for the early tectonic evolution of the southern McArthur Basin is discussed. Specific details of individual chapters include:

Regional geology: Chapter 2 reviews the established stratigraphy and structural setting of the McArthur Basin, and outlines its relationship to other Proterozoic terranes of the North Australian Craton.

Sedimentology and volcanology: Chapter 3 describes the characteristic facies associations of each Tawallah Group formation. This data forms the basis for interpretation and comparison with current sedimentological and volcanological facies models. An event stratigraphy and the palaeo-environmental architecture of the Tawallah Group are defined by combining detailed facies logs for each formation with regional geological mapping.

Volcanic geochemistry: Chapter 4 outlines the petrographic and geochemical characteristics of igneous formations within the Tawallah Group. Major and trace element (including rare earth element) concentrations are used to classify, constrain the setting and dynamics of tectonism and establish the source characteristics for each formation.
Fault zone mechanics: Chapter 5 describes the brittle fault zones exposed in the study region. Field observations are combined with petrographic examinations to delineate the meso- and micro-structural processes that were operative during deformation.

Structural geometry: Chapter 6 presents an inverse palaeostress analysis of fault-slip data measured from primary and secondary faults in the study region. Results of the analysis are used to establish a deformation event hierarchy and to document the geometric and kinematic characteristics of each event.

Fluid dynamics: Chapter 7 examines the nature of hydrothermal fluids associated with post-Roper Group (D3) strike-slip deformation in the Batten Range. Quartz-hosted fluid inclusions in D3 hydraulic breccias were analysed by microthermometry and laser Raman spectroscopy to: determine the likely fluid compositions and depositional processes, estimate depths of formation and to discuss heat flow in the McArthur Basin.

Discussion: Chapter 8 combines the geological and geochemical results of previous chapters into an integrated tectono-stratigraphic model for the southern McArthur Basin. The model is expanded to constrain and critically assess existing models for the early tectonic development of the southern McArthur Basin.

Conclusions: Chapter 9 summarises the main findings of the thesis.
Chapter 2 - Regional Geology
CHAPTER 2 - Regional Geology

2.1 INTRODUCTION

This chapter provides a regional geological framework for the more detailed descriptions of western McArthur River region geology outlined in later chapters. The geology and tectonic setting of the McArthur Basin, and its relationship to other Proterozoic terrains of the North Australian Craton are discussed. In the final section, previous models for the tectonic evolution of the southern McArthur Basin are reviewed, prior to the new model proposed in Chapter 8.

2.2 GEOLOGY OF THE NORTH AUSTRALIAN CRATON

Early Proterozoic domains of the North Australian Craton are part of the North Australian Orogenic Province, and include the Halls Creek Province, Granites-Tanami Inlier, Pine Creek Inlier, Tennant Creek Block and Arnhem Inlier (Plumb et al., 1990; Fig. 2.1). Archaean inliers that underlie the North Australian Orogenic Province include the Rum Jungle and Nanambu Complexes (West Australian Orogenic Province; Plumb et al., 1981). All Early Proterozoic domains of the North Australian Craton were deformed and subject to high-temperature low-pressure metamorphism during the Barramundi Orogeny (1880-1850 Ma; Etheridge et al., 1987). Emplacement of widespread granitic batholiths, comagmatic silicic pyroclastics and lavas with minor mafic lavas and sediment was associated with, or immediately post-dated, the Barramundi Orogeny (eg. between 1870-1800 Ma; Rawlings, 1994). This suite forms the basal element of the North Australian Platform Cover, and has been classified as the transitional phase of volcanism in the McArthur Basin (Rawlings, 1994). Subsequent to the transitional volcanic phase, sedimentation and volcanism occurred throughout the Middle Proterozoic (Upper Palaeoproterozoic to Mesoproterozoic) of Northern Australia in a number of individual sedimentary basins. These Middle Proterozoic sedimentary basins form the North Australian Platform Cover, and include the McArthur Basin, Kimberley Basin, Birrindudu Basin, Victoria River Basin, South Nicholson Basin and the Lawn Hill Platform (Plumb et al., 1990). Together, the Early Proterozoic Inliers and Middle Proterozoic sedimentary basins comprise the North Australian Craton (Fig. 2.1).

The southern and eastern margins of the North Australian Craton are bound by Proterozoic mobile belts of the Central Australian Orogenic Province, and include the southern Arunta Inlier and Musgrave Block to the south (Central Australian Mobile
Fig. 2.1 Major crustal subdivisions of Australia (after Plumb et al., 1981).
Belts) and the Mount Isa Inlier to the east (Northeast Orogens; Fig. 2.1). Deformation, metamorphism and magmatism continued along the southern margin until 1000 to 900 Ma (Plumb et al., 1990), and the final deformation event at Mount Isa occurred between 1600 and 1500 Ma (Blake, 1990).

There is little evidence for complex ductile deformation and high grade metamorphism within the Middle Proterozoic sedimentary basins of the North Australian Craton. Plumb et al. (1981) proposed that these basins are typified by broad stable shelves containing shallowly dipping stratigraphy up to 5.0 km thick that are separated by narrow fault-bounded zones (mobile zones). The 'mobile zones' contain up to 12 km of stratigraphy and are moderately deformed.

The McArthur Basin lies close to the eastern margin of the North Australian Craton. The exposed portion of the basin covers an area of approximately 18 000 km² that extends north-south along the western edge of the Gulf of Carpentaria to the Queensland-Northern Territory border (Fig. 2.2). Traditionally, the basin has been divided into two main regions; the northern McArthur Basin and the southern McArthur Basin. These are separated by the NNE-trending Urapunga Fault Zone. The Urapunga Fault Zone has been interpreted to represent a structurally controlled positive topographic feature that isolated two distinct depositional domains (Plumb and Wellman, 1987). However, broad stratigraphic correlations can be made between the two regions, and the north-south subdivision of the McArthur Basin is currently regarded as purely geographical (Haines, 1994).

The boundaries of the northern McArthur Basin are defined by contacts with Early Proterozoic Inliers that are exposed at the western (Pine Creek Inlier) and eastern (Arnhem Inlier) edges of the basin respectively (Fig. 2.2). The Arafura Basin (Palaeozoic) unconformably overlies the McArthur Basin to the north. The southern extent of the McArthur Basin is largely unknown, as western and south-eastern exposures are covered by Palaeozoic (Cambrian Georgina and Cretaceous Dunmárra) and Mesozoic (Carpentaria) sedimentary basins respectively. The southern McArthur Basin is separated from the Lawn Hill Platform and Mount Isa Inlier by the Early Proterozoic Murphy Inlier (Fig. 2.2).

The 'mobile zones' of the McArthur Basin are the Batten and Walker Fault Zones (Fig. 2.2). The NNW-trending Batten Fault Zone reaches a maximum width of 80 km (Plumb and Wellman, 1987), is bounded by the Emu and Four Archers fault systems and flanked by the Bauhinia and Wearyan Shelves (Fig. 2.2). The NNE-trending Walker Fault Zone separates the Arnhem and Caledon Shelves of the northern McArthur Basin and attains a maximum width of 50 km at its northern extremity (Rawlings et al., 1993).
Fig. 2.2 Principal tectonic elements of the McArthur Basin - Mount Isa Inlier region, Northern Australia showing Early Proterozoic domains (orange) and younger cover sequences (yellow, italics; after Plumb et al., 1980).
Two models have been proposed for the tectonic evolution of Palaeo- to Mesoproterozoic terranes in Northern Australia. Some workers have proposed that Proterozoic Australia existed as a single intact continent, with Palaeo- to Mesoproterozoic tectonism and magmatism being largely intracratonic in nature (e.g. Etheridge et al., 1987). In this model, Precambrian tectonics were typically ensialic and characterised by vertical, rather than lateral, lithospheric accretion (Rutland, 1976). Basin formation and orogeny are suggested to have been controlled by recurrent cycles of extensive crustal thinning, lithospheric delamination and crustal restacking (Kröner, 1984). Sea-floor spreading and subduction are considered to have been relatively unimportant in the orogenic process. Evidence favouring an ensialic tectonic evolution of the Early to Middle Proterozoic North Australian Craton include:

- the lack of typical Wilson-cycle signatures in most Proterozoic mobile belts (i.e. absence of ophiolitic rocks and paired metamorphic belts; Rutland, 1976; Etheridge et al., 1987);
- the paucity of volcanics with arc or oceanic crust affinities (Wyborn et al., 1987);
- the lack of palaeomagnetic evidence for significant relative motion between Proterozoic cratons (Etheridge et al., 1987);
- the similar tectono-stratigraphic histories of Early Proterozoic inliers (Etheridge et al., 1987);
- the uniform nature of post-Barramundi orogeny magmatic suites (Rawlings, 1994);
- the presence of broad basins that contain mostly shallow water sedimentary sequences.

Based on the ensialic tectonic model, Early Proterozoic basins of the North Australian Craton (e.g. Halls Creek or Pine Creek Inliers) have been subdivided into three tectono-stratigraphic packages which define the 'Barramundi sequence' (Etheridge et al., 1987). A basal fluvial clastic sequence containing predominantly mafic volcanic rocks is interpreted to have been deposited during the initiation of crustal extension and rifting. Extension is suggested to have been the final phase of rapid, small scale mantle convection that developed during heating of the upper mantle beneath a slow-moving continental plate (McKenzie and Weiss, 1975). Initially, small-scale mantle convection produced elongate belts of uplift and underplating that separated broad, mostly unaffected regions (Archaean nuclei; Fig. 2.3). Extension resulted from gravitational spreading of the hot, uplifted and thickened belts (Etheridge et al., 1987).
Overlying the basal succession is a finer grained, clastic sequence that may contain carbonates and iron formations. This sequence is inferred to have been deposited during the thermal subsidence (sag) phase of basin evolution, following the cessation of small-scale mantle convection (Etheridge et al., 1987). An upper turbidite facies is interpreted to have formed after the termination of thermal subsidence and during the onset of orogenesis (Barramundi Orogeny). The Barramundi Orogeny was typified by substantial crustal shortening (thrusting and upright folding) and low-pressure high-temperature metamorphism (Rutland et al., 1990). Extensive emplacement of I-type granitoids and related volcanics (transitional suite; Rawlings, 1994; Wyborn et al., 1987) accompanied or immediately postdated the Barramundi Orogeny. Crustal extension and basin formation is suggested to have resumed following the cessation of the Barramundi Orogeny, with two temporally distinct basin-forming episodes; the Leichhardt Event (1810-1740 Ma) and the McArthur Event (1740-1600 Ma; Etheridge and Wall, 1994). The majority of the North Australian Platform Cover was deposited during one or both of these post-Barramundi basin-forming episodes, with the McArthur Basin formed during the younger event (Rutland et al., 1990). Sediments and volcanics deposited during the Leichhardt and McArthur events mostly overlie Early Proterozoic rather than Archaean basement. However, the basins are not entirely coincident with the Barramundian provinces (Etheridge et al., 1987). The sedimentary basins of the North Australian Platform Cover differ from the Barramundi sequences, with basal successions comprised of quartz-rich clastics and bi-modal volcanics, overlain by finer clastics, carbonates and evaporites (Plumb et al., 1980).

The alternative model for the tectonic evolution of Early to Middle Proterozoic terranes in Northern Australia incorporates modern concepts of orogeny, and the
various components of the Wilson cycle. Evidence favouring a plate tectonic model include:
• the presence of pre-1800 Ma polymetallic VMS-type deposits in granulite facies rocks (Solomon and Groves, 1994);
• the similarity between some Proterozoic sequences and modern passive continental margins (Foden et al., 1988);
• the possible development of foreland basins during orogenesis (e.g. formation of the Bangemall Basin during Proterozoic reactivation of the Capricorn Orogen, which separates the Archaean Pilbara and Yilgarn Cratons; Myers et al., 1994).

Myers et al. (1994) suggested that crustal fragments of a remnant Archaean supercontinent were reassembled by plate tectonic processes to form three isolated cratons by 1800 Ma (West Australian, South Australian and North Australian Cratons). The North Australian Craton is believed to have formed during accretion of the Kimberley, Rum Jungle, Lucas and Aljawarra crustal fragments, and the development of the Halls Creek Orogen, Tennant Creek fold-belt and 'pre-Isan' fold-belt. Repeated terrane accretion and associated orogenic activity along the southern margin of the North Australian Craton occurred during the Strangways (1880-1870 Ma) Arglike (1680-1660) and Chewings (1620-1580 Ma) events (Myers et al., 1994). In this model, the McArthur Basin was produced during an episode of intracratonic rifting between 1740 and 1640 Ma. Part of the McArthur Basin was then deformed along the eastern margin of the North Australian Craton by the Isan Orogeny (1600 - 1500 Ma). Accretion of the three isolated cratons between 1300 and 1000 Ma led to the final assembly of Proterozoic Australia as part of a Rodinian supercontinent (Myers et al., 1994).

2.4 GEOLOGY OF THE SOUTHERN McARTHUR BASIN

Present day exposures in the McArthur Basin represent the erosional remnants of a thick platform sequence that may have covered a large portion of the North Australian Craton (Plumb, 1979). Unconformably resting on Early Proterozoic basement, the southern McArthur Basin sequence consists of four stratigraphic packages (Tawallah, McArthur, Nathan and Roper Groups) that were deposited in shallow marine, alluvial/fluvial and lacustrine intracratonic settings (Jackson et al., 1987; Rawlings et al., 1993). Each of these packages are separated by regional unconformities (Pietsch et al., 1991). The stratigraphic relations of Proterozoic units in the southern McArthur Basin are shown in Table 2.1.
Table 2.1 Proterozoic stratigraphy of the southern McArthur Basin (after Pietsch et al., 1991).
2.4.1 Scrutton Volcanics

A number of Early Proterozoic (Orosirian) basement inliers are exposed in the southern McArthur Basin (Fig. 2.2). The Scrutton Volcanics crop out in the southern parts of the Tawallah Range, and consist of silicic to intermediate volcanics and pyroclastics, sandstone, mudstone and minor basaltic lavas (Rawlings, 1994). SHRIMP analyses of zircon grains by R.W. Page (unpublished data) indicate an age of $1851 \pm 7$ Ma for the Scrutton Volcanics, similar to the Cliffdale Volcanics of the Murphy Inlier (Haines et al., 1993).

Rawlings et al. (1993) provide detailed lithological and petrological descriptions of the Scrutton Volcanics that are briefly summarised here. Volcanic rocks exposed in the basement inliers include porphyritic dacitic lava, minor intrusions and rhyolitic to dacitic pyroclastic rocks. The pyroclastic component of the Scrutton Volcanics consists of crystal-rich rhyolitic ignimbrite that contains abundant phenocrysts of K-feldspar, quartz, plagioclase and ferromagnesian minerals in a devitrified matrix, and airfall tuff. Tuffaceous intervals are preserved as thin horizons between ignimbrite sheets (co-ignimbrite ashfall) or as composite laminated intervals (plinian ashfall). Rare accretionary lapilli and crystal-rich tuffs are also present. In upper parts of the Scrutton Volcanics succession, fine- to medium-grained volcanioclastic sandstones and mudstones are present.

The volcanic components of the Scrutton Volcanics succession are interpreted to have been largely deposited in subaerial environments (Rawlings et al., 1993). Shallow marine and/or fluvial incursions associated with clastic sedimentation are suggested to have increased towards the top of the succession (Haines et al., 1993).

2.4.2 Tawallah Group

The Tawallah Group is the oldest exposed sedimentary package in the southern McArthur Basin, unconformably overlying the Scrutton Volcanics. Depositional ages are constrained between the Scrutton Volcanics ($1851 \pm 7$ Ma) and the Tanumbirini Rhyolite ($1713 \pm 6$ Ma; Haines et al., 1993; Table 2.1). Sandstone-dominated tractional sediments of alluvial/fluvial and shallow marine origins characterise the Tawallah Group (Chapter 3). However, lesser intervals of siltstone, lacustrine carbonates, mafic volcanics and shallow intrusions and felsic volcanics are also present.

Although the combined thickness of Tawallah Group stratigraphy is approximately 4500 m (Jackson et al., 1987), seventy five percent of this estimate is encompassed by the two basal sandstone units (Yilyintyi Sandstone/Westmoreland Conglomerate and Sly Creek Sandstone). Plumb and Wellman (1987) have suggested
that the thickness of the Tawallah Group is constant in the Batten Fault Zone and on the adjacent stable shelves.

The Tawallah Group is interpreted to have formed during an episode of continental extension in the Palaeoproterozoic of Northern Australia, that was terminated during a period of uplift and erosion (Pietsch et al., 1991b). Fault-controlled subsidence subsequent to the uplift event is suggested to have controlled deposition of the overlying McArthur Group carbonate and fine-grained clastic formations (Haines et al., 1993).

2.4.3 McArthur Group

The McArthur Group was characterised by extensive shallow water deposition of carbonates and lutites, with subordinate fine-grained arenitic intervals and no proximal volcanism (Haines et al., 1993). Abundant evidence for shallow marine intertidal and/or lacustrine evaporitic and emergent conditions is preserved throughout the McArthur Group succession (Rawlings et al., 1993). A single age has been reported from the McArthur Group; 1690 ± 25 Ma (Page, 1981) for a tuffaceous horizon within the Barney Creek Formation (Table 2.1). The McArthur Group has an combined maximum thickness of approximately 3500 m (Jackson et al., 1987).

Based on the identification of several local unconformities, the McArthur Group has been subdivided into the Umbolooga and Batten Sub-groups by Jackson et al. (1987; Table 2.1). The unconformity is marked by erosional surfaces, karstic features, silcreted regoliths or breaks in the sequence adjacent to fault zones (Haines et al., 1993).

The McArthur Group is mostly confined to the Batten Fault Zone, with thinned equivalents on the Bauhinia and Wearyan Shelves. Plumb and Wellman (1987) suggested that this architecture resulted from deposition in a N-S-trending graben or half graben, with only minor deposition occurring on adjacent shelves. Pietsch et al. (1991b), propose that more widespread deposition may have taken place, with the thickened McArthur Group stratigraphy a consequence of local preservation in fault controlled depressions.

2.4.4 Nathan Group

The Nathan Group was defined by Jackson et al. (1987), and is comprised of a relatively thin (50 m), basal conglomeratic sandstone (Smythe Sandstone) of alluvial/fluvial origin, overlain by thicker carbonate and siliciclastic formations (Baibirini Dolomite - 900 m; and Dungaminnie Formation - 240 m). The upper Nathan Group formations are interpreted to have been deposited in continental (sabkha) to
shallow water environments (Haines et al., 1993). The Nathan Group contains similar facies associations to the underlying McArthur Group, and has a similar geographical distribution. The Nathan Group is mostly exposed in the Batten Fault Zone, with only thin equivalents on the adjacent Bauhinia and Wearyan Shelves. The main difference between the two groups is that the Nathan Group is a significantly thinner (1600 m), and more widespread sequence than the McArthur Group (Pietsch et al., 1991b).

2.4.5 Roper Group

The Roper Group differs significantly from the 'rift-related' carbonates of the underlying McArthur and Nathan Groups. Five major sequence cycles were deposited in an intracratonic basinal setting during Roper Group times (Pietsch et al., 1991b). Each cycle consists of quartz arenite, mudstone and siltstone lithologies that are interpreted to have been deposited in response to gradually decreasing water depths across the basin (Powell et al., 1987). The Roper Group depocentre was located approximately 200 km west of the Batten Fault Zone, with a maximum stratigraphic thickness of 1000 m in Arnhem Land increasing to approximately 5000 m southwest of the Bauhinia Shelf in the Beetaloo Sub-basin (Plumb and Wellman, 1987). Rb-Sr dating of illite in carbonate lithologies of the McMinn Formation (Table 2.1) gave a minimum diagenetic age of 1429 ± 31 Ma the formation (Kralik, 1982), and a maximum depositional age for the Roper Group (Powell et al., 1987). A minimum depositional age of 1280 Ma is based on K-Ar dating of dolerite sills that have intruded upper parts of the Roper Group (McDougall et al., 1965).

2.4.6 Cambrian formations

Gently dipping Cambrian formations overlie Proterozoic rock types in the southern McArthur Basin. Pietsch et al. (1991b) suggest that the Cambrian formations exposed in the basin are the northernmost extensions of the Georgina Basin. There is no evidence to suggest that Proterozoic fault systems reactivated during Cambrian sedimentation. Pietsch et al. (1991b) provide a detailed description of the Cambrian rock units exposed in the southern McArthur Basin; a short summary is provided here.

The Early Cambrian Bukalara Sandstone unconformably overlies Proterozoic rocks of the southern McArthur Basin, Mount Isa Inlier and South Nicholson Basin, and is a thin- to thick-bedded, fine- to coarse-grained feldspathic quartz sandstone, typically 30 - 100 m thick. The most abundant sedimentary structures are trough cross-bed sets that display average amplitudes of 2 - 3 m. Trough cross-bedded intervals are overlain by shale, ripple-laminated sandstone or pebbly sandstone. Vertical Skolithos burrows
occur throughout the entire thickness of the formation and imply a shallow marine (littoral zone) depositional environment (Haines et al., 1993).

The Top Springs Limestone disconformably overlies the Bukalara Formation, and unconformably overlies Proterozoic rocks of the southern McArthur Basin. The formation consists of partially dolomitised, mottled and onkoid limestone with minor bioclastic, brecciated or rare fenestral limestone and cryptagal laminites. Fossiliferous components contain brachiopods, hyoliths, molluscs, sponge spicules, chancelloriides and echinoderm ossicles. The occurrence of *Redlichia* defines a Middle Cambrian age for the formation. The Top Springs Limestone reaches a maximum thickness of 92 m and is interpreted to have formed in shallow marine to peritidal depositional environments (Pietsch et al., 1991b). The formation is correlated with the lower Tindall Limestone (Daly Basin) on the basis of its macro-faunal assemblage and inferred environment of deposition.

2.4.7 Cretaceous formations

Pietsch et al. (1991b) have recognised two distinct Cretaceous lithologies in the southern McArthur Basin. These typically occur as mesa cappings, plateaux and valley infill. The lower lithology consists of pebble to boulder conglomerate with clasts of underlying Cambrian and Proterozoic formations set in a coarse-grained hematitic sandstone matrix. Deposition of this lithology probably occurred in non-marine shallow water and fluvial environments. An upper facies of bleached or ferruginous siltstone and mudstone with minor sandstone intervals was probably deposited in shallow marine settings.

2.4.8 Regional stratigraphic correlations

Regional correlations have been made between the units of the southern McArthur Basin and lithologies of adjacent regions based on broad lithological similarities and U-Pb zircon dating (Plumb et al., 1980; Jackson et al., 1987; Plumb et al., 1990). The most recent revisions of Palaeo- to Mesoproterozoic stratigraphic correlations within the North Australian Craton have been provided by Pietsch et al. (1994) and Rawlings (1994). A brief summary of their suggestions are provided below.

The Scrutton Volcanics (Fig. 2.2) have been classified as part of the 'Transitional Phase' of volcanism and plutonism that post-dated the Barramundi Orogeny and preceded Tawallah Group sedimentation and volcanism. Igneous rocks attributed to this phase in Northern Australia are subdivided into 1870-1850 Ma and 1840-1800 Ma groups. The Scrutton Volcanics belong to the older suite, which also includes the El Sherana Group (Pine Creek Inlier), Leichhardt Volcanics (Mount Isa
Inlier), lower Hatches Creek Group (Davenport Province) and portions of the Cliffdale Volcanics (Murphy Inlier). Comagmatic intrusive rocks of this period include the Nicholson Granite (Murphy Inlier) and Kalkadoon Batholith (Mount Isa Inlier).

The Tawallah Group has been correlated with the Katherine River (Arnhem Shelf), Donydji (Walker Fault Zone) and Spencer Creek Groups (Caledon Shelf) in the northern McArthur Basin. More regional Tawallah Group equivalents include the Peters Creek Volcanics (South Nicholson Basin), Carrara Range Group (Lawn Hill Platform) and the Eastern Creek Volcanics/Haslington Group to Fiery Creek Volcanics section of the north-western Mount Isa Inlier.

In northern and central regions of the northern McArthur Basin, McArthur Group correlates include the Parsons Range, Habgood and Balma Groups. The Vizard Formation is interpreted as the Batten Sub-group equivalent in southern regions of the northern McArthur Basin. The Fickling Group (South Nicholson Basin), McNamara Group (Lawn Hill Platform) and the Surprise Creek to Mount Isa Group section of the north-western Mount Isa Inlier are interpreted to be regional correlates of the Umbolooga Sub-group.

Lateral equivalents of the Nathan Group in the McArthur Basin include the Mount Rigg Group (Arnhem Shelf) and Karns Dolomite (Wearyan Shelf). The only known correlate of the Roper Group is the South Nicholson Group of the South Nicholson Basin.

2.5 TECTONIC EVOLUTION OF THE SOUTHERN McARTHUR BASIN

Early Proterozoic domains of the North Australian Orogenic Province were stabilised during the Barramundi Orogeny, or during the post-Barramundi, Leichhardt Event (Etheridge and Wall, 1994). This established a framework of deep-seated NW-, NNW- to NNE- and NE-trending lineaments that, through subsequent reactivation, are interpreted to have controlled basin geometries during development of the North Australian Platform Cover (Pietsch et al., 1994). Although this pre-existing structural geometry is likely to have influenced the early tectonic evolution of the southern McArthur Basin, and the associated sedimentary facies distributions during Tawallah and McArthur Group deposition, two contrasting models have been proposed for the orientation of initial rifting and related transfer zones. The models, which are briefly outlined below, are examined critically in Chapter 8 by comparison with the structural, palaeogeographical and tectonic models developed for the western McArthur River region during this study.

21
2.5.1 E-W extension model

Plumb and co-workers (Plumb, 1979; Plumb et al., 1980; Plumb et al., 1981; Plumb and Wellman, 1987, Plumb et al., 1990; Plumb, 1994) proposed a model for the evolution of the McArthur Basin that involved northerly-trending asymmetric rifts separated by NW-trending transfer faults and transverse ridges. The rifts are the 30 to 80 km wide, 100 to 300 km long Batten and Walker Fault Zones (Fig. 2.2). Tawallah Group deposition, although not well constrained, is considered to have occurred during a widespread extensional event, with sedimentation localised in terranes of linked, N-S-striking extensional faults (eg. the Emu Fault; Fig. 2.2). These terranes are interpreted to have been precursors of the Batten and Walker Fault Zones, which were the primary depositional sites during McArthur-Balma-Habgood times.

Post-Tawallah Group sedimentation was controlled by NW-directed oblique extension, with dextral strike-slip reactivation of NNW- to NNE-trending faults (eg. the Emu Fault) and large sinistral movements on NW-trending faults (eg. the Mallapunyah, Calvert and Bullman Faults; Fig. 2.2) generating large-scale pull-apart basins. In the southern McArthur Basin, dextral strike-slip reactivation and growth faulting along the Emu Fault Zone during NW-directed extension resulted in dramatic stratigraphic thickness changes. McArthur Group formations, particularly the Barney Creek Formation and Batten Subgroup, thin westwards from the Emu Fault. This geometry is interpreted to indicate that McArthur Group deposition occurred in an asymmetric half-graben. A basin geometry comprising north-trending half-grabens helps to explain the 12 km of accumulative stratigraphy exposed within the Batten Fault Zone, as opposed to 4 km or less on the adjacent shelves.

2.5.2 N-S extension model

Etheridge and Wall (1994) have proposed an alternative model for the tectonic evolution and associated structural architecture of the southern McArthur Basin. Large-scale structural lineaments within Early Proterozoic terranes of the Australian continent are considered to have developed during the initial stages of the Leichhardt Event (1810-1740 Ma). (N)NE-(S)SE extension produced WNW- to NW-trending normal faults and NNE- to NE-trending transfer zones that are interpreted to have accommodated, bounded and compartmentalised many of the rift basins that developed across the North Australian Craton during this period. The McArthur Basin is believed to have developed during a subsequent phase of north-south extension and thermal subsidence (the McArthur Event; 1740-1600 Ma). Rift basins were generated during this event when small, approximately east-west-trending structures were linked and compartmentalised by N- to NNW-trending sidewall, transfer or strike-slip faults (eg.
2.6 SUMMARY

The formation of the southern McArthur Basin represents an important chapter in the tectonic evolution of the North Australian Craton and the Proterozoic Australian continent. The regular array of major structural lineaments that were developed across Northern Australia during the Early Proterozoic are likely to have had some influence on Middle Proterozoic sedimentary basin geometries and local depositional patterns. The combination of Early and Middle Proterozoic structural geometries may also provide some control on the spatial position of Middle Proterozoic base metal mineralisation. Each facet of the local geology examined in following chapters will ultimately allow for an evaluation of the possible control of deep-seated basement structures on the tectonic development of the southern McArthur Basin.
Chapter 3 - Sedimentology and Volcanology
CHAPTER 3 - Sedimentology and Volcanology

3.1 INTRODUCTION

In Chapter 2, the regional stratigraphy of the McArthur Basin was discussed. This chapter examines the sedimentological characteristics of Tawallah Group rock types in the western McArthur River region. The study region comprises a series of north-south trending fault blocks that contain well-exposed portions of the Tawallah Group succession. Including alluvial/fluvial and shallow marine clastics, minor carbonates and volcanics, the Tawallah Group has been interpreted as the initial rift-package of the southern McArthur Basin (Plumb, 1994). The main aims of this chapter are to evaluate the event stratigraphy and palaeo-environmental architecture of the Tawallah Group, using detailed facies logs for each formation and 1:25 000-scale regional geological mapping. This data forms the basis for interpretation and comparison with modern and ancient sedimentological and volcanological facies models. The Tawallah Group stratigraphic nomenclature used in this study was originally defined by Smith (1964) and further refined by Jackson et al. (1987) and Pietsch et al. (1991), and is summarised in Table 3.1. The grainsize classification scheme adopted for description of sedimentary rock types is shown in Table 3.2. Locations of individual measured sections are denoted by the AMG coordinates of basal and upper contacts respectively, and are shown in Appendix 1b.

3.2 YIYINTYI SANDSTONE

The Yiyintyi Sandstone comprises a thick (< 2200 m) succession of medium- to thick-bedded, medium- to coarse-grained sandstone that contains gravel and pebbles in its lower half. In the western McArthur River region, the Yiyintyi Sandstone unconformably overlies the Scrutton Volcanics, or is in faulted contact with younger formations. Haines et al. (1993) suggested that the lower half of the formation is of fluvial to alluvial fan origin, whereas high-energy, shallow marine facies associations are characteristic of the upper half. A facies log for the Yiyintyi Sandstone (Fig. 3.1) was measured from a semi-continuous series of well-exposed cliffs and ridges in the southeast Tawallah Range (57°55'E/82°199N - 57°91'E/82°181N). The base of the section was a faulted contact with lower McArthur Group rock types (Rosie Creek Fault). Recessive exposures of the Seigal Volcanics conformably overlie the Yiyintyi Sandstone at this locality.
<table>
<thead>
<tr>
<th>Stratigraphic Name</th>
<th>Max. Thickness</th>
<th>Lithology</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mallapunyah Formation</td>
<td>450 m</td>
<td>Dolomitic sandstones, shales and stromatolitic dolomites. Cahilllflower</td>
<td>Continental and coastal sabkha (Pietsch et al., 1991).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sherds, gypsum and halite casts.</td>
<td></td>
</tr>
<tr>
<td>Masterton Sandstone</td>
<td>650 m</td>
<td>Cross-bedded and ripple-laminated quartzarenite, minor recessive siltstone.</td>
<td>Alluvial fan and braided river (But, 1994).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basal conglomerates.</td>
<td></td>
</tr>
<tr>
<td>Nyanantu Formation</td>
<td>450 m²</td>
<td>Pebble sandstone and pebble-cobble conglomerate. Abundant spherulitic</td>
<td>Braided river.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rhylolitic cherts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gypsum and halite casts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cross-bedded and ripple-laminated sandstone. Basal conglomerate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternating grain-size lamination.</td>
<td></td>
</tr>
<tr>
<td>Tanumbrini Rhyolite</td>
<td>100 m</td>
<td>Porphyritic rhyolitic lava with Qtz and Kspar, phenocrysts set in a</td>
<td>Subaerial lava flows and domes (Pietsch et al., 1991).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>spherulitic gneissmass.</td>
<td></td>
</tr>
<tr>
<td>Warramana Sandstone</td>
<td>120 m</td>
<td>Cross-bedded and ripple-laminated sandstone. Basal conglomerate.</td>
<td>Nearshore with backshore lagoons.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternating grain-size lamination.</td>
<td></td>
</tr>
<tr>
<td>Gold Creek Volcanics</td>
<td>180 m</td>
<td>Basaltic-doleritic sills and dykes.</td>
<td>Shallow mafic sills and subaerial lavas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrolastic breccia (peperite).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>quartzarenite.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>siltstone.</td>
<td></td>
</tr>
<tr>
<td>Settlement Creek Volcanics</td>
<td>190 m</td>
<td>Spherically-weathering basaltic-doleritic lavas and sills. Intercalated</td>
<td>Shallow mafic sills.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hornfelsed sediments.</td>
<td></td>
</tr>
<tr>
<td>Wunumnytala Sandstone</td>
<td>520 m</td>
<td>Plane cross-bedded and ripple-laminated sandstone. Abundant shale clasts.</td>
<td>Proximal to distal braidplain.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basal conglomerate.</td>
<td>Locally shallow subaqueous.</td>
</tr>
<tr>
<td>Aquarium Formation</td>
<td>200 m</td>
<td>Stromatolitc dolostones with local ovold nodules. Interbedded HCS sandstone</td>
<td>Storm influenced subtidal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and siltstone.</td>
<td></td>
</tr>
<tr>
<td>Rosie Creek Sandstone</td>
<td>160 m</td>
<td>Feldspathic, ferruginous or glassiclastic sandstone. Abundant shale clasts.</td>
<td>Braid-delta with nearshore reworking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Siltstone.</td>
<td></td>
</tr>
<tr>
<td>Sly Creek Sandstone</td>
<td>770 m</td>
<td>Cross-bedded quartzarenite, minor gravel. Rare shale clasts and siltstone</td>
<td>Distal braidplain.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intervals.</td>
<td></td>
</tr>
<tr>
<td>Seigal Volcanics</td>
<td>400 m</td>
<td>Amygdaloidal basalt lava and doverite sills.</td>
<td>Subaerial flood basalts (Rawlings et al., 1993).</td>
</tr>
<tr>
<td>Yiyintyi Sandstone</td>
<td>2200 m</td>
<td>Cross-bedded quartzarenite, cross-bedded pebbly sandstone in lower half.</td>
<td>Medial to distal braidplain.</td>
</tr>
</tbody>
</table>

Table 3.1 Stratigraphy of the Tawallah Group and lower McArthur Group in the study region. ¹ From Pietsch et al. (1991). ² From Haines et al. (1993). ³ From this study (unless otherwise acknowledged).

<table>
<thead>
<tr>
<th>Name</th>
<th>Average grain-size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>256 - 4096</td>
</tr>
<tr>
<td>Cobble</td>
<td>64 - 256</td>
</tr>
<tr>
<td>Pebble</td>
<td>4 - 64</td>
</tr>
<tr>
<td>Granule (gravel)</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.25 - 0.5</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.125 - 0.25</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.062 - 0.125</td>
</tr>
</tbody>
</table>

Table 3.2 The Udden-Wentworth grain-size scale used for the description of clastic sedimentary rocks in this study (adapted from Ehlers and Blatt, 1982).
Fig. 3.1 Ylyintyi Sandstone measured facies log.
3.2.1 Trough cross-bedded gravelly sandstone facies

Trough cross-bedded gravelly sandstone occurs in the lower half of the Yiyintyi Sandstone, where it constitutes approximately sixty percent of the measured section. The facies consists of white, buff to pink coloured, medium- to coarse-grained gravelly quartz sandstone, and is characterised by laterally extensive beds containing medium- to large-scale trough cross-bed sets (Plate 3.1a). Cross-bed amplitudes vary from 0.5 to 2 m (average amplitude 0.7 m). Lower bed contacts are low relief concave surfaces that, in many cases, are overlain by a thin (1 to 5 cm) layer of gravel. Above this surface, gravel occurs along foresets with isolated pebbles scattered throughout (Plate 3.1b). Individual cross-bed sets occur as isolated 1 to 5 m thick beds, or are stacked to form composite units up to 15 m thick. In the latter case, both the amplitude of trough cross-bed sets and the gravel/pebble content of the sandstone decreases upwards. Small-scale planar cross-laminated sandstone interbedded with flat- and ripple-laminated medium-grained sandstone can occur in the upper parts of composite units. Alternatively, the fining-upward cycles are truncated so that only the basal, large-scale, gravelly bedforms are preserved. In these cases, composite units comprise repetitions of 1 to 5 m thick cycles, with 2 to 6 large-scale trough cross-bed sets per cycle.

Interpretation

Medium- to large-scale trough cross-bedded sandstone typically forms during the migration of three dimensional, sinuous crested, subaqueous dunes under low-flow-regime conditions (Martins-Neto, 1994; Miall, 1977). In the Yiyintyi Sandstone however, the lateral continuity of cross-bed sets, and the presence of gravel and/or pebbles is interpreted to indicate that this facies formed in high energy, laterally migrating, broad fluvial channels (McCormack and Grotzinger, 1993). Features such as crude upward fining and decrease in bedform amplitude can occur where a fluvial channel shallows due to lateral migration (Rust and Gibling, 1990). Planar-cross-laminated or rippled sands that overlie trough cross-bed sets are interpreted to have formed by cross-channel migration of shallow bar complexes. Composite units that contain repetitive cycles of basal large-scale bedforms imply either non-deposition of the finer-grained facies, or its erosion during subsequent channel establishment. Concentrations of gravel and pebbles immediately above basal surfaces indicate that deposition took place in deep parts of active channels (up to 8 m water depth; Browne and Plint, 1994).
Plate 3.1 Sedimentary facies of the Yiyintyi Sandstone

a) Amalgamated cross-bed sets in the trough cross-bedded gravelly sandstone facies. Rounded to subrounded red (hematitic) sandstone pebbles occur along foreset laminae throughout this facies interval (Tawallah Range section - 132 m).

b) Red (hematitic), coarse-grained sandstone and silicified sandstone pebbles/gravel in the trough cross-bedded gravelly sandstone facies (Tawallah Range section - 158 m).

c) High-angle foreset truncations in the trough cross-bedded sandstone facies (Tawallah Range section - 75 m).

d) Moderate angle, concave-up foresets in the trough cross-bedded sandstone facies (Tawallah Range section - 822 m).

e) Planar-bedded sandstone facies containing gravel (pb). The basal surface of this facies has truncated underlying foresets of the trough cross-bedded sandstone facies (txb; Tawallah Range section - 887 m).

f) Planar bedded sandstone facies (pb) containing gravel and pebbles occurring between trough cross-bedded gravelly sandstone facies intervals (Tawallah Range section - 206 m).

g) Ripple-laminated facies association containing planar-bedded sandstone (pb) and ripple-laminated sandstone cycles (rl), separated by a trough cross-bedded sandstone interval (txb) at the centre of the exposure (Tawallah Range section - 986 m).
3.2.2 Trough cross-bedded sandstone facies

Trough cross-bedded sandstone occurs throughout the Yiyintyi Sandstone and is particularly well developed in the upper half of the formation. The facies is typified by white to buff coloured, medium- to coarse-grained and moderately sorted quartz sandstone. Rare gravel horizons occur along foresets in the basal half of the Yiyintyi Sandstone.

Apart from a reduced grainsize and the absence of pebbles, this facies is distinguished from the trough cross-bedded gravely sandstone facies by the scale of trough-cross-bedding. In this case, the characteristic trough cross-bed sets are small- to medium-scale (0.1 to 0.5 m amplitudes), and occur in laterally extensive, 0.8 to 3 m thick beds that contain 2 to 6 sets per bed (Plate 3.1c and d). Basal surfaces are generally sub-horizontal.

**Interpretation**

Trough-cross-bedded sandstone that contains no pebbles and only minor gravel is similar to the previous facies, particularly the abundance of moderate-flow-regime sedimentary structures and the lateral continuity of beds. A similar depositional scenario involving broad, laterally migrating channels is therefore proposed. The lack of pebbles and gravel may have resulted from deposition under lower flow-regime conditions than for the trough cross-bedded gravely sandstone facies. Another possibility is that gravel from source areas was unavailable during the periods that this facies was deposited. This is likely for the upper Yiyintyi Sandstone, where the average grainsize rarely exceeds coarse sand-size.

3.2.3 Planar-bedded sandstone facies

Planar-bedded sandstone occurs in two associations in the Yiyintyi Sandstone. In lower parts of the section, it is present as thin beds (< 0.5 m) between intervals of the trough cross-bedded gravely sandstone facies. Lower planar surfaces truncate underlying bedforms, and are overlain by coarse-grained, planar-stratified sandstone, typically with gravel and minor pebbles (Plate 3.1e). Upper surfaces are overlain by the succeeding trough-cross-set.

The second occurrence of planar-bedded sandstone is typified by 0.3 to 0.7 m thick beds of medium- to coarse-grained quartz sandstone that grade upwards into the ripple-laminated sandstone facies association. Small-scale scours are developed locally along sharp and planar basal surfaces. The planar-bedded to ripple-laminated sandstone facies association occurs throughout the Yiyintyi Sandstone, although is best developed
in the upper half of the formation, where it is interbedded with the trough cross-beded sandstone facies (Plate 3.1f).

**Interpretation**

In tractional sedimentary successions, planar-bedded sandstone can develop during upper- or lower-flow-regime conditions (Harms et al., 1982). However, the formation of lower-flow-regime bedforms is largely restricted to coarse- or very-coarse grained sand. Although planar-bedded sandstone in the Yiyintyi Sandstone is generally medium- to coarse-grained, the erosional nature of basal surfaces is interpreted to indicate upper plane-bed depositional conditions for this facies.

The association of planar-bedded sandstone with trough cross-beded gravelly sandstone is interpreted to indicate fluctuating moderate- to high-flow-regime conditions in an active alluvial channel. Browne and Plint (1994) suggested that planar-bedded sandstone typically forms in this setting under plane-bed conditions during falling-flood stage, where water depths in active channels are locally shallow. Plane-bed conditions are generated when the channel floor becomes a traction carpet and particle movement is virtually continuous (Miall, 1977). Horizontal stratification occurs by rapid migration of small bedform trains (Singh and Bhardwaj, 1991).

Planar-bedded sandstone intervals showing locally scoured or sharp lower surfaces are typically associated with the lower-energy ripple-laminated sandstone facies association. These deposits are interpreted to have formed during discrete episodes of widespread sheet-flooding (section 3.2.4).

**3.2.4 Ripple-laminated sandstone facies association**

The ripple-laminated sandstone facies association occurs above intervals of planar-bedded sandstone, and in some cases, above trough cross-beded sandstone. Contacts are gradational in both cases. The ripple-laminated sandstone facies association consists of white to buff coloured, fine- to medium-grained quartz sandstone and comprises a variety of individual bedforms, one or all of which may be present in a single exposure.

Low angle (< 20°), small-scale planar cross-laminated sandstone grades laterally or vertically into flat-laminated sandstone. Lower contacts of the flat-laminated sandstone facies are typically non-erosional. Planar cross-laminated and flat-laminated sandstone intervals are overlain by, or interbedded with, fine- to medium-grained ripple-laminated sandstone (Plate 3.1g). Ripples may be either symmetrical or asymmetrical, with medium- to large-scale (ripple wavelengths 3 to 7 cm) straight-
crested varieties the most abundant (Plate 3.2a). The total bed thickness attained by this facies association ranges between 0.5 and 5 m.

**Interpretation**

The association of planar cross-laminated, planar and ripple-laminated sandstone is interpreted to have formed under waning flow-regime conditions, following discrete flood events. Together with the planar-bedded sandstone facies (flood conditions), this association resembles the Bijou Creek vertical profile model of Miall (1977). Bijou Creek is a modern example of an ephemeral sandy braidplain system, where catastrophic flooding events deposited horizontally-stratified sand in shallow water under upper-flow-regime conditions. These deposits were overlain by ripple-laminated or planar cross-laminated medium-grained sands during falling flood stages. Planar cross-laminated sandstone typically formed during downstream accretion of subaqueous dunes, whereas ripple-laminated sandstone was the product of current-ripple migration (Martins-Neto, 1993).

Symmetrical ripples in modern fluvial systems can result from secondary processes acting against the primary stream current. One such mechanism involves the generation of lateral waves at channel margins by stream pulsation (Rust, 1972). If the axes of lateral waves are approximately normal to the primary current direction, symmetrical ripples are developed.

**3.2.5 Depositional Environment**

Based on the abundance of coarse-grained and high-energy sedimentary facies, the Yiyintyi Sandstone is interpreted to have been deposited in a sand-dominated alluvial system. The lack of an exact modern analogue that includes all facies described for the formation is unsurprising, given the dynamics of Proterozoic fluvial sedimentation. Rust (1978) suggested that modern braided alluvial deposits mostly occur in restricted drainage systems, and in areas of reduced vegetation. Pre-Devonian alluvial deposits were, however, far more widespread. Without vegetative protection, pre-Devonian braided alluvium was deposited mostly on alluvial plains, in response to deeper and more frequent flooding events. Fedo and Cooper (1990) proposed that under fluctuating flow conditions, channel widening rather than channel incising would have occurred, leading to the development of wide (km-scale) shallow channels. Channels with these dimensions would be difficult, if not impossible, to recognise in the rock record.

The Yiyintyi Sandstone is interpreted to have accumulated in a braidplain depositional system that was characterised by broad, laterally accreting channels,
periodically affected by catastrophic flooding events. The abundance of trough cross-bedding in channel deposits is interpreted to indicate low-sinuosity streams in which bars and islands were insignificant (Miall, 1977). The channel deposits are similar to braidplain facies described from the Pennsylvanian Boss Point Formation, Cumberland Basin, Canada (Browne and Plint, 1994). In the Boss Point sequence, trough cross-beded sandstones with or without pebbles form under high-flow-regime conditions, in deeper parts of active channels. Planar-bedded sandstone occurring between succeeding trough cross-bedded intervals are interpreted as falling-stage deposits. Where complete shallowing cycles are exposed, trough cross-beds grade up through planar cross-laminated (bars in shallow parts of channels) to horizontal- and ripple-laminated facies (bar top deposits). However, braidplain facies in the Yiyintyi Sandstone differ from those of the Boss Point Formation in that mudstone, either as sedimentary units or as clasts within channel lag deposits, is absent.

The lower Yiyintyi Sandstone is interpreted to have been deposited in a medial sandy braidplain environment, where catastrophic flood events were confined to deep channels. The absence of gravel/pebbles and the abundance of shallow channel deposits in the upper Yiyintyi Sandstone are consistent with a more distal braidplain setting, where reduction of palaeoslope decreased the ability of the river to move larger particles (Rust, 1972). Consequently, sedimentation during high-flow-regime conditions was unlikely to have been confined to channels. Instead, sheet-flood facies associations similar to the ephemeral Bijou Creek deposits described by Miall (1977) were formed. Bhattacharyya and Morad (1992) suggested that all recent braided ephemeral river systems are typified by stream-flow deposits capped by sheet flood deposits, and sedimentary structures indicative of upper plane-bed conditions. Using these criteria, the upper Yiyintyi Sandstone is interpreted as an ephemeral braidplain succession. The trough-cross-beded sandstone facies is interpreted to have formed during the lateral migration of broad, shallow and low sinuosity channels. During flood events, these deposits were blanketed by widespread deposition of planar-bedded sandstone (high-flow-regime conditions). Overlying planar cross-laminated, planar and ripple-laminated sandstone facies (low-flow-regime conditions) were deposited in response to waning flow.

The upper Yiyintyi Sandstone has previously been described as a shallow marine, wave and tidally influenced succession (Jackson et al., 1987; Pietsch et al., 1991). However, the absence of features such as clay drape laminations in cross-beded sandstone facies, which commonly develop during subordinate and/or destructive current phases in nearshore marine deposits (Fedo and Cooper, 1990), HCS sandstone and mudstone/siltstone intervals is inconsistent with a shallow subaqueous interpretation. In addition, transitional facies associations that should separate the proposed terrestrial and marine Yiyintyi Sandstone successions, such as braid-delta,
tidal flat or lagoonal deposits, have not been recognised. The predominance of coarse-grained, high energy sedimentary facies in the upper Yiyintyi Sandstone is interpreted here to indicate deposition in a sand-dominated braidedplain system.

3.3 SEIGAL VOLCANICS

The Seigal Volcanics comprise a poorly exposed, 100 to 400 m thick sequence of amygdaloidal basalt that sharply and conformably overlies the Yiyintyi Sandstone. Poor exposure in the Batten and Tawallah Ranges has prevented a detailed facies analysis. However, the vesicular nature of the basalts and the lack of intercalated sediment are consistent with a subaerial extrusive setting. Doleritic sills that intrude the Yiyintyi Sandstone exposures are thought to be feeders for the Seigal Volcanics (Rawlings et al., 1993). Distinct lava flow units in the Seigal Volcanics and rare hyaloclastite (indicating partly subaqueous emplacement) have been described north of the study region (Rawlings et al., 1993). In southern parts of the McArthur Basin, thick (up to 1600 m), well-exposed Seigal Volcanics intervals are interpreted as a regionally extensive succession of sheet-like lava flows that erupted during a period of subaerial flood volcanism (Rawlings, 1994).

3.4 SLY CREEK SANDSTONE

The Sly Creek Sandstone comprises a thick succession (< 770 m; Pietsch et al., 1991) of medium- to coarse-grained sandstone with minor gravel, and is broadly similar to the upper Yiyintyi Sandstone. Jackson et al. (1987) suggested that the Sly Creek Sandstone was deposited in marine environments, from offshore deep marine to shoreline beach and associated littoral settings. In the study region, it disconformably overlies the Seigal Volcanics and has a gradational relationship with the overlying Rosie Creek Sandstone Member. Detailed facies logs were measured in two localities. In the southeast Tawallah Range (5791E/82181N - 5800E/82169N; Fig. 3.2a), the Sly Creek Sandstone crops out as well exposed, semi-continuous cliff and creek sections. In the Batten Range (5805E/81835N - 5796E/81839N; Fig. 3.2b), the lower 120 m of the formation is well exposed in an erosional scarp. Above this, broken outcrop occurs along resistant strike-ridges or in creek sections.

3.4.1 Basal breccia facies

In the Batten Range, red to brown, gravelly to pebbly matrix-supported breccia forms the basal 2 to 3 m of the Sly Creek Sandstone (Plate 3.2b). This facies is massive to coarsely stratified and displays no internal grading. Angular, decimetre- to
Fig. 3.2a Sly Creek Sandstone measured facies log (Batten Range).
Legend

- Ripples-laminated facies association
- Planar bedded sandstone facies with mud-chip horizons
- Trough cross-bedded sandstone facies
- Planar cross-bedded sandstone facies (Batten Range)
- Basal breccia facies (Batten Range)

Fig. 3.2b Sly Creek Sandstone measured facies log (Tawallah Range).
Plate 3.2 Sedimentary facies of the Yiyintyi Sandstone and Sly Creek Sandstone

a) Straight-crested ripples preserved on a bedding surface in the ripple-laminated facies association of the Yiyintyi Sandstone (Tawallah Range section - 1206 m).

b) Gravelly to pebbly, matrix-supported polymict breccia at the base of the Sly Creek Sandstone (basal breccia facies; Batten Range section - 0 m).

c) Photomicrograph of the basal breccia facies (Sly Creek Sandstone). Fragments of basalt (bas), amygdaloidal material (am), sandstone (ss) and quartz are supported by a siltstone matrix (Batten Range section - 0.5 m).

d) Two metre amplitude cross-bed set in the trough cross-bedded sandstone facies of the Sly Creek Sandstone (Tawallah Range section - 47 m).

e) Trough cross-bedded sandstone facies of the Sly Creek Sandstone (Batten Range section - 11 m).

f) Nested trough-sets near the top of a trough cross-bedded sandstone facies interval in the Sly Creek Sandstone (Batten Range section - 230 m).
millimetre-sized clasts consist predominantly of mafic volcanic fragments derived from the underlying Seigal Volcanics. In thin section, basalt fragments are irregularly shaped, amygdaloidal and contain relict plagioclase phenocrysts altered to sericite (Plate 3.2c). The remainder of the lithic breccia component consists of amygdaloidal material such as polycrystalline quartz, bladed feldspar, celadonite, chalcedony and chert. Fine- to coarse-grained, subrounded quartz grains occur in minor proportion. Lithic fragments are supported by a fine-grained siltstone or mudstone matrix. The fine-grained matrix has also filled vesicles in basalt clasts.

**Interpretation**

Sand-sized, matrix-supported gravel with crude internal stratification indicates aqueous transport at an energy level where sand and gravel are co-deposited (Rust and Koster, 1984). Based on the provenance, textural and compositional immaturity, crude stratification and basal stratigraphic position, this facies is interpreted to have been deposited during short-lived sheet-flood conditions, above a subaerially-exposed volcanic terrain.

3.4.2 Trough cross-bedded sandstone facies

In the Tawallah Range section, this facies is identical to the trough cross-bedded sandstone described from the upper Yiyintyi Sandstone. Interbeds of medium-scale trough cross-bedded sandstone (average thickness of 5 m) and the planar bedded to ripple-laminated sandstone facies association characterise the section. However, at several intervals in the section, stacked large-scale trough cross-bed sets with amplitudes of 3 to 5.1 m occur as amalgamated units up to 8 m thick (Plate 3.2d).

Medium- to coarse-grained, trough cross-bedded quartz sandstone occurs throughout the Batten Range section. Trough cross-bed amplitudes typically range between 0.4 to 0.7 m, with 2 to 4 sets contained within an individual bed (Plate 3.2e). At some localities, the scale of bedforms decreases near the top of the facies interval, so that tens of small scale cross-sets (amplitudes < 0.1 m) occur within a single bed (Plate 3.2f). Basal surfaces are planar to sub-horizontal and, in many cases, have truncated underlying bedforms. Amalgamated trough cross-bedded sandstone intervals up to 15 m thick occur throughout the Batten Range section (eg. between 219 and 234 m; Fig. 3.2a).
Interpretation

In both sections, the lateral continuity of the trough cross-bedded sandstone facies, and the scale of bedforms is similar to facies as described from the Yiyintyi Sandstone (section 3.2.2). Consequently, trough cross-bedded sandstone facies in the Sly Creek Sandstone are similarly interpreted as broad, laterally migrating and relatively shallow channel deposits that accumulated in a sandy alluvial environment. In modern systems, the formation of nested trough-sets has been attributed to vertical infilling of channels by stacked sinuous crested bedforms; examples include the Donjek and South Saskatchewan braided streams (Miall, 1978).

3.4.3 Planar-bedded to ripple-laminated sandstone facies association

In the Tawallah Range section, this facies association appears similar to the planar-bedded to ripple-laminated association described for the upper Yiyintyi Sandstone (section 3.2.4; Plate 3.3a and b). An important distinction however, is that mud-chip intraclasts are locally preserved in the basal planar-bedded sandstone facies.

In the Batten Range, the planar-bedded to ripple-laminated (PB-RL) facies association forms approximately 60 % of the Sly Creek Sandstone section. At the base of cycles, planar-bedded, medium- to coarse-grained sandstone occurs above a sharp or scoured surface that have truncated underlying bedforms (Plate 3.3c). In the lower 30 m of the section, the basal facies occurs as horizontally-stratified gravel, where gravel clasts consist of angular mud-chips and quartz set in a coarse-grained quartz sandstone matrix (Plate 3.3d). The basal planar-bedded sandstone facies grades through low-angle (\(< 20^\circ\) ), medium-grained, planar cross-laminated sandstone to ripple-laminated and/or flat-laminated, fine- to medium-grained sandstone. Ripples are straight-crested or bifurcating, with symmetric and asymmetric varieties present (Plate 3.3e). One to all of these upper bedforms can be observed in a single exposure. Monotonous sequences of the PB-RL facies association (\(< 25 \) m thick), containing multiple repetition of 0.2 to 1.5 m thick cycles occur throughout the Batten Range section.

Interpretation

The PB-RL facies association of the Sly Creek Sandstone is identical to the planar-bedded sandstone facies and ripple-laminated sandstone facies association cycles of the Yiyintyi Sandstone (section 3.2.4). This enables a similar comparison to the Bijou Creek Type vertical succession of Miall (1977), where catastrophic flood events deposited horizontally-stratified and coarse-grained sandstone under upper plane-bed
Plate 3.3 Sedimentary facies of the Sly Creek Sandstone and Rosie Creek Sandstone

a) Planar-bedded to ripple laminated sandstone facies association of the Sly Creek Sandstone. Planar-bedded sandstone (pb), planar cross-laminated sandstone (pxl) and ripple-laminated sandstone (rl) cycles are overlain by a trough cross-bedded sandstone interval (txb; Tawallah Range section - 64 m).

b) Planar-bedded sandstone (pb) and flat-laminated/ripple-laminated sandstone (rl) cycles in the Sly Creek Sandstone. An erosional contact between ripple-laminated sandstone and overlying planar-bedded sandstone occurs near the base of this exposure (arrow; Tawallah Range section - 145 m).

c) Scoured basal surface of the planar-bedded sandstone facies (Sly Creek Sandstone; Batten Range section - 217 m).

d) Planar-bedded sandstone facies containing angular mud-chip fragments in lower parts of the facies interval (Sly Creek Sandstone; Batten Range section - 18 m).

e) Straight-crested and birfurcating ripples on a bedding surface in the ripple-laminated sandstone facies (Sly Creek Sandstone; Batten Range section - 411 m).

f) Planar cross-laminated sandstone with low angle foresets in the Rosie Creek Sandstone. Black heavy mineral concentrations define coarse-grained laminae in this exposure (Batten Range section - 6 m).
Mud-chips that are locally preserved at the base of cycles (planar-bedded facies) are interpreted to have been derived from thin mudstone (vertical accretion) deposits that formed outside of the main channels during waning flood-stage conditions (McCormick and Grotzinger, 1993). Fedo and Cooper (1990) proposed that these deposits are cannibalised and resedimented as intraformational breccias during ensuing flood events. Multiple repetition of cycles in the Batten Range section is interpreted to indicate that this region experienced flood pulses at a higher frequency than the southeast Tawallah Range. Alternatively, entrenched alluvial channels were of lesser importance in the Batten Range depositional system.

3.4.4 Planar-cross-bedded sandstone facies

Exposures of this facies occur in the upper 60 m of the Sly Creek Sandstone at the Batten Range locality. White to pink, sub-rounded and moderately sorted, medium-to coarse-grained sandstone is characterised by the presence of quartz granules and small (2 cm diameter), sub-rounded sandstone clasts dispersed throughout. Sedimentary structures comprise medium-scale planar cross-bed sets (amplitudes of 0.5 to 0.7 m) that are contained within 3 to 5 m thick beds. Basal surfaces are low angle (<10°) to sub-horizontal.

**Interpretation**

In braided fluvial environments, planar cross-bedded sandstone is generally interpreted to result from the downstream migration of straight-crested bedforms such as sandwaves, transverse bars or linguoid bars under low-flow-regime conditions (Miall, 1977). Amireh et al. (1994) proposed that planar cross-bedded sandstone tends to form in braided channels with a high width-to-depth ratio. In these settings, subordinate facies, such as trough-cross-bedded sandstone, develop only along deeper parts of channels under upper low-flow-regime conditions.

3.4.5 Depositional Environment

Although separated from the Yiyintyi Sandstone by the Seigal Volcanics, broad similarities in facies types and associations suggest that the Sly Creek Sandstone is a continuation of the upper Yiyintyi Sandstone depositional system. The sheet-like geometry and regional similarity of facies, evidence of frequent changes in flow strength and depth, low-relief morphology of erosional surfaces bounding falling flood
cycles and absence of diagnostic shallow marine features are interpreted to indicate deposition in a distal, ephemeral sandy braidplain environment (Martins-Neto, 1994; Browne and Piint, 1994; Rust and Gibling, 1990). Trough cross-bedded sandstone facies are interpreted to have formed during the lateral migration of broad (km-scale), shallow channels. The prominence of trough cross-bedded sandstone facies in channel deposits is indicative of low-sinuosity streams (Miall, 1977). However, the occurrence of planar cross-bedded sandstone, which is interpreted to have been formed by the migration of straight-crested cross-channel bars in sinuous braided streams (Walker and Cant, 1984), indicates some variation in the depositional setting for upper parts of the formation.

Sheet-flood facies associations resembling the ephemeral Bijou Creek Type succession of Miall (1977) occur as planar-bedded (high-flow-regime) to ripple-laminated (waning-flow-regime) sandstone cycles. Multiple repetition of cycles in the Batten Range section indicates a depositional environment characterised by successive flood events where entrenched alluvial channel systems were of minor importance. Incorporation of mud-chips into the basal planar-bedded facies probably resulted from erosion and subsequent resedimentation of vertical accretion deposits during plane-bed conditions. Vertical accretion deposits develop outside of the main channel system during latter flood stages (Walker and Cant, 1984), and although not observed in this study, thin mudstone horizons have been documented elsewhere in the Sly Creek Sandstone (Haines et al., 1993).

### 3.5 ROSIE CREEK SANDSTONE MEMBER

The Rosie Creek Sandstone Member marks a change from the medium-bedded, clean quartz sandstones of the Sly Creek Sandstone to thinner bedded, fine- to coarse-grained, feldspathic, ferruginous or glauconitic sandstone and minor siltstone (Pietsch et al., 1991). In the study region, the member is not always present, and the Sly Creek Sandstone is directly overlain by the Aquarium Formation at many localities. Where present, the Rosie Creek Sandstone Member grades conformably from the underlying Sly Creek Sandstone (Haines et al., 1993). Exposures of the member are generally moderate to poor, occurring as a series of small ridges separated by recessive intervals. The best exposures of the Rosie Creek Sandstone Member in the study region occur in the Batten Range (5817E/81876N-5814E/81876N), where a semi-continuous, 75 m thick section from the underlying Sly Creek Sandstone grades upwards into the overlying Aquarium Formation. The facies log measured from this locality is shown in Figure 3.3. Haines et al. (1993) suggested a periodically evaporitic, shallow marine depositional environment for the Rosie Creek Sandstone Member.
Fig. 3.3 Rosie Creek Sandstone Member measured facies log.
3.5.1 Flat-laminated to planar cross-laminated sandstone facies

The most abundant facies type in the Rosie Creek Sandstone Member is pink to buff coloured, medium- to coarse-grained, flat-laminated to planar cross-laminated quartz sandstone (Plate 3.3f). Laminae are between 0.1 and 1 cm thick, and occur as alternating medium- and coarse-grained bands. Heavy mineral concentrations define coarse-grained laminae locally. Planar cross-bed sets are small- to medium-scale (0.2 to 0.7 m amplitudes) with low to moderate angle foresets (5 to 15°). Amalgamated cross-bed sets form composite units up to 5 m thick. Symmetrical, straight crested or birfurcating small-scale ripples (average wavelength 1 cm) occur in the upper parts of this facies.

3.5.2 Ripple-laminated sandstone facies

This facies occurs as isolated beds of amalgamated ripples 0.5 to 1 m thick, or directly overlies the flat-laminated to planar cross-laminated sandstone facies. Medium-grained, white to buff coloured quartz sandstones are characterised by small- to medium-scale (2 to 7 cm wavelength), mostly symmetrical, straight crested, birfurcating or interference ripples (Plate 3Aa). Ripple-laminated beds up to 5 cm thick are interbedded with medium-grained, massive to flat-laminated sandstone that locally contain small-scale ripple cross-lamination (< 5 cm amplitude).

3.5.3 Mud-chip intraclast facies

This facies is characterised by angular gravel-, pebble- and rare cobble-sized mud-chip intraclasts that occur in the basal 0.2 to 0.3 m of 0.5 to 3 m thick beds (plate 3Ab). Mud-chip intraclasts are supported by a medium- to coarse-grained sandstone matrix which fines upward into massive and structureless, red to buff coloured, medium-grained quartzo-feldspathic sandstone (Plate 3Ac).

3.5.4 Siltstone facies

Recessive, thinly bedded (< 2 cm), red-purple siltstone intervals occur throughout the Rosie Creek Sandstone Member and increase in abundance towards the top of the formation. The facies comprises finely laminated siltstone with minor interbeds of thin (< 2 cm), fine-grained sandstone. The thickness of this facies is variable and ranges from a few centimetres to 2.8 m.
Plate 3.4 Sedimentary facies of the Rosie Creek Sandstone and Aquarium Formation

a) Straight-crested to birfurcating, symmetrical ripple pavement in the ripple-laminated sandstone facies of the Rosie Creek Sandstone (Batten Range section - 14 m).

b) Bedding surface exposure of gravel to pebble mud-chip intraclast breccia in the Rosie Creek Sandstone. Mud-chip fragments are supported by a massive, medium-to coarse-grained sandstone matrix (Batten Range section - 67 m).

c) A siltstone facies interval in the Rosie Creek Sandstone overlain by the mud-chip intraclast facies. The mud-chip intraclast breccia grades to medium-grained massive sandstone over the facies interval (Batten Range section - 59 m).

d) Hummocky-cross-stratified sandstone facies of the Aquarium Formation. The lateral transition between the hummock and swale is marked by low-angle truncation of internal laminae (Batten Range section - 81 m).

e) Well-developed hummocky-cross-stratification in the Aquarium Formation (Batten Range section - 58 m).

f) Flute casts preserved on the basal surface of the hummocky-cross-stratified sandstone facies (Aquarium Formation; Batten Range section - 38 m).

g) Bedding surface exposure of the mud-chip intraclast facies in the Aquarium Formation (Batten Range section - 171 m).
3.5.5 Depositional Environment

A detailed interpretation for the depositional environment of the Rosie Creek Sandstone is hindered by poor exposure. Nevertheless, the facies recognised within the Rosie Creek Sandstone provide important clues as to its overall depositional environment. Features such as heavy mineral lamination, abundant mud-chip intraclast beds and intervals of siltstone all occur in braid-delta platform environments (Bergh and Torske, 1986; Fedo and Cooper, 1990; McCormick and Grotzinger, 1993).

An environmental interpretation for the Rosie Creek Sandstone succession can be made by comparison with the lower member of the Proterozoic Skoadduvarri Sandstone Formation (Bergh and Torske, 1986). A typical sequence consists of a basal matrix-supported mud-clast conglomerate overlain by massive, flat-laminated or planar cross-laminated sandstone. These deposits are capped by a ripple-laminated sandstone facies. Bergh and Torske (1986) interpret this sequence as a lower delta plain association (braid-delta in the classification of McPherson et al., 1987), with mud-covered intertidal flats and older channel deposits dissected and reworked by fluvial-marine and/or tidal creeks, resulting in the development of the basal facies. Flat-laminated to planar-laminated sandstones were generated near the mouths of shifting channels by wave action reworking on swash platforms. Applying a similar interpretation to the Rosie Creek Sandstone requires siltstone facies intervals to be preserved intertidal flat regions. Abundant wave and interference ripples and well developed ripple cross-lamination are interpreted to indicate a tidally-influenced setting for the ripple-laminated facies. A transition to marine, rather than lacustrine, conditions is indicated by the presence of glauconite grains within some sandstone lithologies (Rawlings et al., 1993).

3.6 AQUARIUM FORMATION

The Aquarium Formation comprises approximately 200 m of interbedded siltstone and fine- to medium-grained sandstone with minor carbonate intervals. Exposure is generally poor, occurring as weathered discontinuous outcrops in alluvium-covered valleys between the ridge-forming Sly Creek or Rosie Creek Sandstone, and the overlying Wununnmantyala Sandstone. Lower contact relationships with the Rosie Creek Sandstone are gradational where exposed. The basal contact was defined by the first occurrence of carbonate and/or hummocky cross-stratified sandstone. Detailed facies logs were measured from three separate localities. In the Batten Range (5821E/81876N - 5817E/81876N; Fig. 3.4a), a continuous section from the Rosie Creek Sandstone to the overlying Wununnmantyala Sandstone is exposed, and is the recognised type section of Pietsch et al. (1991). An incomplete section measured in the Scrutton
Fig. 3.4a Aquarium Formation measured facies log (Batten Range).
Fig. 3.4b Aquarium Formation measured facies log (Scrutton Range) and 3.4c Carbonate facies (Tawallah Range). Ptn denotes the Wununnmantyala Sandstone.
Range (5614E/82133N - 5606E/82128N; Fig. 3.4b) and a section through the upper carbonate facies in southeast Tawallah Range (5815E/82167N - 5824E/82162N; Fig. 3.4c) constitute the other localities examined during this study. Aquarium Formation exposures in the study region are correlated with the McDermott Formation (B. Pietsch, D. Rawlings and P. Haines, pers. comm.). The McDermott Formation occurs in the southeast McArthur Basin where stromatolitic carbonates, cauliflower cherts and hopper halite casts have been interpreted to indicate a shallow marginal marine to evaporitic shoreline depositional setting for the formation (Jackson et al., 1987).

3.6.1 Hummocky cross-stratified sandstone facies

This facies occurs throughout the Aquarium Formation and consists of buff coloured, fine- to medium-grained quartz sandstone. The most prominent sedimentary structures within the facies are hummocky cross-stratification (HCS) and associated symmetrical, straight-crested or interference ripples. HCS sandstone occurs as thin tabular beds (0.1 to 0.4 m), or as composite units that contain multiple amalgamated cross-sets and attain thicknesses of 1 to 10 m. HCS is defined by low amplitude (< 20 cm), long wavelength (1 to 3 m), convex and concave upward lamination (hummocks and swales; Plate 3.4d and e). The lateral transition between hummocks and swales is marked by low-angle truncation (< 15°) of internal laminae. Erosional features such as flute casts or small scours filled with massive medium-grained sand occur along basal surfaces of the HCS sandstone units (Plate 3.4f). Rare gravel-sized mud-chip intraclasts occur immediately above this surface (Plate 3.4g). Load casts locally occur at the base of composite HCS intervals. Rippled horizons overlie the HCS sandstone, and also occur as thin (< 5 cm) horizons at the lateral extremities of hummocks.

Interpretation

HCS is thought to form below fairweather wave-base in a shallow marine or lacustrine environment during storm conditions (Walker, 1984). Sharp lower surfaces and sole marks (flute casts and scours) are interpreted to result from rapid emplacement rates. Walker (1981) attributed these features, and the intimate association with siltstone facies (section 3.6.2), to indicate storm-generated density (turbidity) current deposition, with degradation of beach or beach ridge sands by storm waves leading to sediment mobilisation downslope as a density current. Duke et al. (1991) proposed an alternative model for offshore sediment transport, whereby shore-normal bottom currents were generated during storm conditions and interacted with faster wave-orbital bottom motions. Initially, the interaction between these motions resulted in coarse debris being driven offshore during the seaward wave oscillation to scour the muddy substrate.
Coastal sand was transported offshore by intermittent suspension and as bed load under the combined bottom flow conditions. In either model, sands deposited below fairweather-, but above storm-wave-base are subsequently imprinted with HCS under combined oscillatory and unidirectional flow conditions (Nottvedt and Kreisa, 1987). The presence of mud-chip intraclasts, particularly in composite HCS units, may indicate that violent or long-lived storm events eroded upper tidal flat regions and deposited thicker sand bodies offshore.

3.6.2 Siltstone facies

Thinly bedded (< 5 cm) intervals of red-green, fine-laminated siltstone similar to that described in the Rosie Creek Sandstone are interbedded with the HCS sandstone facies (Plate 3.5a). In the Aquarium Formation, fine-laminated siltstone constitutes approximately 40% of the section at the Batten Range locality. Thin (< 5 cm), tabular interbeds of fine-grained massive sandstone are locally present. Exposures are generally recessive, and breaks in the measured sections may indicate the presence of this rock type.

Interpretation

A shallow subaqueous (i.e. below fairweather wave-base) environment is proposed for the siltstone facies, based on the close relationship with the HCS sandstone. Intervals of interbedded siltstone and fine-grained massive sandstone may have been deposited by storm-induced density currents below storm wave-base. This style of density flow sedimentation has been documented in the Jurassic Fernie-Kootenay transition of southern Alberta (Hamblin and Walker, 1979).

3.6.3 Carbonate facies

Two carbonate intervals occur in the Aquarium Formation. In the Batten Range, carbonate intervals occur in the basal 25 m, and between 105.3 - 166 m (Fig. 3.4a). Although the lower interval is absent at the Scrutton and Tawallah Range localities, the upper interval, beginning at around 100 m, is present in each case (Fig. 3.4b and c).

Where present, the lower carbonate interval consists of grey to pink, fine-laminated to massive dolomite interbedded with the siltstone facies. Discontinuous beds containing concentric-laminated ovoid concretions (average length of long axes: 10 cm; Plate 3.5b) and domal stromatolite horizons (Plate 3.5c) occur at several intervals
Plate 3.5 Sedimentary facies of the Aquarium Formation

a) Interbedded hummocky-cross-stratified sandstone and siltstone facies (Batten Range section - 76 m).

b) Concentric-laminated ovoid concretions in the lower carbonate facies (arrows; Batten Range section - 16 m).

c) Domal stromatolite horizon in the lower carbonate facies of the Aquarium Formation (Batten Range section - 22 m).

d) Flat-pebble-breccia bed occurring laterally from the stromatolite horizon shown in Plate 3.5c (Batten Range section - 22 m).

e) Interbedded massive to fine-laminated dolomite and dolomitic siltstone in the upper carbonate facies (Tawallah Range section - 105 m).

f) Domal stromatolite in a massive dolomite horizon; upper carbonate facies (Tawallah Range section - 117 m).
within the facies. Stromatolites reach approximately 0.3 m in height, but become distorted and broken up, grading laterally into flat-pebble breccia beds (Plate 3.5d). Fine-grained dolomitic sandstone occurs between 23 - 25 m (Fig. 3.4a), although sandstone interbeds become progressively coarser grained and less dolomitic up-section.

The upper carbonate interval is best exposed at the Tawallah Range locality. Here, it comprises alternating intervals of cream to grey, massive to fine-laminated dolomite and thinly bedded (< 5 cm) dolomitic siltstone (Plate 3.5e). Domal stromatolites occur at several stratigraphic levels within the upper interval, and compared to those in the lower package, appear undisturbed (Plate 3.5f). Thin (< 20 cm) dolomitic sandstone beds and flat-pebble conglomerate horizons occur in the upper 10 m of the interval.

**Interpretation**

The intimate association of carbonate facies with siltstone, and the vertical progression into flat-pebble conglomerate and HCS sandstone is consistent with a predominantly below-fairweather wavebase depositional setting. Flat-pebble breccia has been interpreted to indicate a variety of shallow, subaqueous environments including intertidal settings (Braun and Friedman, 1969), supratidal flats or strandline deposits on tidal channel margins (Sepkoski, 1982). Similar deposits have also been described from shallow marine settings, where they are interpreted to have formed by erosion of sub-fairweather wave-base sediments during storm conditions and minor post-storm reworking by tidal currents (eg. Wisonant, 1987; Mount and Kidder, 1993). A storm-influenced, subaqueous setting is favoured for flat-pebble conglomerate development in the Aquarium Formation, based on the absence of diagnostic inter- and supratidal features (eg. evaporites; Warren, 1991).

**3.6.4 Depositional Environment**

Facies associations within the Aquarium Formation are indicative of a shallow subaqueous depositional environment. HCS sandstone and siltstone interbeds are interpreted to have been deposited between storm and fairweather wave-base. The consistent stratigraphic position of the upper carbonate facies is interpreted to indicate shallow platform deposition during a period of regional quiescence. Generation of storm-induced density currents is considered to be the primary transport mechanism for shoreline sands that were eroded and re-deposited offshore. HCS was developed by subsequent wave reworking of these deposits above the storm wave-base (Walker, 1981; Nottvedt and Kreisa, 1987; Duke et al., 1991). Sandstone intervals that do not
display internal HCS are interpreted to have been deposited by storm-induced density currents below the storm wave-base. A marine setting for the Aquarium Formation is indicated by the presence of glauconitic sandstone intervals (Pietsch et al., 1991).

In a broader stratigraphic context, the interpreted depositional settings of the Aquarium Formation and the Rosie Creek Sandstone explain the absence of foreshore, shoreface or transitional beach face deposits between the formations. Ly (1982) suggested that shoreline deposits are likely to be eroded prior to burial. During a marine transgression, wave action tends to rework and transport shoreline sediments offshore, reducing their chance of preservation. Kumar and Sanders (1976) suggested that ancient nearshore deposits will mostly consist of storm deposits, with products of fairweather conditions only occurring in minor proportion. Evidence of storm-related facies and their erosive depositional style in the Aquarium Formation is consistent with an interpretation that beachface sediments were reworked into deeper subaqueous environments, and therefore, not preserved in the rock record.

3.7 WUNUNMANTYALA SANDSTONE

The Wununmantyala Sandstone consists of medium- to thick-bedded hematitic quartz sandstone, with pebble to cobble conglomerate and gravel occurring locally in basal parts of the sequence. The formation crops out as well-exposed cliffs and strike-ridges throughout the western McArthur River region and attains a maximum thickness of approximately 210 m. Detailed facies logs were measured from two localities. In the southwest Tawallah Range (5780E/82090N - 5783E/82071N; Fig. 3.5a), erosional and unconformable contacts separate the Wununmantyala Sandstone from the underlying Aquarium Formation (Fig. 3.6). In the Scrutton Range (5638E/82090N-5633E/82086N; Fig. 3.5b), the formation is in faulted contact with lower McArthur Group stratigraphy, and is overlain by the Settlement Creek Volcanics. Local facies variations in the Wununmantyala Sandstone have been investigated by comparison with a semi-continuous section in the north Batten Range (5813E/81909N - 5812E/81916N; Fig.3.5c), and with general facies descriptions from the southern Batten Range (5795E/81867N) and western Tawallah Range (5650E/82206N). Pietsch et al. (1991) proposed a sublittoral depositional environment for the Wununmantyala Sandstone.
Fig. 3.5a Wununmantyala Sandstone measured facies log (Tawallah Range).
Fig. 3.5b Wununmartyala Sandstone measured facies log (Scrutton Range).
Legend

- Ripple-terminated sandstone
- Upper sandstone facies (Batten Range)
- Planar cross-bedded sandstone facies
- Massive sandstone (Scrubton Range)
- Mud-chip intraclast facies (Scrubton Range)
- Planar cross-bedded gravelly sandstone facies (Tawallah and Batten Range)
- Conglomerate facies (Tawallah and Batten Range)

Fig. 3.5c Wununmantyala Sandstone measured facies log (Batten Range).
3.7.1 Basal coarse-grained facies

Conglomeratic and gravelly sandstone lithologies are characteristic of the basal sections of the Wununmantyala Sandstone in the southwest Tawallah Range and north Batten Range localities (Fig. 3.5a and c). These deposits can be broadly subdivided into conglomerate and planar cross-bedded gravelly sandstone subfacies.

a) Conglomerate subfacies

In the southwest Tawallah Range section, the conglomerate subfacies consists of closed-framework, pebble, cobble to (rarely) boulder conglomerate (Plate 3.6a). Bed thickness varies from 0.1 to 4 m, and although generally massive, beds can have crude internal stratification (Plate 3.6b). Rounded to sub-rounded, medium- to coarse-grained, silicified and/or hematitic quartz sandstone fragments are the most abundant clast type. Minor gravel- to pebble-sized felsic igneous fragments are present locally, and contain quartz phenocrysts set in a purple, aphanitic matrix (Plate 3.6c). Larger sandstone clasts contain remnant sedimentary structures such as ripple- or cross-laminations. In thicker beds (0.3 to 4 m), the clasts are preferentially orientated to define a crude horizontal imbrication. Where bed thickness is less than 0.3 m, no obvious clast orientation was observed and upper contacts are gradational into the overlying planar cross-bedded gravelly sandstone subfacies. Sub-horizontal to irregular lower contacts are typically erosional, having truncated underlying bedforms in many cases.

In the north Batten Range, thin (< 20 cm) intervals of clast-supported, massive pebble conglomerate are preserved throughout the lower 85 m of the Wununmantyala Sandstone section. Clasts consist of silicified quartz sandstone, and are locally

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**Fig. 3.6** Stereographic projection of poles to bedding showing an angular discordance at the Aquarium Formation/Wununmantyala Sandstone contact in the: a) southwest Tawallah Range; and b) southeast Tawallah Range.

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a) b)
**Plate 3.6** Sedimentary facies of the Wununmantyala Sandstone

a) Basal clast-supported, pebble/cobble conglomerate subfacies of the Wununmantyala Sandstone (Tawallah Range section - 4 m).

b) Preferred orientation of sandstone clasts defining a well-developed horizontal imbrication in the basal conglomerate subfacies (Tawallah Range section - 30 m).

c) Clast types in the basal conglomerate subfacies. Abundant subrounded sandstone clasts and minor felsic igneous fragments (arrows) are contained within a coarse-grained to gravelly sandstone matrix (Tawallah Range section - 30 m).

d) Planar cross-bedded gravelly sandstone subfacies of the lower Wununmantyala Sandstone (Tawallah Range section - 17 m).

e) Pebbly horizon comprising sandstone and felsic igneous fragments in the planar cross-bedded gravelly sandstone subfacies (Tawallah Range section - 15 m).

f) Planar cross-bedded sandstone facies of the Wununmantyala Sandstone. This example shows the characteristic small- to medium-scale cross-bed sets with moderate angle foresets (Scrutton Range section - 8 m).
supported by a coarse-grained quartz sandstone matrix. Upper contacts of the conglomerate subfacies typically grade into the planar cross-bedded gravelly sandstone subfacies.

b) Planar cross-bedded gravelly sandstone subfacies

The planar cross-bedded gravelly sandstone subfacies consists of very coarse-grained to gravelly, hematitic quartz sandstone (Plate 3.6d). Characteristic small- to medium-scale (0.1 to 0.7 m amplitude), planar cross-bed sets with moderate- to high-angle foresets (20-30°) are contained within laterally extensive, tabular beds up to 0.7 m thick. Clast types include silicified and/or hematitic quartz sandstone, minor wispy mudstone and (in the lower southwest Tawallah Range section) felsic igneous fragments (Plate 3.6e). The abundance of felsic igneous detritus in the southwest Tawallah Range section decreases gradually between 32 and 43 m.

Lower surfaces are typically gradational above the conglomerate subfacies, although sharp basal contacts that have truncated underlying bedforms have been observed locally. Where the conglomerate subfacies is absent, pebble-sized clasts are confined to basal foreset surfaces. Above the pebble-rich basal horizons, gravel occurs along foreset laminae to form crude fining-upward cycles that are 0.5 to 0.7 m thick. In the north Batten Range section, the net gravel content of the subfacies decreases between 85 and 145 m, and the succession grades into planar-cross-bedded sandstone facies (section 3.7.2).

Interpretation

Clast-supported, pebble- to cobble-sized, imbricated conglomerate with crude horizontal stratification is common to alluvial fan, and proximal to medial braided fluvial environments (Miall, 1977; Rust, 1978; Evans, 1990; Martini et al., 1991). In modern proximal/medial braided rivers, this facies is associated with the migration or vertical accretion of longitudinal bars during flood-stage conditions (e.g. Donjek River; Rust, 1972). In contrast, imbricated, closed-framework conglomerates are deposited on alluvial fans during catastrophic sheet-flooding episodes (Blair and McPherson, 1994). In this case, horizontally stratified coarse-grained facies are deposited where sediment-charged flash floods reach a fan and attenuate over the multidirectional fan surface. Blair and McPherson (1994) proposed that the sheetflood facies are characterised by 0.1 to 0.3 m thick, vertically alternating planar-bedded couplets of horizontally stratified conglomerate/gravel and laminated pebbly gravel or granular coarse sand. The lack of planar-bedded couplets, together with an overall absence of debris flow deposits, is
consistent with a proximal to medial braided river depositional environment for the conglomerate subfacies of the Wununmantyala Sandstone.

Planar cross-bedded gravel or coarse-grained sandstone can also occur in both alluvial fan and proximal to medial braided fluvial successions. However, flow attenuation on alluvial fan surfaces results in shallow or rapidly shallowing flows, so that low-angle planar cross-stratified bedforms are developed (Blair and McPherson, 1994). Because deeper and more sustained flows are required to produce high-relief bedforms (Miall, 1977), the planar cross-bedded gravelly sandstone subfacies is interpreted to formed during the migration of transverse bars in a braided river environment. In basal parts of the southwest Tawallah Range section, the subfacies is more gravel-rich, and many beds are laterally discontinuous. These deposits may have been produced by the lateral modification of longitudinal bars (conglomerate subfacies) during waning flood-stage conditions, when current directions diverged from paralleling bar axes (Rust, 1978).

### 3.7.2 Planar cross-bedded sandstone facies

Red (hematitic), medium-grained, planar cross-bedded quartz sandstone is the most abundant facies within the Wununmantyala Sandstone (Plate 3.6f). In the southwest Tawallah Range and north Batten Range (between 145 and 173 m), small- to medium-scale (0.2 to 0.7 m amplitude), planar cross-bed sets with moderate- to high-angle (20-30°) foresets are contained within laterally extensive beds up to 0.7 m thick. Repetitive fining-upward cycles are formed where basal surfaces are overlain by thin (< 10 cm) gravel or coarse-grained sandstone horizons (eg. between 42 and 102 m in the southwest Tawallah Range; Fig. 3.5a). Thin gravel horizons also occur as individual laminations within beds. Gravel clasts are typically elongate fragments of hematitic mudstone. In the southwest Tawallah Range, basal gravel or coarse-grained horizons are absent above 102 m (Fig. 3.5a).

Wununmantyala Sandstone exposures in the Scrutton Range, southern Batten Range and western Tawallah Range consist of monotonous sequences of fine- to medium-grained hematitic quartz sandstone. At these localities, the formation is characterised by small- to medium-scale (0.1 to 0.5 m amplitude) planar cross-bed sets with low- to moderate-angle foresets (10 to 20°). Cross bed-sets are laterally extensive, but rarely exceed 0.5 m in thickness. Coarse-grained sandstone locally defines the lower parts of individual foresets.

The planar cross-bedded sandstone facies locally grades upward into fine-grained, flat-laminated or ripple-laminated hematitic quartz sandstone. Ripples are generally asymmetric and small- to large-scale (3 to 10 cm wavelength), with straight-
crested or birfurcating morphologies. In southwest Tawallah Range, the abundance of ripple-laminated sandstone increases towards the top of the section.

**Interpretation**

In sandy braided fluvial settings, the development of planar cross-stratification results from downstream migration of straight-crested bedforms such as transverse or linguoid bars under low- to moderate-flow-regime conditions (Amireh *et al.*, 1994; Martins-Neto, 1994). The predominance of planar cross-stratification in the Wununmantyala Sandstone succession indicates that bedforms such as these were the primary depositional features. In terms of a modern braided fluvial analogue, this association resembles the distal south Platte River of Colorado and Nebraska, North America (Smith, 1970). Miall (1977) suggested that the Platte River is representative of shallow braided fluvial systems, or those without marked topographic differentiation, so that sedimentary deposition is mostly controlled by the migration of transverse or linguoid bars. Sedimentary facies are therefore characterised by well-defined internal planar cross-stratification. Ripple-laminated and flat-laminated sands are deposited during low-energy subaqueous sedimentary transport across bar tops, capping planar cross-bedded sandstone deposits (Smith, 1970).

### 3.7.3 Mud-chip intraclast facies

The mud-chip intraclast facies occurs in the southern Batten Range and throughout the Scrutton Range section (Fig. 3.5b). It consists of thin (< 0.2 m) intervals of moderately-sorted, gravel- to pebble-sized, matrix-supported mud-chip breccia. Clasts are sub-angular and although generally observed as casts, are interpreted to have been platy or elongate mud-chip fragments (Plate 3.7a). Mud-chip clasts are supported by a massive, medium- to coarse-grained and hematitic quartz sandstone matrix. Erosional features such as small-scale scours and flute casts typically occur on lower surfaces of this facies (Plate 3.7b). Scours are less than 0.15 m deep and locally contain small-scale trough cross-laminae.

**Interpretation**

The mud-chip intraclast facies is interpreted to have formed by erosion and resedimentation of pre-existing vertical accretion (mudstone) deposits that developed outside main channel systems (Walker and Cant, 1984). The presence of basal flute casts and scours are interpreted to indicate high energy, possibly flood-stage conditions prior to deposition during waning flow.
Plate 3.7 Sedimentary facies of the Wununmantyala Sandstone

a) Bedding plane exposure of the mud-chip intraclast facies. Elongate mud-chip fragments and casts are supported by a massive, medium-grained sandstone matrix in this example (Scrutton Range section - 20.5 m).

b) Flute casts occurring on the lower surface of the mud-chip intraclast facies (Scrutton Range section - 88 m).

c) Planar cross-laminated sandstone subfacies of the upper Wununmantyala Sandstone, with characteristic low-angle foresets and alternating medium- and coarse-grained lamination (Batten Range section - 172 m).

d) Evaporite pseudomorphs, possibly after displacive gypsum, in the upper sandstone facies (Batten Range section - 187 m).

e) Small-scale trough cross-laminated (txl) and ripple-laminated sandstone (rl) interval in the upper Wununmantyala Sandstone (Batten Range section - 181.5 m).

f) Abundant sandstone spheroids occurring on bedding planes in the upper sandstone facies (Tawallah Range; 5649E - 82209N).
3.7.4 Upper sandstone facies

Upper parts of the Wununmantyala Sandstone section in the north Batten Range (upper 25 m; Fig. 3.5c) and western Tawallah Range consist of fine- to medium-grained sandstones with a distinctive set of sedimentary structures. Two general subfacies are recognised in the upper sandstone facies; a planar cross-laminated sandstone subfacies and a ripple-laminated sandstone subfacies.

a) Planar cross-laminated sandstone subfacies

The planar cross-laminated sandstone subfacies consists of red to buff coloured, sub-rounded quartz sandstone, with alternating medium- and coarse-grained parallel lamination distinguishing it from other planar cross-bedded facies of the Wununmantyala Sandstone (Plate 3.7c). Medium- to large-scale (0.5 to 2 m amplitude), planar cross-lamination with low-angle foresets (< 15°) are contained within 2 to 5 m thick intervals (Plate 3.7c). Cross-laminae are defined by thin coarse-grained layers (0.5 to 2 cm) that grade upwards into thicker (0.5 to 7 cm), medium-grained layers. Fine- to medium-grained, ripple-laminated sandstone locally occurs along upper foresets. Large, biconvex (long axes < 5 cm), evaporite pseudomorphs (? displacive gypsum) occur between 186 and 187 m in the north Batten Range section (Plate 3.7d; Fig. 3.5c).

b) Ripple-laminated sandstone subfacies

Thin (< 1 m) intervals of fine- to medium-grained, ripple-laminated sandstone are interbedded with the planar cross-laminated sandstone subfacies. Ripples are typically medium to large scale (5 to 7 cm wavelength), with symmetric, asymmetric and interference varieties present. In the north Batten Range, thin (< 0.3 m), laterally discontinuous beds characterised by planar-bedded and small-scale (< 0.2 m amplitude) trough cross-laminated sandstone separate ripple-laminated intervals (Plate 3.7e). Some of the basal foresets are defined by coarse-grained sandstone or (rarely) gravel laminae. In western Tawallah Range, medium-grained sandstone spheroids occur sporadically on rippled bedding planes (Plate 3.7f). The spheroids average 4 cm in diameter and are restricted to the upper 5 m of the section.

Interpretation

The change in lithological texture and bedform geometry in the upper sandstone facies is interpreted to have resulted from a local change in the Wununmantyala Sandstone depositional environment. Large-scale, low-angle planar cross-bed sets with parallel lamination and grain-size alternation are indicative of high-
energy foreshore deposits (Clifton et al., 1971; Ly, 1982; Hoyanagi and Nishimura, 1994). Grainsize alternation is developed in the swash zone of foreshore settings, where minor deviations of beach surface slope within a single tidal cycle or between different cycles results in low-angle cross-lamination (Clifton, 1969). The large (?) displacive gypsum pseudomorphs in the northern Batten Range are interpreted to have formed during an episode of emergence, with consequent desiccation and fall in the local water table producing interstratal evaporites in the capillary zone (Warren, 1991). However, no additional evidence for emergence was observed (e.g. desiccation cracks or evaporite crusts), and the gypsum pseudomorphs may have a later diagenetic origin.

In a nearshore setting, the ripple-laminated sandstone subfacies is likely to have been deposited in the upper shoreface zone. The trough cross-bedded and ripple-laminated sandstone were probably deposited in troughs or depressions at the transition between the swash and surf zones (Clifton et al., 1971), whereas planar-bedded sandstone is interpreted to have been deposited in the surf zone (Ly, 1982). The vertical and (sometimes) lateral gradation between the facies may have resulted from short-lived changes in wave energy, and the consequent shoreward or landward migration of the various nearshore zones (Reinson, 1984). In the western Tawallah Range, the sandstone spheroids preserved on Wununmantyala Sandstone rippled surfaces occur beneath a conformable contact with overlying carbonates of the Wollogorang Formation, and are interpreted as oncolites. Oncolites form during subaqueous sediment agitation, where blue-green algae progressively adhere sediment grains (Friedman and Sanders, 1978). Seaward from the recent sabkha deposits near Abu Dhabi (Persian Gulf), oncolitic sands are being generated on the flanks of 2 km wide and 7 to 10 m deep channels that separate barrier islands of Holocene and Pleistocene carbonate (Purser and Evans, 1973). Oncolites along channel margins form where sandstone grains are agitated by opposing onshore waves and offshore ebb currents or winds (Warren, 1991). Using the Persian Gulf as a modern analogue, the upper Wununmantyala Sandstone in the western Tawallah Range is interpreted to have been deposited in a barred nearshore environment, with onlapping carbonates of the Wollogorang Formation (section 3.9) forming a barrier island in shallow waters offshore.

3.7.4 Depositional Environment

In the study region, facies associations within the Wununmantyala Sandstone are interpreted to have formed in response to an abrupt change from shallow marine (Aquarium Formation) to subaerial conditions. In the southwest Tawallah Range and north Batten Range, lower parts of the succession are interpreted to have formed in a proximal/medial braidplain setting, with conglomerate and gravelly sandstone deposits
developed during the migration, accretion and lateral modification of longitudinal bars in laterally extensive channel systems. Because felsic volcanics are not present in the lower Tawallah Group, the presence of felsic igneous clasts in the basal coarse-grained facies (southwest Tawallah Range) is difficult to explain unless the source region consisted partly of uplifted Scrutton Volcanics rock types. Similarly, the silicified sandstone clasts are inferred to have been sourced from uplifted lower Tawallah Group sandstones. The erosional nature of the Aquarium Formation/Wununmantyala Sandstone contact is consistent with intrabasinal uplift having occurred at this stratigraphic level.

The upper southwest Tawallah Range, lower western Tawallah Range, Scrutton Range and southern Batten Range successions are interpreted to have formed in medial/distal, sand-dominated braided fluvial settings, where transverse and linguoid bars were the main depositional features. This proposed depositional setting is analogous to the Platte-type vertical profile model of Miall (1977). However, one minor difference is the abundance of sheetflood deposits (mud-chip intraclast facies) in the Scrutton Range succession. Consequently, a more ephemeral setting is proposed for the Wununmantyala Sandstone than for the modern-day Platte River. The vertical change from proximal/medial to more distal braided river environments in the southwest Tawallah Range has probably resulted from erosion and retreat of the elevated source region, so that coarse material became progressively unavailable. This is supported by the gradual decrease and disappearance of felsic igneous (Scrutton Volcanic-derived) clasts over a 10 m vertical interval.

Upper sections of the north Batten Range and western Tawallah Range are interpreted as shallow subaqueous nearshore deposits. Large gypsum pseudomorphs in the upper north Batten Range section possibly formed during a period of emergence and desiccation prior to the formation of terrestrial soils (palaeosol horizon in northwest Batten Range). Sandstone oncolites preserved in the upper western Tawallah Range succession are interpreted to have formed in an agitated, barred nearshore environment, with onlapping Wollogorang Formation carbonates forming local barrier islands offshore.

3.8 SETTLEMENT CREEK VOLCANICS

The Settlement Creek Volcanics are exposed as a 100 m thick succession of mafic rock types and minor intercalated sediments. In the study region, the Settlement Creek Volcanics are restricted to the Scrutton Range, where they crop out poorly as discontinuous low hills and scree. The contact with the overlying Wollogorang Formation is poorly exposed, and is marked by a 1 to 5 m brecciated interval in Wollogorang Formation carbonates. Lower Settlement Creek Volcanics contacts are not
exposed in the study region. Rawlings et al. (1993) suggested that the Settlement Creek Volcanics were formed during widespread bimodal subaerial volcanism and high-level intrusive activity, with synvolcanic clastic deposition occurring in lakes and lagoons. The formation mostly consists of mafic lavas and sill-like bodies that have been locally intruded by thinly banded and autobrecciated rhyolite (Pietsch et al., 1991).

Representative facies have been described from surface exposure, and from investigation of BHP drill hole GSD2. GSD2 is located on Kiana Station within the Emu Fault Zone (approximately 70 km southeast of the study area; Appendix 1c), and provides a detailed continuous section through 43 m of Wollogorang Formation dolomite lithologies before passing into 60 m of upper Settlement Creek Volcanics (Fig. 3.7). The mineralogy and geochemistry of the Settlement Creek Volcanics are outlined in Chapter 4

3.8.1 Coherent dolerite facies

Coherent dolerite forms the bulk of the Settlement Creek Volcanics in GSD2, in surface exposures throughout the study region and elsewhere in the southern McArthur Basin (Bull, 1993). Fresh samples comprise red-brown, medium- to coarse-grained, sparsely amygdaloidal, subophitic dolerite (Plate 3.8a and b). Although poor exposure precludes any thickness estimate for this facies, discontinuous bodies that can be traced for several hundred metres along strike are at least tens of metres thick.

3.8.2 In situ dolerite breccia facies

In situ, jigsaw-fit breccia occurs over a 7 m interval beneath the Wollogorang Formation contact in GSD2, in sharp contact with the underlying coherent dolerite facies. Angular, centimetre- to decimetre-sized dolerite clasts are separated by planar, calcite/chlorite-filled fractures (Plate 3.8c). The breccia is interpreted to have formed by non-explosive quench and/or mechanical marginal brecciation during emplacement of a mafic intrusion. Quench fragmentation can occur in response to thermal stress acquired during rapid cooling, and stress imposed on chilled outer margins by continued movement of the viscous interior (McPhie, 1993). Localisation of brecciation at the top of the coherent dolerite is consistent with subvolcanic dolerite emplacement, the quenching fluid derived from unconsolidated, water-saturated sediment.

3.8.3 Dolomite breccia facies

The dolomite breccia facies is exposed at the base of the Wollogorang Formation in the Scrutton Range, and consists of a pebble to cobble breccia with no
Fig. 3.7 Settlement Creek Volcanics measured facies log (drill hole GSD2) and possible intrusive mode of emplacement into the Wollogorang Formation.
Plate 3.8 Igneous and sedimentary facies of the Settlement Creek Volcanics

a) Coherent dolerite facies of the Settlement Creek Volcanics in the Scrutton Range. Coarse-grained plagioclase, magnetite and minor chalcopyrite are visible in this sample, and are contained within a chlorite-sericite matrix. The pale green spots in this sample are carbonate pseudomorphs after plagioclase (sample 93-80).

b) Coherent dolerite facies of the Settlement Creek Volcanics in drillhole GSD2. The characteristic coarse-grained, intergranular texture of this facies has been highlighted in this example by potassic alteration of plagioclase crystals (176-181 m).

c) In situ breccia facies of the Settlement Creek Volcanics (Pte) occurring below the contact with overlying Wollogorang Formation (Pto) carbonate lithologies in drillhole GSD2 (133-139 m).

d) Typical exposure of the monomict dolomite breccia that forms the basal 1 to 5 m of the Wollogorang Formation in the Scrutton Range (5620E - 82087N).

e) Coarse-laminated and brecciated dolomite occurring within the coherent dolerite facies in the Scrutton Range (5618E - 82089N).

f) Fine-laminated dolomitic siltstone intercalated with the coherent dolerite facies in the Scrutton Range (5632E - 82086N).
internal structure or preferred clast orientation. Clasts consist of fine- to crude-laminated or massive dolomite set in a fine-grained calcareous matrix (Plate 3.8d). This facies attains a maximum thickness of approximately 5 m.

3.8.4 Dolomite/dolomitic siltstone facies

In the Scrutton Range, pink, thin, discontinuous and locally brecciated dolomites and dololutites are intercalated with the Settlement Creek Volcanics (Plate 3.8e and f). The sediments lack any internal structure, apart from fine, disrupted and wavy lamination. Petrographically, this facies is characterised by fine-laminated dolomite that locally contains biconvex evaporite pseudomorphs (Plate 3.9a), ooidal dolomite (Plate 3.9b) and fine-grained dolomitic siltstone.

3.8.5 Mode of emplacement

The Settlement Creek Volcanics have been interpreted as a bimodal, mostly subaerial volcanic sequence (Pietsch et al., 1991). However, the uniform coarse grain size of coherent dolerite facies and the marginal breccia facies developed along upper dolerite contacts in GSD2 are consistent with an intrusive origin for the Settlement Creek Volcanics. In the Mallapunyah Dome (70 km south of the study region), the Settlement Creek Volcanics are also volumetrically dominated by medium-to coarse-grained mafic rocks. Fine-grained, glassy groundmass or vesicular textures in the Mallapunyah Dome exposures are rare (Bull, 1993). The coarse grain size of mafic units and the presence of closed-framework, jigsaw-fit marginal breccias are again, consistent with a shallow intrusive model for the Settlement Creek Volcanics (Donovan, 1993). At the Mallapunyah Dome, the Settlement Creek Volcanics are interpreted to have been emplaced as mafic sills at the base of the Wollogorang Formation (Bull, 1993).

The sharp contact between coherent dolerite and the quench/mechanical breccia in GSD2 is unusual, as gradational relationships from coherent to brecciated facies are more typical (McPhie et al., 1993). The contact in GSD2 is interpreted to have formed by continued intrusion into pre-existing dolerite breccia during progressive lateral movement of the mafic magma (Fig. 3.7). The dolomite breccia facies in the Scrutton Range is interpreted to have formed via the dissolution of carbonate, and subsequent collapse of Wollogorang Formation carbonate lithologies, during enhanced circulation of connate fluids associated with the intrusion of the Settlement Creek Volcanics. Similar solution collapse features have been documented from carbonate-hosted volcanic breccia pipe systems (McCallum, 1985).
Carbonate horizons intercalated with the dolerite sills in the Scrutton Range are interpreted to be rafts of Wollogorang Formation dolomite or dolomitic siltstone that were incorporated into the sills during intrusion at the base of the formation. The silicified and fine-laminated nature of the carbonates have led previous workers to incorrectly interpret them as rhyolitic dykes (eg. Pietsch et al., 1991). Although true rhyolite dykes comprise a volumetrically small percentage of the Settlement Creek Volcanics elsewhere in the southern McArthur Basin (Rawlings, 1994; Wright, 1993), the formation is primarily a mafic sequence.

3.9 WOLLOGORANG FORMATION

The Wollogorang Formation attains a maximum thickness of 150 m in the southern McArthur Basin, and is characterised by recessive dolostones and ridge-forming sandstones. Diagnostic features include cherty stromatolites, laminated shales and bituminous nodules (Jackson et al., 1987). Six separate lithofacies have been identified within the Wollogorang Formation, and are interpreted to have been mostly deposited in lacustrine environments (Jackson, 1982; Jackson et al., 1987): I - red shale facies (quiet deposition in a saline mudflat or lagoonal environment); II - crystalline dolomite facies (shallow water marginal marine carbonate shelf); III - dololutite facies with evaporite pseudomorphs and algal laminations (playa-lake or supratidal environment); IV - black shale facies with a varied assemblage of poorly preserved microfossils (anoxic quiet water distal lacustrine environment); V - grey dolostone facies (shallow high-energy lacustrine environment with evaporitic overprint); VI - clastic facies with abundant K-feldspar and felsic volcanic fragments (braided fluvial to open shallow marine environments).

In the study region, the Wollogorang Formation is largely restricted to the Scrutton Range. However, thin intervals (< 10 m) of massive to laminated dolomite (Wollogorang Formation lithofacies V in the subdivision of Jackson et al., 1987) separate the Wununmantyala Sandstone and Masterton Sandstone in the western Tawallah Range. A detailed facies log was measured from a 145 m thick Wollogorang Formation section in the Scrutton Range (5621E/82083N - 5618E/82081N; Fig. 3.8). At this locality, the lower and upper contacts have been obscured by intrusion of the Settlement Creek and Gold Creek Volcanics respectively. Conformable contacts with the underlying Wununmantyala Sandstone and overlying sediments in the Gold Creek Volcanics probably existed prior to the emplacement of the mafic formations. The Wununmantyala Sandstone is conformably overlain by Wollogorang Formation dolomite in the western Tawallah Range.
Plate 3.9 Sedimentary facies of the Settlement Ck. Volcanics and Wollogorang Fm.

a) Photomicrograph of biconvex evaporite pseudomorphs (? after gypsum; arrows) in the dolomitic siltstone interval shown on Plate 3.8f (plain light; sample 94-58)

b) Photomicrograph of an oolitic dolomite clast sampled from the brecciated dolomite exposure shown on Plate 3.8e (crossed polars; sample 93-74).

c) and d) Thick, wavy-laminated dolomite (Subfacies I) and massive dolomite (Subfacies II) interbeds in the carbonate facies of the Wollogorang Formation. Thin chert horizons occur throughout subfacies I intervals in this exposure (Scrutton Range section - 11 m).

e) Planar cross-bedded sandstone with low-angle (< 20°) foresets in the sandstone facies of the Wollogorang Formation. Elongate mud-chip clasts locally define foreset laminae (Scrutton Range section - 29 m).

f) Biconvex evaporite pseudomorphs (? after gypsum) in the sandstone facies of the Wollogorang Formation (Scrutton Range section - 100.5 m).
3.9.1 Carbonate facies association

In the Scrutton Range, carbonate rock types occupy the lower 25 m of the Wollogorang Formation section (Fig. 3.8). This interval comprises an interbedded sequence of dolomite and minor dolomitic siltstone, and is further subdivided into three main subfacies.

Subfacies I consists of thick- and wavy-laminated dolomite beds up to 5 m thick (Plate 3.9c and d). Individual laminae are less than 2 cm thick, and have been locally disrupted to form intraformational breccias. Thin (0.1 to 10 cm), irregular and discontinuous chert horizons occur throughout (Plate 3.9c). Subfacies II is characterised by grey to buff coloured, thinly bedded (1 to 60 cm), fine-laminated (0.5 to 5 mm) to massive dolomite (Plate 3.9c and d). Subfacies III occurs in minor proportions and consists of red to black, finely bedded (<2 cm) dolomitic siltstone.

3.9.2 Sandstone facies association

The sandstone facies association is exposed in the upper portion of the Wollogorang Formation section, where it gradationally overlies the carbonate facies and is overlain by peperitic breccias of the Gold Creek Volcanics. The sandstone facies comprises a poorly-exposed, 121 m thick sequence of silicified, red to purple (hematitic), medium- to coarse-grained quartz sandstone. Massive to flat-laminated sandstone was the most abundant facies type recognised in the association. Planar cross-bedded sandstone with low-angle (<20°) foresets occurs locally (Plate 3.9e). Ripple-laminated sandstone, typically with straight crested, bifurcating or interference ripples, occurs as thick beds (0.5 to 3 m) that overlie flat-laminated or planar cross-bedded sandstone intervals. A characteristic feature of the sandstone facies association is the presence of small rounded casts (<5 cm diameter) that are interpreted as pseudomorphs after gypsum (Plate 3.9f). Elongate casts that define flat- and cross-laminae were probably dolomite or siltstone flakes (Plate 3.9e).

3.9.3 Depositional Environment

The carbonate and sandstone facies associations of the Wollogorang Formation described in this study resemble the grey dolostone facies (V) and clastic facies (VI) defined by Jackson et al. (1987). A summary of their palaeo-environmental interpretations are provided below. The absence of lower Wollogorang Formation facies at the Scrutton Range locality (lithofacies I-IV of Jackson et al., 1987) is interpreted to be a function of the intrusive nature of the underlying Settlement Creek Volcanics. Isolated intercalations of dolomite and dololutite that occur throughout the
Settlement Creek Volcanics were previously and incorrectly interpreted as syn-volcanic sediments or rhyolitic dykes. These rock types are re-interpreted to be remnant rafts of lower Wollogorang Formation units that were incorporated into the dolerite during intrusion of the Settlement Creek dolerites.

The grey dolostone facies (V) is characterised by thick, irregular and disrupted bedding, and is interpreted to have been deposited in a moderate energy, shallow, proximal lacustrine environment (Jackson, 1982). Discontinuous chert laminae are thought to have originally been evaporite horizons. Intraformational breccias are interpreted to have formed by slumping or collapse during dissolution of the evaporitic horizons. Regionally, the grey dolostone facies preserves evidence of emergent conditions (desiccation cracks and intraclast breccias; Jackson, 1982). However, such features were not observed in the Scrutton Range region. Based on the regional extent and conformity of the lower carbonate-dominated Wollogorang Formation facies, a largely subtidal marine depositional environment has been proposed by Rawlings et al. (1993).

The blocky quartz sandstone subfacies (VI), although containing no diagnostic features, is interpreted to have been deposited in an open shallow marine or shelf environment. The siltstone/dolomite flakes within cross-bed sets throughout the Scrutton Range sequence are interpreted to have been derived from a local sediment source region that was subject to periodic emergent conditions (tidal flat). Fine-grained sediment derived from these regions were probably reworked in a high energy, shallow subaqueous depositional environment. The abundant gypsum pseudomorphs are interpreted to have formed in shallow, hypersaline waterbodies with restricted circulation (Paull and Paull, 1994).

3.10 GOLD CREEK VOLCANICS

The Gold Creek Volcanics are a thick succession of mafic rocks and intercalated, fine- to medium-grained lithic sandstones and siltstones. Igneous rock types include fine-grained massive to amygdaloidal basalt, coarse-grained dolerite and volcanic breccia interpreted to be mafic peperite (Rawlings, 1993). A lacustrine environment of deposition, with mafic sills and dykes intruding the sedimentary pile prior to lithification, has been proposed for the Gold Creek Volcanics (Pietsch et al., 1991). In the study region, the Gold Creek Volcanics are confined to the Scrutton Range, where they overlie the Wollogorang Formation. A local erosional unconformity marks the upper contact with the overlying Warramana Sandstone. Exposure is generally moderate to poor, occurring in recessive valleys and low relief areas. Total thickness varies from 175 m (central Scrutton Range) to approximately 250 m in the
southern Scrutton Range. A facies map (5637E/82067N - 5632E/82065N; Fig. 3.9a) was constructed from exposures in southern parts of the Scrutton Range.

3.10.1 Coherent dolerite facies

Coherent dolerite/microdolerite is the most abundant facies recognised in the Gold Creek Volcanics. Laterally extensive, fine- to medium-grained dolerite bodies up to 20 m thick vary from porphyritic to equigranular in the basal 5 to 10 m (Plate 3.10a). Above this, amygdules are ubiquitous and show a marked upward increase in abundance (Plate 3.10b). Vertical polygonal jointing is preserved locally where the coherent dolerite facies is well-exposed (Plate 3.10c). Many porphyritic samples have a sub-horizontal alignment of plagioclase phenocrysts, which define a laminar flow texture similar to that described by Cas and Wright (1987; Plate 3.10d).

3.10.2 Volcanic breccia facies

Marginal volcanic breccias occur along contacts between the coherent dolerite and sandstone facies (section 3.10.3). The breccia is unique to Gold Creek Volcanics exposures in the study region and consists of vesicular, centimetre- to decimetre-sized blocky clasts set in a fine-grained sandstone matrix (Plate 3.10e and f). Rawlings (1993), in a detailed study of the volcanic breccia in the Scrutton Range, observed that vesicular clasts tend to have sinuous, lobate margins, and poorly vesiculated clasts have more angular surfaces. In most cases, clast margins have been intensely fractured and are surrounded by a veneer of retextured sediment (Plate 3.10g). The breccia has been classified as a blocky peperite by Rawlings (1993). The peperite was probably generated during mixing of coherent magma with unconsolidated, wet sediment and subsequent hyaloclastic fragmentation (McPhie, 1993).

3.10.3 Sandstone facies

Clastic lithologies occur throughout the Gold Creek Volcanics in the study area, and consist of fine- to medium-grained hematitic quartz sandstone with minor siltstone. Planar cross-stratification with low- to moderate-angle foresets and ripple marks are the most abundant sedimentary structures recognised within sandstone intervals (Plate 3.10h). Individual beds are thin (0.5 to 5 m), laterally discontinuous and irregularly shaped. In most respects, the sandstone lithologies in the Gold Creek Volcanics are similar to the sandstone facies described from the upper Wollogorang Formation.
Fig. 3.9a Gold Creek Volcanics facies map. Patterned/dark regions represent mapped exposures, shaded regions represent probable extent of facies.
Fig. 3.9b Schematic cross-section depicting progressive development of the Gold Creek Volcanics at the Scrutton Range locality. i) Rising magma, focussed upwards along an extensional structure, is emplaced laterally once magma density equals that of the overlying sediment pile. ii) Occasionally, rising magma must have breached the sediment-water interface to produce subaqueous basalt lava flows. iii) Successive emplacement of sills during subsidence and clastic sedimentation.
Plate 3.10 Igneous and sedimentary facies of the Gold Creek Volcanics.

a) Aligned plagioclase phenocrysts in a porphyritic sample from the lower part of a coherent dolerite facies interval (sill) in the Gold Creek Volcanics (Scrutton Range section - 193 m; sample 94-41).

b) Amygdaloidal dolerite sampled from the upper part of a coherent dolerite facies interval (sill) in the Gold Creek Volcanics (Scrutton Range section - 142 m; sample 94-49).

c) Vertical polygonal jointing preserved in the coherent dolerite facies (Scrutton Range; 5634E - 82062N).

d) Photomicrograph of aligned plagioclase crystals and stretched amygdules, defining a laminar flow texture similar to that described by Cas and Wright (1987) for the coherent dolerite facies (plain light; sample 93-108).

e) and f) Typical exposures of the volcanic breccia which occurs at the margins between coherent dolerite and sandstone facies in the Gold Creek Volcanics. The brown, vesicular, blocky dolerite clasts are contained within a buff-coloured, fine-grained sandstone matrix (Scrutton Range section - 15 m and 245m).

f) Photomicrograph of a clast margin in the volcanic breccia facies. Finer-grained (?) recrystallised) sandstone and coarse-crystalline carbonate separate the fractured dolerite clast from the coarser-grained sandstone matrix (crossed polars; sample 93 - 122).

g) Planar cross-stratification with low- to moderate-angle foresets in the sandstone facies of the Gold Creek Volcanics (Scrutton Range section - 73 m).
3.10.4 Mode of emplacement

The facies associations recognised in the Gold Creek Volcanics are interpreted to have formed during high-level emplacement of mafic sills and dykes into wet and unconsolidated, shallow marine sediments, as initially proposed by Rawlings (1993). Sub-volcanic interaction of mafic magma and water-saturated sediment led to the development of blocky peperitic textures during hyaloclastic fragmentation. Vertical repetition of coherent dolerite, peperite and undisturbed sediment sequences (Fig. 3.9a) can be interpreted to have resulted from sill emplacement occurring at many levels in the sub-volcanic environment. Alternatively, volcanic activity may have been coeval with sedimentary deposition, so that mafic magmas were emplaced at a constant depth below surface, but in vertical succession as the sediment pile thickened (Fig. 3.9b). Synchronous sedimentation and sill emplacement is supported by the presence of subaqueous lava flows in the Gold Creek Volcanics succession north of the study region (Costello Range; Rawlings et al., 1993). In this model, sandstone facies are interpreted to be the continuation of the upper Wollogorang Formation succession, and deposited in shallow subaqueous environments.

3.11 WARRAMANA SANDSTONE

The Warramana Sandstone contains abundant thick-bedded (0.4 to 1 m), fine- to coarse-grained sandstone with minor conglomerate and siltstone. Haines et al. (1993) described a minimum thickness of 240 m for an incomplete Warramana Sandstone section to the north of the study area on MOUNT YOUNG, and recognised four distinct lithological units: Unit 1 - red-brown, medium-grained, thin- to medium-bedded, trough cross-stratified and ripple-laminated litharenite (basal 66 m); Unit 2 - thin, recessive interval of massive to pisolitic ironstone, hematitic mudstone and ferruginous pebbly mudstone (< 5 m thick); Unit 3 - pink to white, fine- to coarse-grained sublitharenite (77 m thick); Unit 4 - lithologically similar to Unit 1, with abundant felsic volcanics fragments interpreted to have been derived from the Tanumbirini Rhyolite (30 m thick). A shallow marine environment of deposition has been proposed for the Warramana Sandstone, with source regions containing significant proportions of silicic volcanic material (Rawlings et al., 1993).

In the study region, the Warramana Sandstone is restricted to the Scrutton Range, where it crops out along an erosional scarp between the recessive Gold Creek Volcanics and the overlying Tanumbirini Rhyolite or Masterton Sandstone. The formation thickens over an exposed strike-length of 8 km, from 2 m in the north to 45 m in the south. A detailed facies log was measured in the southern part of the exposure (5618E/82075N, Fig. 3.10a). Basal conglomerates in the Warramana Sandstone section
are interpreted to be a regressive lag deposit, forming a locally unconformable contact with the upper Wollgoran Formation/Gold Creek Volcanics succession.

3.11.1 Conglomerate facies

This facies forms the basal 0.5 to 2 m of the Warramana Sandstone and comprises discontinuous lenses of poorly sorted, open framework, pebble to cobble conglomerate. Clasts are subrounded to subangular, randomly orientated and supported by a coarse-grained, structureless sandy matrix (Plate 3.11a). Clast types include medium-grained hematitic and/or silicified quartz sandstone. The conglomerate facies is typically massive, although crude internal stratification occurs in places.

3.11.2 Planar cross-bedded sandstone facies

The most abundant facies type recognised in the Warramana Sandstone is medium- to coarse-grained, planar cross-bedded hematitic quartz sandstone. Bedform thickness and foreset angles vary such that two separate subfacies can be identified.

Subfacies I is defined by sub-horizontal to low-angle (< 10°) planar foresets that are truncated by inclined surfaces parallel to overlying cross-laminae. Maximum coset thickness rarely exceeds 0.5 m. A characteristic feature of subfacies I is that individual cross-bed sets consist of alternating coarse- and medium-grained laminae (less than 0.5 cm thick), resulting in a unique banded appearance (Plate 3.11b).

Subfacies II constitutes approximately 30% of the facies in the study area, and contains bedforms with higher-angle (< 30°) planar to gently convex foresets (Plate 3.11c). Amalgamation of 2 to 3 cross-bed sets have formed the thick (< 1.5 m) beds that are characteristic of subfacies II intervals. Internal truncation angles within cosets lie between 30 and 50°. Most of the foreset bases are defined by coarse-grained to granular laminae.

3.11.3 Ripple-laminated sandstone facies

Ripple-laminated, white to pink (hematitic), predominantly fine-grained quartz sandstone occurs throughout the Warramana Sandstone. Large scale (3 to 10 cm wavelength), symmetric and asymmetric, straight crested, bifurcating and interference ripples are characteristic (Plate 3.11d). The ripple-laminated sandstone facies is typically overlain by, or interbedded with, fine-grained flat-laminated sandstone (Plate 3.11e). Thin intervals of this facies overlie planar cross-bedded intervals, and locally occur as composite, ripple-laminated beds up to 1 m thick.
Fig. 3.10 Measured facies logs of the: a) Warramama Sandstone; and b) Nyanantu Formation.
Plate 3.11 Sedimentary facies of the Warramana Sandstone.

a) Poorly sorted, open framework, pebble to cobble conglomerate that occurs as 0.5 to 2 m thick, discontinuous lenses at the base of the Warramana Sandstone (Scrutton Range section - 1 m).

b) Planar cross-bedded sandstone subfacies I in the Warramana Sandstone, with characteristic sub-horizontal to low-angle planar foresets and alternating coarse- and medium-grained laminae (Scrutton Range section - 13 m).

c) Planar cross-bedded sandstone subfacies II in the Warramana Sandstone, with typical higher-angle, planar to gently convex foresets (Scrutton Range section - 16.5 m).

d) Symmetrical ripple-laminated sandstone interbedded with fine-grained flat-laminated sandstone in the Warramana Sandstone (Scrutton Range section - 26 m).

e) Straight-crested to lobate ripples preserved on a bedding surface in the ripple-laminated facies of the Warramana Sandstone (Scrutton Range section - 10 m).

f) Finely bedded siltstone facies interval in the Warramana Sandstone (Scrutton Range section - 8 m).
3.11.4 Siltstone facies

Several intervals of recessive, red to purple, finely bedded/laminated (<3 cm) siltstone are exposed in the lower half of the Warramana Sandstone (Plate 3.11f). Thin (<5 cm) interbeds of fine-grained sandstone occur throughout the facies. Thinly bedded siltstone only constitutes a minor proportion of the section, but discrete intervals locally attain a maximum thickness of 2 m.

3.11.5 Depositional environment

The facies associations of the Warramana Sandstone succession superficially resemble those described from older sandstone-dominated Tawallah Group formations which are interpreted as alluvial/fluvial deposits. However, closer analysis of subtle features within each facies of the Warramana Sandstone has led to the interpretation that it was deposited in a clastic, high-energy, nearshore environment. Planar cross-stratification can be produced in many settings, and in the nearshore environment by various processes including tidal reworking (Uhlir et al., 1988), current-generated dunes or sandwaves (Nakayama and Masuda, 1989) and in rip channels (Yagishita, 1994). However, the interbedded coarse- and medium-grained laminae within the Warramana Sandstone are a characteristic feature of upper foreshore depositional settings (Clifton et al., 1971; Bergh and Torske, 1986). Laminations that have marked grain-size alternation can be developed during grain segregation under plane-bed, swash and backwash flow conditions on an active foreshore (Clifton, 1969). High-angle planar foresets in this environment have been interpreted to result from the landward migration of foreshore sand-ridges or bars (Davis and Fox, 1972; Elliot, 1986). Ripple-laminated and flat-laminated sandstone are deposited under lower energy conditions, and are likely to have developed seaward from the swash zone. In the classification of Clifton et al. (1971), interbedded ripple-laminated and flat-laminated sandstone are 'outer planar facies', and form beneath the wave build-up and outer surf zones. The siltstone facies is also typical of low-energy conditions, and based on the lack of HCS sandstone and other diagnostic offshore marine features, is interpreted to have been deposited in a lagoonal depositional setting above a barred shoreline.

The basal cobble conglomerate is interpreted to be a regressive lag deposit, similar to the phosphatic pebble beds described from the Shannon Sandstone of central Wyoming, North America (Walker and Plint, 1992). Thin pebbly horizons in the Shannon Sandstone were deposited above an erosional surface that was interpreted to have developed during sea level regression and relocation of the active beachface. The lowstand shoreface was subsequently overlain by nearshore sediments once the depositional system stabilised.
Facies associations within the Warramana Sandstone appear to be consistent with a barred beach-face succession. A general shallowing from the shallow subaqueous settings of the Gold Creek Volcanics is therefore inferred prior to Tanumbirini Rhyolite emplacement.

3.12 TANUMBIRINI RHYOLITE

The Tanumbirini Rhyolite is a 100 m thick interval of porphyritic rhyolite that overlies the Warramana Sandstone, and is the youngest volcanic formation in the Tawallah Group (Plate 3.12a and b). A typical Tanumbirini Rhyolite sample has a phenocryst assemblage that consists of quartz (<10 mm diameter), altered K-feldspar (<12 mm diameter) and subordinate iron oxide, set in a fine-grained groundmass of devitrified quartzo-feldspathic glass. A disconformable lower formation contact is marked by the presence of small (up to 0.1 m) rhyolite apophyses that intrude the Warramana Sandstone (Plate 3.12c). No evidence of hyaloclastic brecciation has been observed along the irregular lower contact, implying that Tanumbirini Rhyolite emplacement occurred subaerially over a dry sediment substrate. These features are consistent with the model of Pietsch et al. (1991), who proposed that the Tanumbirini Rhyolite was emplaced as a series of localised subaerial lava domes and flows.

3.13 NYANANTU FORMATION

In the study region, the Nyanantu Formation crops out in the Scrutton Range where it conformably overlies (or is laterally equivalent to) the Tanumbirini Rhyolite, and is unconformably overlain by the Masterton Sandstone. Pebby coarse-grained sandstones and minor polymict conglomerates are well exposed in a 30 m thick succession of limited lateral extent. A detailed facies log measured from the Scrutton Range section (5618E/82071N) is provided in Figure 3.10b. Haines et al. (1993) proposed a fluvial origin for the 450 m thick Nyanantu Formation type section located in the Sawtooth Range, approximately 30 km northeast of the Scrutton Range.

3.13.1 Conglomerate facies

Pink to bleached, poorly sorted, subangular, granule to cobble conglomerate occurs throughout the Nyanantu Formation section (Plate 3.12d). Individual conglomerate beds are generally clast-supported and massive, although some thicker intervals (>0.5 m) are crudely stratified. The conglomerate deposits have lensoidal geometries, resulting in variable bed thicknesses (2 cm to 0.7 m). Compositionally, the conglomerate facies is characterised by abundant felsic volcanic fragments (Plate
Plate 3.12 Tanumbirini Rhyolite and sedimentary facies of the Nyanantu Formation.

a) Typical exposure of the Tanumbirini Rhyolite (Scrutton Range; 5620E - 82058N).

b) Characteristic porphyritic texture of the Tanumbirini Rhyolite (Scrutton Range; 5628E - 82053N).

c) Small rhyolite apophyses that have intruded the underlying Warramana Sandstone along the basal contact of the Tanumbirini Rhyolite (Scrutton Range; 5612E - 82092N).

d) and e) Intervals of the pebble to cobble conglomerate facies in the Nyanantu Formation with abundant felsic volcanic fragments and minor coarse-grained hematitic quartz sandstone clasts (Scrutton Range section - 5 and 17.5 m).

f) and g) Planar cross-bedded pebbly sandstone facies of the Nyanantu Formation (Scrutton Range section - 3 and 15 m).
3.12e), with coarse-grained hematitic quartz sandstone pebbles and cobbles occurring locally. The matrix is comprised of coarse-grained to granular quartz and feldspar, probably derived from the Tanumbirini Rhyolite.

3.13.2 Planar cross-bedded pebbly sandstone facies

This is the most abundant facies in the Nyanantu Formation, and consists of pink to bleached, coarse-grained to gravelly, lithic quartzo-feldspathic sandstone (Plate 3.12f and g). Stacked, large-scale planar cross-bed sets (0.4 to 0.8 m amplitude) occur as monotonous intervals up to 6 m thick. Felsic volcanic pebbles and cobbles are dispersed throughout the facies, and occur in crude, fining-upward cycles.

3.13.3 Depositional environment

Facies associations in the Nyanantu Formation resemble those described for the basal Wununmantyala Sandstone succession, and a similar proximal/medial braided river depositional environment is proposed. The conglomerate facies may have formed as noncohesive debris flows (clast-rich flows lacking clay-sized sediment), although as discussed in the interpretation of the Wununmantyala Sandstone, the association with large-scale planar cross-bedded pebbly sandstone precludes an alluvial fan origin (Blair and McPherson, 1994). The conglomeratic facies is therefore interpreted to have been deposited during the migration or lateral accretion of longitudinal bars during flood-stage conditions in a braided fluvial setting (Rust, 1972). The planar cross-bedded facies is interpreted to have formed during the downstream migration of linguoid or transverse bars (Miall, 1977). The abundance of felsic volcanic clasts within each facies implies that the proximal/medial palaeo-braided fluvial system existed when the Tanumbirini Rhyolite was exposed and subject to active mechanical erosion.

3.14 MASTERTON SANDSTONE

The Masterton Sandstone forms the basal unit of the McArthur Group, and consists of fine- to medium-grained, medium- to thickly bedded quartz sandstone, minor siltstone and local basal conglomerate (Pietsch et al., 1991). In the study region, the total thickness of the Masterton Sandstone varies from 200 m in the Scrutton Range to approximately 450 m in the Batten Range. The contact between the Masterton Sandstone and the underlying Tawallah Group is typically disconformable. The Masterton Sandstone grades conformably into the evaporitic sediments of the overlying Mallapunyah Formation (Jackson et al., 1987)
Pietsch et al. (1991) identified two main lithofacies in the Masterton Sandstone: The *basal conglomerate facies* consists of a basal conglomerate bed (8 to 10 m thick) overlain by interbedded cobble to boulder conglomerate and coarse-grained to pebbly trough cross-bedded sandstone (60 to 80 m thick); and the *upper sandstone facies* is a sequence of fine- to medium-grained, medium-bedded quartz sandstone with minor coarse-grained mottled ferruginous sandstone and recessive siltstone intervals (< 350 m thick). The conglomeratic facies are interpreted as an alluvial fan or braided fluvial succession, whereas the upper sandstones were probably deposited in a shallow marine environment (Pietsch et al., 1991).

### 3.14.1 Basal conglomerate facies

In the study region, conglomerate, minor pebbly sandstone and gravel lithologies occur in the lower parts of the Masterton Sandstone in the Batten and Scrutton Ranges. The thickness of the conglomerate facies generally ranges between 5 and 50 m, although a maximum thickness of approximately 150 m is attained adjacent to the Pandanus Creek Fault in central Batten Range (Appendix 4a). Conglomerate intervals are typically monomict, massive to locally imbricated, clast-supported and have a medium- to coarse-grained sandstone matrix. Clast types include silicified and/or hematitic fine- to medium-grained quartz sandstone. In the Scrutton Range, minor felsic volcanic clasts, probably derived from the Tanumbirini Rhyolite, are also present in the basal conglomerate facies of the Masterton Sandstone (Plate 3.13a).

In the Batten Range, the roundness and maximum size of conglomerate clasts defines two separate subfacies. Subfacies I is typified by massive to locally imbricated, clast-supported conglomerate containing sub- to well-rounded, pebble- to cobble-sized clasts (Plate 3.13b). Conglomerate subfacies II contains randomly orientated, subangular to angular, pebble- to boulder-sized clasts that are locally supported by a medium- to coarse-grained, structureless sandstone matrix (Plate 3.13c). Adjacent to the Pandanus Creek Fault, the basal 150 m of the Masterton Sandstone comprises thick (< 50 m) conglomerate subfacies II intervals separated by thinner (< 5 m) gravelly to pebbly, cross-bedded sandstones. Subfacies II intervals at this locality typically comprise thick (< 10 m), poorly sorted conglomerate and thin (< 0.5 m) gravelly sandstone interbeds (Plate 3.13d). The entire succession is restricted to a narrow fault-bound block within the Pandanus Creek Fault Zone, so that lateral relationships with subfacies I are difficult to ascertain. However, a marked increase in the total thickness of the Masterton Sandstone occurs across the Pandanus Creek Fault, with decreasing thickness towards the south defining a wedge-shaped geometry for the formation (Appendix 4a). If the Pandanus Creek Fault was a growth fault during Masterton Sandstone deposition, conglomerate subfacies I could be laterally equivalent to
conglomerate subfacies II. Elsewhere in the Batten Range, conglomerate subfacies I forms the basal 5 to 50 m of the Masterton Sandstone section above a disconformable contact with the underlying Wununmankyala Sandstone.

3.14.2 Upper sandstone facies

Jackson et al. (1987) designated a 55 m thick sequence of quartz sandstone and minor siltstone in Archies Creek, Mallapunyah Dome as the type section for the Masterton Sandstone. Although markedly thicker in the study region (< 350 m), the upper sandstone facies of the Masterton Sandstone is similar to the Mallapunyah Dome type section (Bull, 1994). The upper sandstone facies consists of variably hematitic, thin- to thickly-bedded (0.1 to 2 m), fine- to medium grained quartz sandstone. Bedding is generally tabular, and broad shallow channel features are present locally (Jackson et al., 1987). The most abundant sedimentary structures are planar to low-angle truncations, medium- to large-scale cross-bedding (amplitudes of 0.5 to 1 m; Plate 3.13e) and rippled pavements. Ripples are typically asymmetric and small- to medium-scale (< 5 cm wavelength) with straight crested to (rarely) lunate morphologies (Plate 3.13g). At the type section and throughout the study region, the contact with the overlying Mallapunyah Formation is gradational and marked by hematitic spots or biconvex laths, probably after gypsum, and rare halite casts in the uppermost sandstones of the Masterton Sandstone (Jackson et al., 1987; Bull, 1994; Plate 3.12f).

3.14.3 Siltstone facies

In the Tawallah Range, recessive intervals (< 10 m thick) of red to black, thinly bedded (< 5 cm), rippled, fine-grained sandstone and siltstone separate resistant Masterton Sandstone ridges. The bulk of the ridge-forming sandstones are similar to the upper sandstone facies described from the Mallapunyah Dome type section, and from elsewhere in the study region (Jackson et al., 1987). Interbedded with the thinly bedded, fine-grained lithologies are thicker (20 to 40 cm), cross-bedded sandstones that are similar to the upper sandstone facies. Based on this relationship, a genetic relationship is inferred for the two facies associations (Bull, 1994).

3.14.4 Depositional Environment

The basal conglomerate facies of the Masterton Sandstone resemble the coarse-grained facies that occupy the basal Wununmankyala Sandstone section in southwest Tawallah Range (section 3.7.1), and a proximal to medial braidplain depositional setting is proposed. However, the randomly orientated, angular and (up to)
**Plate 3.13 Sedimentary facies of the Masterton Sandstone.**

a) Abundant silicified and/or hematitic fine- to medium-grained quartz sandstone and minor Tanumbrin Rhyolite-derived clasts (TRhy) in the basal conglomerate subfacies I (Scrutton Range; 5617E - 82072N).

b) Characteristic subrounded to rounded pebble- to cobble-sized clasts in the basal conglomerate subfacies I (Batten Range; 5780E - 81889N).

c) Subangular to angular, pebble to boulder conglomerate subfacies II of the Masterton Sandstone (Batten Range; 5790E - 81878N).

d) Massive and poorly sorted conglomerates interbedded with thin (< 0.5 m) gravelly sandstone intervals (conglomerate subfacies II) near the Pandanus Creek Fault in the Batten Range (5790E - 81878N).

e) Medium-scale cross-bedding (amplitude of 0.5 m) in the upper sandstone facies (Tawallah Range; 5783E - 82065N).

f) Evaporite pseudomorphs (? after gypsum) in the upper sandstone facies, two metres below a gradational contact with the overlying Mallapunyah Formation (Scrutton Range; 5588E - 82153N).

g) Rippled pavement in the upper sandstone facies of the Masterton Sandstone (Tawallah Range; 5783E - 82065N).
boulder-sized clasts in the conglomerate subfacies II are inconsistent with a braidplain depositional environment (Miall, 1977; Rust, 1978). Conglomerate subfacies II is interpreted as a talus slope deposit generated during the incipient stages of alluvial fan formation (Mustard, 1991). In the early stages of alluvial fan development, poorly sorted pebble to boulder conglomerate can be produced by two mechanisms; colluvial slide or rock avalanche (Blair and McPherson, 1994). Colluvial slide involves the collapse of bedrock cliffs, and can be triggered in a dry state (in response to earthquakes) or by addition of rainfall in volumes sufficient to saturate the sediment (Reneau et al., 1990). Rock avalanche occurs by catastrophic and rapid collapse of fractured bedrock cliffs to produce shattered and granular deposits (Blair and McPherson, 1994). The close proximity of conglomerate subfacies II to the Pandanus Creek Fault, and the typically non-brecciated nature of constituent clasts are consistent with a colluvial slide origin for the subfacies, adjacent to an active fault. Conglomerate facies I deposits near the Pandanus Creek Fault, particularly those in excess of 50 m thick, can be interpreted as non-cohesive debris flows in an alluvial fan model. Debris flows typically post-date talus breccia sedimentation, when an alluvial fan surface is stabilised (Blair and McPherson, 1994). Conglomerate subfacies I debris flows then grade laterally into the proximal to medial braidplain settings more typical of the subfacies elsewhere in the Batten Range.

Bull (1994) proposed a braided fluvial or braidplain depositional environment for the upper sandstone facies in the study region, based on the abundance of high-energy sedimentary structures and the lack of diagnostic shallow marine features (e.g., swash or hummocky cross-stratification). Measured palaeoflow directions from cross-bed foresets are broadly unidirectional throughout the Masterton Sandstone section, suggesting a genetic relationship (interfingering) between the basal conglomerate and upper sandstone facies (Bull, 1994). The ripple-laminated sandstone and fine-grained sandstone/siltstone deposits are interpreted to have formed in ephemeral lakes or pools developed on the low-relief braidplain (Bull, 1994). Alternatively, the lower energy deposits may have been deposited in shallow subaqueous conditions (Pietsch et al., 1991), if the Masterton Sandstone alluvial fan/braidplain system fed directly into adjacent shallow marine or lacustrine settings.

3.15 DISCUSSION - FACIES ARCHITECTURE

The Tawallah Group is interpreted to have accumulated during the onset and evolution of Late Palaeoproterozoic rifting in the southern McArthur Basin, prior to regional thermal relaxation and subsequent carbonate-dominated McArthur Group sedimentation. This initial stage of basin evolution was characterised by coarse-grained, tractionally deposited, and regionally extensive clastic successions. In the study region,
the Tawallah Group can be subdivided into three major packages. Each package is separated by a bounding discontinuity where discrete changes in both the basin architecture and palaeo-environmental conditions are interpreted to have occurred (Table 3.3).

3.15.1 Basal package

The basal Tawallah Group package incorporates the Yiyintyi Sandstone through to the Aquarium Formation (Fig. 3.11), and was deposited during the initial episode of Late Palaeoproterozoic continental extension and subsidence in the southern McArthur Basin. The Yiyintyi Sandstone is interpreted to have accumulated in a sandy braidplain system that was characterised by broad, low-sinuosity and laterally accreting channels. Coarse-grained (gravely to pebbly) sandstone-dominated channel facies associations are characteristic of the lower Yiyintyi Sandstone succession, whereas medium- to coarse-grained channel sandstone facies associations are more typical of the upper Yiyintyi Sandstone section. Channel deposits in the Yiyintyi Sandstone are interbedded with finer-grained facies associations that are interpreted to have formed during unconfined, high-energy sheet-flood events.

Widespread subaerial basaltic flood volcanism (Seigal Volcanics) temporarily interrupted sedimentation. High-energy, clastic alluvial sedimentation was re-established with the deposition of the Sly Creek Sandstone in a distal sandy braidplain environment. Subtle differences from the upper Yiyintyi Sandstone succession include increased sheet-flood episodes and development of thin vertical accretion (mudstone) deposits that were cannibalised and resedimented as intraformational breccias during ensuing flood events.

Continued extension and subsidence resulted in the formation of a transgressive sequence, with the Sly Creek Sandstone braidplain system grading to braid-delta (Rosie Creek Sandstone) and ultimately, to shallow marine settings (Aquarium Formation). The Aquarium Formation was characterised by below-fairweather wave-base, clastic and carbonate sedimentation. Abundant HCS sandstone and the occurrence of flat pebble breccia horizons in the carbonate facies associations are interpreted to indicate a depositional environment characterised by storm-influenced conditions. The regional occurrence of low-relief shallow platform carbonates at a similar stratigraphic level in the Aquarium Formation succession (upper carbonate facies association) is interpreted to indicate a period of tectonic quiescence. This may indicate that extension and subsidence rates were either greatly reduced, or equalled the rate of total sediment input into the basin.
Table 3.3 Interpreted depositional settings and subdivision of the Tawallah Group stratigraphy in the study region. Asterisk designates sites of erosion or non-deposition prior to Masterton Sandstone (basal McArthur Group) sedimentation.

Fig. 3.11 Proposed depositional environments of the lower Tawallah Group formations: Westmoreland Conglomerate (alluvial fan; Jackson et al., 1987), Yiyintyi Sandstone (proximal to distal braidplain), Sly Creek Sandstone (distal braidplain), Rosie Creek Sandstone (braid-delta) and Aquarium Formation (shallow subaqueous). The depositional system shown is only a schematic representation; a basin-scale, linked depositional architecture is depicted for the sake of simplicity.
Regional setting

The Yiyintyi Sandstone unconformably overlies the Scrutton Volcanics and is interpreted to be the distal equivalent of the Westmoreland Conglomerate, a thick (up to 1900 m), alluvial fan deposit that overlies Early Proterozoic basement rocks along the southeast basin margin (Jackson et al., 1987). Measured palaeocurrent directions, clast compositions and upward fining cycles in the Westmoreland Conglomerate are consistent with derivation from a basement source that underwent multiple periods of tectonic uplift (Ahmad et al., 1984). The exposures of Yiyintyi Sandstone in the study region occur at least 300 km from the southeast basin margin (Murphy Inlier; Jackson et al., 1987), implying the existence of a widespread clastic depositional system during the initial stages of basin formation. Coarse-grained braidplain systems can extend up to 500 km from alluvial fan source regions (Rust and Koster, 1984). However, local intrabasinal sources were probably also important in the early stages of Yiyintyi Sandstone deposition, due to the presence of basal pebbly sandstones in the study region. Local structural controls on the basal Yiyintyi Sandstone facies architecture are currently poorly understood.

The upper Yiyintyi Sandstone and the Sly Creek Sandstone are interpreted to have been deposited in a sand-dominated braidplain system, based on the abundance of high-energy sedimentary structures and the lack of diagnostic shallow marine features. The Rosie Creek Sandstone marks a transition from the sandy braidplain settings to shallow marine depositional environments (Aquarium Formation), and is lithologically variable on a regional scale. North of the study region (MOUNT YOUNG), cauliflower chert after anhydrite and rare halite pseudomorphs in the Rosie Creek Sandstone are interpreted to indicate evaporitic to shallow marine depositional conditions (Haines et al., 1993). In contrast, the same facies associations have been noted from the Aquarium Formation wherever it has been studied (eg. CALVERT HILLS, BAUHINIA DOWNS and MOUNT YOUNG, Haines et al., 1993; Pietsch et al., 1991). Upper carbonate lithologies of the Aquarium Formation occur at similar stratigraphic levels throughout the southern McArthur Basin, consistent with the interpretation that the formation was deposited during a basin-wide episode of tectonic quiescence and stable platform sedimentation.

3.15.2 Middle package

In the study area, the base of the Wununmantyala Sandstone marks a transition from shallow marine (Aquarium Formation) to subaerial depositional environments. Local angular unconformities or irregular, erosional unconformities are characteristic of the Aquarium Formation/Wununmantyala Sandstone contact in the study region (Fig. 3.6). The presence of clasts derived from the lower Tawallah Group and Scrutton
Volcanics in basal coarse-grained facies of the Wununmantyala Sandstone is interpreted to indicate that a period of intrabasinal uplift preceded Wununmantyala Sandstone deposition. Unimodal, west-directed palaeocurrents measured from cross-bedded Wununmantyala Sandstone facies indicate that uplift of lower Tawallah Group and Scrutton Volcanics stratigraphy occurred along a N-striking fault system, east of the southwest Tawallah Range (Bull, 1993). The uplift event (D1; Chapter 6) is thought to have re-established subaerial sedimentation with the development of a braidplain system that had its proximal reaches near the southwest Tawallah Range, and graded toward more distal settings in the Scrutton, Batten and western Tawallah Ranges (Fig. 3.12a). Shallow subaqueous facies associations were preserved in the upper Wununmantyala Sandstone succession locally. Erosion of topography with the resumption of crustal extension and subsidence ultimately resulted in the deposition of the low-relief and low-energy facies associations of the Wollogorang Formation (Fig. 3.12b).

Facies associations consistent with a gradational transition between the subaerial Wununmantyala Sandstone and subaqueous Wollogorang Formation are rare in the study region. This is interpreted to have resulted from the intrusion of the Settlement Creek Volcanics into the basal 100 m of the Wollogorang Formation (Fig. 3.12b). The Gold Creek Volcanics were predominantly emplaced sub-volcanically, although rare lava flows (Rawlings et al., 1993) and the stacked nature of shallow sills are interpreted to indicate that clastic sedimentation was continuous during successive intrusions (Fig. 3.13a).

Regional setting

The Wununmantyala Sandstone, like the upper Yiyintyi Sandstone and Sly Creek Sandstone successions, was originally interpreted as a wave-influenced, shallow marine deposit (Pietsch et al., 1991; Haines et al., 1993). Although this interpretation is plausible where gradational relationships with the underlying Aquarium Formation can be demonstrated, a shallow marine setting is not appropriate for Wununmantyala Sandstone exposures in the study region. The arguments in favour of a sandy braidplain depositional environment discussed previously for the Yiyintyi and Sly Creek Sandstone can similarly be applied for the Wununmantyala Sandstone. In the study region, the deposition of the Wununmantyala Sandstone is interpreted to have been controlled by intrabasinal tectonic uplift. However, in areas where sedimentation was not directly controlled by uplift, shallow marine conditions might have persisted at this stratigraphic interval.
Fig. 3.12 Generalised depositional architecture of the middle Tawallah Group package in the study region. **a)** Basal Wununmantyala Sandstone braidplain succession. **b)** Shallow subaqueous Wollogorang Formation deposition (carbonate facies association) and intrusion of the Settlement Creek Volcanics (some time after Wollogorang Formation deposition).
The upper Wununmantyala Sandstone is interpreted to have graded laterally into the regionally extensive and low-relief platform facies associations of the Wollogorang formation (e.g. western Tawallah Range; Fig. 3.12b). A below-fairweather wave-base, storm-dominated marine depositional environment has been proposed for the Wuraliwiuntya Member of the Wununmantyala Sandstone (Haines et al., 1993). This unit forms upper sections of the Wununmantyala Sandstone in the TAWALLAH RANGE region, and could be interpreted as the transition to subaqueous Wollogorang Formation depositional settings.

3.15.3 Upper package

The upper Tawallah Group package comprises the Warramana Sandstone, Tanumbirini Rhyolite and Nyanantu Formation, and represents a second transition to subaerial depositional environments (Fig. 3.13a). The package is separated from the Wollogorang Formation/Gold Creek Volcanics succession by a regressive lag deposit (Warramana Sandstone conglomerate facies), and comprises a vertical progression from nearshore (Warramana Sandstone) to braided fluvial depositional environments (Nyanantu Formation) with intervening subaerial felsic volcanism (Tanumbirini Rhyolite).

The upper Tawallah Group package was disconformably overlain by the basal unit of the McArthur Group (Masterton Sandstone) during a period of relaxation that preceded regional suppression of relief and deposition of the carbonate-dominated McArthur Group sequences. In the Batten and Tawallah Ranges, the Masterton Sandstone is separated from the Wununmantyala Sandstone by a disconformity or palaeosol horizon (Appendix 4b). If the upper Tawallah Group stratigraphy was deposited at this locality, the entire package must have been removed by erosion prior to Masterton Sandstone deposition. It is more likely that these regions remained as topographic highs and sites of non- or restricted deposition during middle/upper Tawallah Group sedimentation and intrusive/volcanic activity, which occurred in adjacent, topographically lower areas (Fig. 3.13a). In this model, the Masterton Sandstone was deposited as a clastic blanket that covered the basal Tawallah Group package and Wununmantyala Sandstone in the Batten and Tawallah Ranges, and the upper Tawallah Group package in low relief areas (e.g. Scrutton Range; Fig. 3.13b). Bull (1994) proposed that the Masterton Sandstone accumulated in a proximal alluvial fan system that graded to sandy braidplain settings distally. Palaeocurrent patterns in the basal McArthur Group formation are similar to those measured from the underlying Wununmantyala Sandstone, indicating that the Masterton Sandstone alluvial fan/braidplain system was also shed from N-S elongated topographic highs in the Batten and Tawallah Ranges (Bull, 1994).
Fig. 3.13 Generalised depositional architecture of the upper Tawallah Group package and basal McArthur Group (Masterton Sandstone) in the study region. a) Following syn-sedimentary intrusion of the Gold Creek Volcanics (coeval with the Wollogorang Formation sandstone facies association), deposition of the Warramana Sandstone in a shallow subaqueous setting (actual position of palaeo-shoreline unknown). b) Deposition of the basal Masterton Sandstone alluvial fan and braidplain succession above the Wununmantyala Sandstone (Batten and Tawallah Ranges) and upper Tawallah Group package (Scrutton Range).
Regional setting

Haines et al. (1993) proposed that Tanumbirini Rhyolite emplacement and the local accumulations of fluvial/alluvial Nyanantu Formation facies associations marked the onset and consequences of tectonic uplift respectively. However, it is not necessary to invoke tectonic uplift in order to produce the volume of lithic-rich Nyanantu Formation deposits exposed in the Scrutton Range. These deposits could be accounted for by normal erosive processes operating on a subaerial Tanumbirini Rhyolite dome complex (Cas and Wright, 1987). Furthermore, the period of regression that is interpreted to have initiated in the upper Wollogorang Formation (upper sandstone facies) was not controlled by abrupt tectonic or fault-controlled uplift (ie. compressional deformation; Chapter 6). The basin must have retained an extensional geometry throughout this entire period of regression to allow high-level intrusion and extrusive emplacement of mafic and felsic magmas (Cas and Wright, 1987). In within-plate tectonic settings, elevation of the ambient geothermal gradient has been proposed as a viable mechanism for crustal uplift (Vagnes and Amundsen, 1993). Heat advection associated with small-scale-mantle convection at the lithosphere-asthenosphere boundary has been interpreted to result in up to 1 km of crustal uplift (Vogt, 1991). Crustal uplift may also be facilitated by associated asthenospheric decompression melting and the consequent addition of mafic material to the crust by underplating or intrusion (Rainbird, 1993). White and McKenzie (1989) suggested that a 200°C elevation of the ambient asthenospheric temperature, and the associated increase in the volume of mafic material added to the crust, will reduce the amount of crustal subsidence from 2.5 km to only 0.5 km, or result in crustal uplift. The emplacement of mafic volcanics during the mid/upper Tawallah Group regression, and their within-plate tholeiitic geochemistry (Rawlings et al., 1993; Chapter 4), is consistent with a 'thermal elevation' model for uplift.

3.16 SUMMARY

Cycles of sedimentary deposition and igneous activity in the Palaeoproterozoic Tawallah Group provide important insights into the tectonic evolution of the southern McArthur Basin. Major changes in the basin architecture and palaeo-environmental conditions resulted in three main depositional packages occurring in the Tawallah Group.

The basal Tawallah Group package was formed during a period of continental extension and subsidence in the Late Palaeoproterozoic, with a transgressive transition from alluvial braidplain (Yiyintyi Sandstone and Sly Creek Sandstone) through braid-delta (Rosie Creek Sandstone) to shallow subaqueous (Aquarium Formation)
depositional environments. An episode of widespread and largely subaerial mafic flood volcanism (Seigal Volcanics) occurred prior to Sly Creek Sandstone deposition. The development of low-relief, shallow platform carbonates in the upper Aquarium Formation succession occurred across the entire southern McArthur Basin during a period of regional tectonic quiescence.

The middle Tawallah Group package is interpreted to have formed during a second extension-subsidence depositional cycle and transgressive phase, and incorporates the Wununmantyala Sandstone (braidplain) and Wollogorang Formation (shallow subaqueous). The transition from subaqueous (Aquarium Formation) to subaerial braidplain depositional environments at the base of this package was primarily controlled by intrabasinal tectonic uplift of lower Tawallah Group and Scrutton Volcanics stratigraphy. The structural evidence for, and tectonic implications of the D₁ deformation event are outlined in Chapters 6 and 8 respectively. The Settlement Creek and Gold Creek Volcanics are also included in the middle Tawallah Group package. The Settlement Creek Volcanics intruded lower Wollogorang Formation dolomite and dolomitic siltstone lithologies, whereas the Gold Creek Volcanics were intruded into unconsolidated and water saturated sediments of the upper Wollogorang Formation sandstone facies.

Deposition of the upper Tawallah Group package commenced after another change to subaerial depositional environments, with a regressive transition from nearshore (Warramana Sandstone) to braided river depositional environments (Nyanantu Formation) and local subaerial felsic volcanism (Tanumbirini Rhyolite). The base of this package is separated from the shallow subaqueous Wollogorang Formation/Gold Creek Volcanics succession by a regressive conglomeratic lag deposit. Because evidence for compressional tectonism is lacking, elevation of the ambient geothermal gradient and the addition of mafic material to the crust by underplating and intrusion during extension (Settlement Creek and Gold Creek Volcanics) are tentatively proposed as uplift mechanisms for this regressive transition.

The Masterton Sandstone (basal McArthur Group) disconformably overlies the Tawallah Group at different stratigraphic levels across the study region. This is interpreted to have resulted from the preservation of post-Aquarium Formation uplift in the Batten and Tawallah Ranges. The uplifted regions remained as sites of non- or restricted deposition during post-Wununmantyala Sandstone sedimentation and igneous activity. In this model, the Masterton Sandstone was deposited above the basal Tawallah Group package and Wununmantyala Sandstone in the elevated regions and the upper Tawallah Group package in areas of low relief (Scrutton Range).
Chapter 4 - Volcanic Geochemistry
CHAPTER 4 - Volcanic Geochemistry

4.1 INTRODUCTION

As discussed in previous chapters, the Tawallah Group has been interpreted to have formed during a period of intracontinental rifting in the Late Palaeoproterozoic of Northern Australia. Consequently, the primary geochemical characteristics of igneous units within the Tawallah Group have the potential to provide useful insights into mantle processes that occurred during early basin development. In the study region, the Tawallah Group contains four distinct igneous formations; the Seigal Volcanics, Settlement Creek Volcanics, Gold Creek Volcanics and Tanumbirini Rhyolite. The principle aims of this chapter are to constrain the geochemical traits of the Tawallah Group igneous rocks, to determine their magmatic affinities and to establish a likely tectonic setting for the suite.

4.2 PETROGRAPHY

4.2.1 Seigal Volcanics

Seigal Volcanics samples have phenocryst assemblages comprising olivine, clinopyroxene (augite) and coarse-grained plagioclase laths, and typically have fine- to medium-grained subophitic textures (Plate 4.1a). Anhedral olivine (< 1.5 mm) constitutes approximately 70% of the phenocryst assemblage, with rare subhedral and euhedral crystals characterised by hexagonal morphologies (Plate 4.1b). Olivine phenocrysts are typically colourless in plane polarised light, medium to highly birefringent, moderate to high relief and contain irregular and discontinuous parallel fractures (Plate 4.1c). Anhedral augite (< 1.3 mm) comprises 30 to 35% of the phenocryst assemblage, and is distinguished from olivine by lower birefringence, faint pink to blue pleochroism, well-developed cleavage planes and inclined extinction angles (Plate 4.1d).

Phenocrysts comprise approximately 10 to 20% of the total rock volume, and occur within a fine-grained plagioclase (65%), olivine (10%), augite (10%) and oxide (< 5%) groundmass. Subophitic textural domains occur where the fine-grained plagioclase laths are partially embedded or have completely dissected olivine and augite phenocrysts. Abundant olivine and clinopyroxene microphenocrysts are present in the groundmass, and are generally altered to hematite and goethite (Plate 4.1e). Oxide
Plate 4.1 Petrographic features of the Seigal Volcanics.

a) Photomicrograph of subophitic texture in the Seigal Volcanics, with plagioclase crystals partially embedded in augite and olivine phenocrysts (crossed polars; sample 94-924).

b) Photomicrograph of euhedral olivine phenocrysts contained in a plagioclase and cryptocrystalline (hematitic) groundmass. Olivine phenocrysts have been replaced by hematite along crystal margins and intergranular fractures (plain light; sample 93-15).

c) Photomicrograph of a subhedral olivine phenocryst contained in a plagioclase and cryptocrystalline groundmass (crossed polars; sample 94-924).

d) Photomicrograph of a subhedral augite phenocryst and part of an olivine phenocryst (at the bottom of the field) in a plagioclase and cryptocrystalline groundmass (crossed polars; sample 94-924).

e) Photomicrograph of characteristic subhedral olivine (ol) and augite (aug), euhedral plagioclase (pl), magnetite (m) and cryptocrystalline material in the groundmass of Seigal Volcanics samples (crossed polars; sample 94-924).
phases in the groundmass include subhedral magnetite, hematite and rare acicular ilmenite.

Plagioclase, augite and olivine phenocrysts or groundmass have been partially altered along cleavage or fracture planes, or completely replaced by sericite, dolomite, chlorite, hematite or (minor) quartz. Plagioclase phenocrysts appear to have been more susceptible to sericite or dolomite alteration, whereas hematite preferentially replaced olivine along crystal margins and internal fractures. Amygdules in the Seigal Volcanics are ubiquitous, and have typically been filled by chalcedony, chlorite and quartz; celadonite, dolomite, feldspar and sericite occur locally.

4.2.2 Settlement Creek Volcanics

Samples of the Settlement Creek Volcanics selected for whole rock chemical analyses (section 4.3) have medium- to coarse-grained, subophitic, intergranular or porphyritic textures (Plate 4.2a and b). Cryptocrystalline and microcrystalline textures have also been described by Rawlings et al. (1993). The Settlement Creek Volcanics have a mineralogy typified by 60 to 70 % plagioclase, 10 to 20 % clinopyroxene (augite), 5 to 10 % olivine and 1 to 5 % magnetite. Subophitic and intergranular samples are generally coarse-grained (> 3 mm) and holocrystalline, containing abundant sub- to euhedral, elongate plagioclase crystals with minor (< 20 %) anhedral augite and magnetite (Plate 4.2c). Augite crystals in the coarse-grained samples are characterised by low birefringence (1st order interference colours), inclined extinction angles and highly fractured to disaggregated crystal morphologies. Plagioclase phenocrysts are abundant in porphyritic samples, with lesser fine-grained (< 0.1 mm diameter) clinopyroxene (? augite), olivine and magnetite microphenocrysts contained within a groundmass of lath-shaped and sericitised plagioclase, interstitial magnetite and cryptocrystalline material.

The dolerites of the Settlement Creek Volcanics have undergone secondary alteration. Alteration assemblages consist primarily of interstitial chlorite and sericite, the latter predominantly replacing plagioclase, with minor quartz, dolomite, K-feldspar and hematite (Plate 4.2d). This assemblage is similar to the chlorite-orthoclase alteration style described from the Settlement Creek Volcanics at Mallapunyah Dome by Cooke et al. (1995), and is interpreted to have been produced during genesis of the surrounding sedimentary sequences. Olivine and clinopyroxene crystals are partially altered to illite and hematite in more weathered samples. Rare amorphous rutile occurs in association with chlorite. Ilmenite occurs as primary exsolution lamellae in magnetite. Secondary pyrite and chalcopyrite occur as disseminations, in microfractures and along plagioclase cleavage planes (Plate 4.2e and f). Rare amygdules in the
Plate 4.2 Petrographic features of the Settlement Creek Volcanics.

a) Photomicrograph of intergranular to subophitic textures in the Settlement Creek Volcanics, with plagioclase, partially embedded in anhedral augite, and magnetite crystals occurring in a chlorite-sericite groundmass (crossed polars; sample 93-71).

b) Photomicrograph of a porphyritic Settlement Creek Volcanics sample, with large plagioclase crystals occurring in a plagioclase, magnetite and chlorite-sericite groundmass (crossed polars; sample 94-100).

c) Photomicrograph of an intergranular plagioclase in a coarse-grained sample of the Settlement Creek Volcanics (crossed polars; sample 93-88).

d) Photomicrograph of plagioclase and magnetite crystals in a typical chlorite-sericite groundmass (pale green; plain light; sample 93-88).

e) and f) Crossed polars and reflected light photomicrographs of secondary chalcopyrite occurring along plagioclase cleavage planes in the Settlement Creek Volcanics (sample 93-71).

g) Photomicrograph of acicular pumpellyite (dark green) occurring in the groundmass and adjacent to a large magnetite crystal (crossed polars; sample 93-71).
porphyritic Settlement Creek Volcanics samples contain quartz, dolomite, chlorite, celadonite or chalcedony.

Rare intergranular pumpellyite may have replaced a pre-existing glassy groundmass (Plate 4.2g). Low grade burial metamorphism of mafic rocks containing fine-grained or glassy material generally results in the formation of zeolite or prehnite-pumpellyite facies mineral assemblages (1 to 5 km burial depth; Ehlers and Blatt, 1982). Consequently, pumpellyite and some of the abundant chlorite in Settlement Creek Volcanics samples are interpreted to have formed where fine-grained or glassy phases became unstable during burial and diagenesis.

4.2.3 Gold Creek Volcanics

Gold Creek Volcanic samples selected for XRF analysis have similar mineral assemblages to the Settlement Creek Volcanics, although they are characterised by finer-grained, micro- to cryptocrystalline or porphyritic textures (Plate 4.3a). Subophitic and intergranular textures have also been described for the Gold Creek Volcanics (Rawlings et al., 1993). Microphenocryst assemblages (average crystal size < 0.2 cm) typically comprise anhedral to subhedral clinopyroxene (augite; 60%), anhedral to subhedral olivine (30%) and elongate euhedral plagioclase (< 5%) with minor oxides (< 5%; Plate 4.3b). Partial replacement of microphenocrysts by hematite occurs along crystal margins and internal fractures. Porphyritic samples contain abundant, partially sericitised plagioclase phenocrysts in a fine-grained groundmass of aligned plagioclase laths, oxides, rare augite and cryptocrystalline material (Plate 4.3c). Aligned plagioclase phenocrysts and crystals in the groundmass and stretched amygdules define laminar flow textures for porphyritic Gold Creek Volcanics samples, similar to those described by Cas and Wright (1987).

Amygdalas are generally filled with dolomite, chlorite, polycrystalline quartz, radiating bladed quartz or chalcedony. Radiating quartz crystals occur where irregular quartz veins intersect the margins of chalcedony-filled amygdules (Plate 4.3d). Chlorite-sericite-dolomite-hematite is the most common alteration assemblage, and is similar to the chlorite-orthoclase alteration style described from the Settlement Creek Volcanics by Cooke et al. (1995). Secondary disseminated pyrite and chalcopyrite occurs locally in the groundmass.

4.2.4 Tanumbirini Rhyolite

Tanumbirini Rhyolite samples collected for whole rock geochemical analyses have porphyritic textures, with abundant coarse-grained quartz phenocrysts (< 15 mm diameter) set in a fine- to medium-grained micropoikilitic quartz groundmass (Plate
Plate 4.3 Petrographic features of the Gold Creek Volcanics and Tanumbirini Rhyolite.

a) Photomicrograph of fine-grained dolerite from the Gold Creek Volcanics (crossed polars; sample 94-37).

b) Photomicrograph of olivine (ol) and augite (aug) phenocrysts occurring in a fine-grained plagioclase and magnetite groundmass (plain light; sample 94-34).

c) Photomicrograph of a porphyritic Gold Creek Volcanics sample, with large plagioclase phenocrysts contained in a fine-grained plagioclase and magnetite groundmass (plain light; sample 94-42).

d) Photomicrograph of radiating quartz crystals formed where a cross-cutting vein had intersected the margins of a chalcedony-filled amygdale (crossed polars; sample 94-34).

e) Photomicrograph of medium-grained micropoikilitic quartz groundmass in the Tanumbirini Rhyolite (crossed polars; sample 93-112).

f) Photomicrograph of irregular quartz phenocryst margin and sericite occurring in the interstices between micropoikilitic quartz crystals in the groundmass (crossed polars; sample 93-121).

g) Photomicrograph of plagioclase laths (arrows) wholly embedded in micropoikilitic quartz crystals in the groundmass (crossed polars; sample 93-121).
4.3e). Lithic fragments, predominantly chert and ferruginous material, typically comprise less than 5% of the total rock volume. The margins of quartz phenocrysts and crystals in the groundmass are typically irregular, with sericite occurring in the interstices between crystals (Plate 4.3f). Randomly orientated feldspar laths are wholly included within some quartz crystals (Plate 4.3g). The micropoikilitic texture of Tanumbirini Rhyolite samples can be attributed to the initial devitrification of a slowly cooling silicic lava (McPhie et al., 1993).

4.3 WHOLE ROCK GEOCHEMISTRY

4.3.1 Sampling and analytical methods

Representative samples of the Settlement Creek Volcanics, Gold Creek Volcanics and Tanumbirini Rhyolite were collected from surface exposures in the Scrutton Range for major and trace element analysis. For comparative purposes, an additional three Settlement Creek Volcanics samples were collected from BHP drillhole GSD2, located within the Emu Fault Zone on Kiana Station (Appendix 1c). Due to the intensely weathered nature of the Seigal Volcanics in the study region, drillcore samples of the formation from the CRAE Namalangi uranium deposit (Appendix 1c) were analysed in this study to obtain a complete geochemical database for the Tawallah Group igneous suite. The Namalangi uranium deposit is situated approximately 250 km southeast of the study region (Appendix 1c). However, the geochemical composition of the Seigal Volcanics at the deposit is similar to samples analysed from regions adjacent to the study area (e.g. BAUHINIA DOWNS; Pietsch et al., 1991; MOUNT YOUNG; Haines et al., 1993). The samples collected from the Namalangi uranium deposit are therefore considered suitable for a discussion of the geochemical characteristics of the Seigal Volcanics.

One kilogram representative samples of the Seigal Volcanics (n=3), Settlement Creek Volcanics (n=13), Gold Creek Volcanics (n=10) and Tanumbirini Rhyolite (n=5) were crushed with a steel jaw crusher, split and pulverised using a tungsten-carbide disc mill. Major and trace elements were analysed on a Phillips XRF spectrometer at the University of Tasmania, following the methods of Norrish and Hutton (1969; Table 4.1). To assess analytical precision, one inhouse rock standard per six samples was analysed. Loss on ignition was estimated by heating each sample to 1000°C for 16 hours and measuring the change in mass. Three samples from each formation and two inhouse rock standards were analysed for rare earth elements using the ionic exchange-XRF analytical procedure of Robinson et al. (1986). Ta, Hf and Th were determined by instrumental neutron activation analysis at Becquerel Laboratories, Lucas Heights, New South Wales. Samples analysed for Ta, Hf and Th were pulverised separately using a
### Table 4.4: Wholerocks of selected samples from the Solielan Volcanics (Ps), Sedimenti Creek Volcanics (Pg), Gold Creek Volcanics (Psg) and Tumwater Rhyolite (Ptc).

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Trace element concentrations in ppm. Fe₂O₃ = total Fe as Fe₂O₃.
ceramic disc mill to avoid Ta contamination from the tungsten-carbide mill. Whole rock analyses of the Tawallah Group igneous formations from Pietsch et al. (1991) and Haines et al. (1993) are included for comparative purposes.

### 4.3.2 Alteration and element mobility

Rocks that have undergone hydrothermal alteration or metamorphism are likely to have experienced variable element mobility (Rollinson, 1993). The igneous rocks of the Tawallah Group have been subject to prehnite-pumpellyite facies metamorphic conditions during burial and diagenesis and regional hydrothermal alteration. Alteration of the mafic Tawallah Group formations is characterised by a regional, texturally destructive and pervasive potassic alteration (orthoclase + quartz ± sericite ± hematite ± dolomite ± anatase ± barite), with texturally non-destructive, selectively pervasive chlorite-orthoclase alteration occurring locally (chlorite - orthoclase - quartz ± dolomite ± sericite ± actinolite ± albite ± anatase; Cooke et al., 1995).

Based on relative mass balance calculations, Cooke et al. (1995) proposed that potassic alteration of the Settlement Creek Volcanics was accompanied by K, Si, Rb and Nd enrichment, and depletion of Na, Ca, Mg, ΣFe, Cu, Pb and Zn relative to least altered (chlorite-orthoclase) samples. The widespread potassic alteration event has been interpreted to represent a regional metasomatic event, related to intrusion of potassic-ultrapotassic plutons at depth (Pietsch et al., 1991). However, an early diagenetic timing for potassic alteration of the Settlement Creek and Gold Creek Volcanics at Mallapunyah Dome is favoured by Cooke et al. (1995). In the diagenetic model, potassic alteration of the volcanics is interpreted to have resulted from the introduction and interaction of low temperature, oxidised and saline basinal brines from nearby evaporitic sediments during early burial.

Regardless of the mechanism responsible for the alteration, high field strength elements (REE, Y, Th, Zr, Hf, Ti, Nb, Ta and P) generally remain immobile in basaltic rocks under low grade alteration and/or metamorphic conditions (up to mid-amphibolite facies; Floyd and Winchester, 1975; Crawford and von Rad, 1994; Rollinson, 1993). A simple check for element mobility is to compare high field strength elements on binary variation diagrams (Stolz, 1992). Element immobility during alteration or metamorphism can then be recognised as data that plots on a linear trend that passes through the origin. Zr variation diagrams (Fig. 4.1) for the samples listed in Table 4.1 illustrate that all high field strength elements have remained immobile and therefore, have retained igneous trends and correlations. Y displays minor deviations from a true linear trend (Fig. 4.1), suggesting that it was locally mobile at some localities.
Fig. 4.1 Variation diagrams showing major and trace element distribution within the Tawallah Group igneous formations. Selected tholeiitic basalts and andesites of the Paraná CFB province after Bellieni et al. (1984), Fodor et al. (1983) and Fodor and Vetter (1984).
Fig. 4.1 (cont.)
4.3.3 Major and trace element compositions

The primary aims of the following section are to classify the Tawallah Group igneous units, and to identify the original tectonic environment of the suite using high field strength element abundances. Two classification schemes have been used in this study: the alkaline/tholeiitic discrimination diagrams of Winchester and Floyd (1976; Fig. 4.2) and the general classification diagram of Winchester and Floyd (1977; Fig. 4.3). The tectono-magmatic discrimination diagrams of Pearce and Norry (1979) and Meschede (1986) are used to assess the affiliation of the Tawallah Group igneous units with respect to modern plate tectonic settings (Fig. 4.4).

**Seigal Volcanics**

Major and trace element abundances are consistent with a basaltic composition for the Seigal Volcanics, which contain between 49.6 and 55.6 wt. % SiO₂ (Table 4.1). Relative to the younger mafic formations, the Seigal Volcanics have low abundances of TiO₂ (1.10-1.44 wt. %), P₂O₅ (0.10-0.16 wt. %), Nb (7-11 ppm), Zr (112-155 ppm) and Y (22-29 ppm). Relatively low Mg numbers (~43) suggest that the basalts are moderately evolved.

High Y/Nb (1.9-3.3) and Zr/P₂O₅ ratios (0.07-0.12) are consistent with a tholeiitic affinity for the Seigal Volcanics (Fig. 4.2), which plot as sub-alkaline basalts or andesite/basalt on the least-mobile element variation diagram (Zr/TiO₂-Nb/Y; Fig. 4.3). The Seigal Volcanics mostly plot in the within-plate basalt fields on tectonic discrimination diagrams that are based on Ti-Y-Nb-Zr abundances, with the few exceptions plotting transitional to the mid-ocean ridge basalt field (Fig. 4.4).

**Settlement Creek Volcanics**

Analysed Settlement Creek Volcanics samples are basaltic in composition. The more evolved samples contain elevated silica compositions, so that SiO₂ abundances range between 48.8 and 60.1 wt. %. Haines *et al.* (1993) suggested that some SiO₂ enrichment may be related to post-compactional metasomatism rather than true magmatic fractionation.

In contrast to the Seigal Volcanics, the Settlement Creek Volcanics have higher immobile element concentrations. TiO₂ (2.18-2.89 wt. %), P₂O₅ (0.40-0.65 wt. %), Nb (9-13 ppm), Zr (161-201 ppm) and Y (34-43) are enriched by a factor of approximately two relative to the older mafic sequence. Y/Nb (2.0-3.3) and Zr/P₂O₅ ratios (0.04-0.05) are indicative of a tholeiitic affinity (Fig. 4.2), although low Zr/P₂O₅ values have resulted in more alkaline compositions than the Seigal Volcanics, particularly with
Fig. 4.2a TiO₂ versus Zr/P₂O₅; 4.2b TiO₂ versus Y/Nb; and 4.2c Nb/Y versus Zr/P₂O₅ (Winchester and Floyd, 1976) for the Seigal Volcanics (circles), Settlement Creek Volcanics (squares) and the Gold Creek Volcanics (diamonds). Samples shown are exclusively mafic to intermediate in composition.
Fig. 4.3 Plot of Zr/TiO$_2$ versus Nb/Y (Winchester and Floyd, 1977) for analysed samples of the Tawallah Group igneous formations.

Fig. 4.4 Trace element discrimination diagrams for basalts. 4.4a Zr/Y versus Zr (Pearce and Norry, 1979) showing fields of volcanic arc basalts (A), MORB (B), within-plate basalts (C), MORB and volcanic-arc basalts (D) and MORB and within-plate basalts (E). 4.4b Zr-Nb-Y (Meschede, 1986) showing fields of within-plate alkali basalts (A-1), within-plate alkali basalts and within-plate tholeiites (A-2), E-type MORB (B), within-plate tholeiites and volcanic arc basalts (C) and N-MORB and volcanic-arc basalts (D).
respect to TiO$_2$. The more alkaline nature of the Settlement Creek Volcanics is also shown by the Zr/TiO$_2$-Nb/Y variation diagram (Fig. 4.3), where most samples plot in the sub-alkaline basalt field. The generally lower Mg numbers (≈ 36) are consistent with the Settlement Creek Volcanics being more evolved than the Seigal Volcanics. Relative abundances of Ti-Y-Nb-Zr define a within-plate setting for the Settlement Creek Volcanics (Fig. 4.4).

**Gold Creek Volcanics**

The Gold Creek Volcanics are generally basaltic in composition, with SiO$_2$ contents between 47.3 and 51.1 wt. % (Table 4.1). Based on immobile major and trace element abundances, two distinct groups have been recognised in the Gold Creek Volcanics. The groups can be also discriminated on their relative stratigraphic position in the Gold Creek Volcanics succession. Lower dolerites (group I) are moderately evolved (Mg number; 31-45), and have lower TiO$_2$ (2.29-2.43 wt. %), P$_2$O$_5$ (0.29-0.32 wt. %), Nb (17-20 ppm), Zr (172-194 ppm) and Y (30-33 ppm) concentrations relative to group II dolerites. Upper dolerites (group II) are highly evolved (Mg number; 23-32), with compositions characterised by increased concentrations of TiO$_2$ (2.80-2.86 wt. %), P$_2$O$_5$ (0.43-0.45 wt. %), Nb (26-27 ppm), Zr (266-271 ppm) and Y (45-46 ppm). Linear data trends on immobile element variation diagrams (Fig. 4.1) are consistent with these compositional differences resulting from variable degrees of fractionation. Group I dolerites have high abundances of Cr (312-355 ppm) and Ni (208-252 ppm) compared with other evolved igneous units of the Tawallah Group. Although the Cr- and Ni-enriched group I samples are similar compositionally to the Seigal Volcanics, their high TiO$_2$ and P$_2$O$_5$ contents suggest a closer relationship to the Settlement Creek Volcanics in terms of the overall genesis of the Tawallah Group igneous rocks.

The Gold Creek Volcanics can be classified as tholeiitic dolerites, based on their Y/Nb and Zr/P$_2$O$_5$ relationships (Fig. 4.2). Nb/Y values are higher than the Seigal Volcanics and Settlement Creek Volcanics samples, so that the Gold Creek Volcanics plot within the subalkaline basalt field of Figure 4.3. High Nb/Y ratios, in association with high Ti and Zr values, result in the Gold Creek Volcanics samples plotting almost completely in the within-plate basalt fields on the tectonic discrimination diagrams shown in Figure 4.4.

**Tanumbirini Rhyolite**

The Tanumbirini Rhyolite is characterised by high concentrations of SiO$_2$ (75.3-81.0 wt. %), Zr (385-414 ppm), La (77-94 ppm), Ce (146-165 ppm), U (3.6-5.7 ppm) and Th (40.1-42.4 ppm) with low K$_2$O (0.19-0.30 wt. %), Na$_2$O (0.03-0.33 wt. %)
and Rb (3-5 ppm). All samples plot within the rhyolite field on the Zr/TiO$_2$-Nb/Y variation diagram (Fig. 4.3). The predominance of quartz, and lack of K-feldspar, has resulted in unusually low alkali contents for Tanumbirini Rhyolite samples. The analysed samples do not have primary igneous compositions due to the effects of alteration (addition of quartz and alteration of K-feldspar to sericite) and surface weathering. In terms of immobile element concentrations however, the Tanumbirini Rhyolite is typical of Proterozoic felsic volcanic suites of similar age from elsewhere in Australia (Wyborn et al., 1987).

4.3.4 Variation Diagrams

Comparisons of elemental variation in the igneous formations of the Tawallah Group are shown on Figure 4.1. SiO$_2$, MgO or FeO*/MgO, which are usually selected as differentiation indicators, were likely to have been mobile during low grade alteration of the Tawallah Group igneous suite (section 4.3.2); consequently, an alternative must be used. Zr has remained immobile in the Tawallah Group igneous formations analysed in this study (section 4.3.2), has the greatest concentration range of all high field strength elements, and is incompatible over most of the basalt-andesite composition range. It has therefore been used as a fractionation index for the Tawallah Group igneous formations in Figure 4.1. For comparative purposes, selected tholeiitic basalts and andesites from the Parana continental flood basalt (CFB) province of Brazil are also shown on Figure 4.1.

The Seigal Volcanics, Settlement Creek Volcanics and Gold Creek Volcanics analyses plot as separate, well-defined fractionation trends, characterised by enrichment of TiO$_2$, P$_2$O$_5$, Y, Nb and La with increasing Zr. The enrichment patterns shown on Figure 4.1 are typical of tholeiitic suites, where olivine, clinopyroxene and plagioclase phenocryst assemblages are formed during low pressure crystal fractionation of MgO-rich picritic parental magmas (Cox, 1980; Crawford and Hilyard, 1990). However, because the trends for each suite are mutually exclusive, the Tawallah Group igneous units probably did not originate by progressive fractionation of a common parental magma, or partial melting of a homogeneous source.

Distinct compositional fields can be defined for the different igneous formations of the Tawallah Group on Figure 4.1. For a given Zr concentration, the Seigal Volcanics are markedly depleted in TiO$_2$, P$_2$O$_5$, Y and La, and enriched in Nb relative to the Settlement Creek Volcanics. Although the Gold Creek Volcanics have similar TiO$_2$ and La contents to the Settlement Creek Volcanics, they are enriched in Nb depleted in P$_2$O$_5$ and Y for a given Zr value. Because the different mafic formations can be distinguished geochemically, XRF analysis may assist identification in areas where exact stratigraphic position is poorly constrained.
The Tawallah Group data fall within the compositional fields defined by, and show similar fractionation trends to, the tholeiitic basalts and andesites of the Lower Cretaceous Paraná CFB province. The Paraná tholeiites were erupted during early continental rifting that preceded true oceanic (N-type MORB) magmatism associated with the opening of the South Atlantic Ocean (Bellieni et al., 1984; Fodor and Vetter, 1984; Fodor et al., 1985). Two geochemically and isotopically distinct groups have been recognised in the Paraná CFB province; those with high $P_2O_5$ and TiO$_2$ (HPT) and those with low $P_2O_5$ and TiO$_2$ (LPT; Bellieni et al., 1984; Mantovani et al., 1985; Fodor, 1987). HPT and LPT tholeiitic basalt groups have been recognised in many CFB provinces, including the Karoo province (Duncan, 1987), Etendeka province of Namibia (Marsh, 1987) and the Kirkpatrick basalts of Antarctica (Siders and Elliot, 1985). At Paraná, the groups are geographically distributed such that HPT tholeiites occur in the northern half of the province, with LPT tholeiites in the south. The processes responsible for the compositional distribution are the subject of some controversy. Whereas Bellieni et al. (1983) and Mantovani et al. (1985) favour mantle source heterogeneities to generate the HPT and LPT tholeiites, Fodor (1987) describes a model that involves a common mantle source but varying degrees of partial melting and crustal assimilation, related to proximity of a mantle hotspot.

The Seigal Volcanics have many compositional similarities to the Paraná LPT tholeiites (Fig. 4.1). The Settlement Creek and Gold Creek Volcanics display significantly higher TiO$_2$ and $P_2O_5$ abundances than the Seigal Volcanics, although not as elevated as the Paraná HPT tholeiites (Fig. 4.1). The distinction between HPT and LPT tholeiites in the Tawallah Group is therefore temporal rather than geographical, in contrast to the Paraná CFB province. The processes responsible for this compositional variation are discussed in Section 4.4.

4.3.5 Rare Earth Elements

Thompson et al. (1984) proposed that the majority of continental flood basalts have compositions consistent with derivation from an ocean island basalt (OIB) source mantle. They also claimed that it is rare for primary, unmodified mantle-derived magmas (N-MORB) to erupt through continental crust. Figure 4.5 shows chondrite-normalised rare earth element (REE) patterns for analysed Tawallah Group mafic rocks compared with average MORB and OIB. In all cases, the Tawallah Group tholeiites are light-REE enriched compared with average N-MORB, but have close similarities to the pattern defined by typical OIB. A slight but significant negative Eu anomaly occurs for all analysed samples, suggesting that either the parental magmas had assimilated crustal material during ascent, or that plagioclase was removed from the melt by crystal
Fig. 4.5 Chondrite-normalised REE diagrams for the: 4.5a Seigal Volcanics; 4.5b Settlement Creek Volcanics; and 4.5c Gold Creek Volcanics compared to average OIB and N-MORB. Normalisation factors, average OIB and average N-MORB from Sun and McDonough (1989).
fractionation (Rollinson, 1993). The majority of Paraná tholeiitic basalts and andesites also have REE patterns typified by negative Eu anomalies (Mantovani et al., 1985).

A comparison of REE patterns for the Tawallah Group mafic formations reveals that the degree of light-REE enrichment progressively increases up stratigraphy. The Seigal Volcanics have moderate light-REE enrichment (La/YbN = 4; La/Yb normalised to chondrite values of Sun and McDonough, 1989) whereas the Settlement Creek Volcanics (La/YbN = 6.6) and Gold Creek Volcanics (La/YbN = 6.7) are both light-REE enriched relative to average N-MORB (Fig. 4.5). The temporal change from flat to inclined heavy-REE patterns in the Tawallah Group mafic suite (Fig. 4.5) is consistent with derivation by progressively lower degrees of partial melting of a mantle source region. Alternatively, a deeper, more enriched mantle source may have become involved during the latter stages of Tawallah Group magma generation.

4.3.6 Multi-Element Variation Diagrams

Normalised multi-element variation diagrams are a useful tool for depicting basalt geochemistry and measuring element deviations from primitive compositions. Multi-element variation diagrams normalised to N-MORB are most appropriately used for evolved basalts and andesites (Rollinson, 1993). The multi-element variation patterns for least-altered (< 4 wt. % K2O) basalts and dolerites from the Tawallah Group mafic suite are shown on Figure 4.6. The order of elements on Figure 4.6 is taken from Crawford and von Rad (1994).

An important feature of the multi-element variation patterns for Tawallah Group mafic formations is the marked negative Nb-Ta anomaly (Fig. 4.6). In general, a pronounced trough at Nb-Ta is one of the diagnostic features of island arc lavas and destructive plate margin (subduction) tectonic settings (Gill, 1981; Woodhead et al., 1993; Hawkesworth et al., 1994). However, the mafic formations of the Tawallah Group have Ti-Y-Nb-Zr relationships typical of a within-plate tectonic setting (section 4.3.2). Thompson et al. (1983) noted that many CFB multi-element variation patterns display a distinct trough at Nb-Ta, and that this feature contrasts with the characteristic Nb-Ta peaks observed for continental and oceanic intra-plate alkali basalts. The origin of the Nb-Ta trough in CFB multi-element variation patterns is widely disputed. Wood (1980) suggested that it results from the incorporation of a recycled crustal component to produce 'arc-type' source signatures. Thompson et al. (1984) proposed an alternative model involving the equilibration of mantle-derived magmas within deep continental crust. Regardless of its origin, the presence of a Nb-Ta trough in the multi-element variation diagrams shown on Figure 4.6 is still consistent with an intra-plate CFB affinity for the Tawallah Group mafic formations. This interpretation is considered to be more appropriate than a supra-subduction zone setting, for which this signature is
Fig. 4.6 N-MORB-normalised multi-element variation diagrams for analysed basalts and dolerites of the: 4.6a Seigal Volcanics, 4.6b Settlement Creek Volcanics and 4.6c Gold Creek Volcanics. 4.6d shows a comparison between the Seigal Volcs. (circles), Settlement Ck. Volcs. (squares), Gold Ck. Volcs. (diamonds), Paraná LPT tholeites (dark shading) and Paraná HPT tholeites (light shading). Normalisation factors from Sun and McDonough (1989), Paraná tholeite fields after Fodor and Vetter (1984).
typical, but where the associated volcanics have < 1 % TiO₂ (Gill, 1981). A CFB affinity for the Tawallah Group mafic formations is also favoured over a continental rift-zone setting, where alkalic volcanism is more characteristic (Wilson, 1989).

Figure 4.6d compares the variation patterns determined for each mafic formation, and as for the REE patterns, indicates a general trend towards more evolved magmas with time. The multi-element variation patterns for the Tawallah Group mafic units also have negative Sr anomalies (Fig. 4.6). Thompson et al. (1983) attributed this to extensive plagioclase fractionation. However, it is likely that some Sr depletion was associated with potassic alteration of the Tawallah Group mafic suite. Cooke et al. (1995) suggested that the Settlement Creek Volcanics in the Mallapunyah Dome region experienced substantial Sr depletion during an early diagenetic, pervasive potassic alteration event.

4.4 DISCUSSION: MAGMATIC AFFINITIES

Zr/Nb, Y/Nb and (La/Yb)N ratios have been used to help interpret the source characteristics of mafic and intermediate rocks associated with extensional tectonic settings (Le Roex et al., 1983; Fodor and Vetter, 1984; Crawford and Hilyard, 1990; Crawford and von Rad, 1994). In the classification scheme of Le Roex et al. (1983), basalts with 'depleted' (N-type MORB) characteristics have high Zr/Nb (> 17), Y/Nb (> 8) and low (La/Yb)N (0.9 - 1.2) values, whereas enriched oceanic basalts with 'plume' signatures (P-type MORB) have low Zr/Nb (5.8 - 6.8), Y/Nb (0.9 - 1.2) and high (La/Yb)N (4.8 - 6.9). Basalts that have intermediate compositions between N-type MORB and P-type MORB are termed transitional (T-type MORB). The majority of CFB tholeiites have trace element compositions intermediate between N-type MORB and P-type MORB tholeiites (Crawford and Hilyard, 1990).

Continued attenuation of the continental crust ultimately leads to rupture, and the generation of oceanic crust at an established spreading centre (Crawford and Hilyard, 1990). Basalt trace element geochemistry suggests that this process causes a change from T-type MORB (CFB) towards steady-state N-type MORB volcanism (Fodor and Vetter, 1984). The igneous formations of the Tawallah Group plot within the field defined by Paraná CFB tholeiites, but in contrast to the theoretical models of Fodor and Vetter (1984), show a trend towards more enriched (P-type MORB) source regions with time (Fig. 4.7). The Seigal Volcanics and Settlement Creek Volcanics have Zr/Nb-Y/Nb-(La/Yb)N relationships typical of T-type MORB tholeiites, and the Gold Creek Volcanics plot closer to the P-type MORB field (Fig. 4.7). A combination of two processes can explain the trend towards more enriched compositions in the Tawallah Group mafic suite, and these are discussed in the following sections.
Fig. 4.7 Plots of Zr/Nb versus (a) Zr/Y, (b) Y/Nb and (c) (La/Yb)$_N$ for basalts, basaltic andesites and dolerites of the Tawallah Group and selected tholeiites from the Paraná CFB province (Fodor et al., 1985; Fodor and Vetter, 1984). N-type, T-type and P-type MORB fields after Le Roex et al. (1983). La and Yb normalised to chondrite (Sun and McDonough, 1989).
4.4.1 Partial melting model

The temporal trend towards more enriched compositions correlates with changes in the physical and geochemical characteristics of the Tawallah Group mafic suite. The Seigal Volcanics is interpreted to be a predominantly subaerial flood basalt sequence of large aerial extent (Chapter 3). The formation is approximately 400 m thick in the study region, and attains a maximum thickness of 1600 m near the southern margin of the McArthur Basin (CALVERT HILLS; Haines et al., 1993). Contrastingly, the Settlement Creek Volcanics and Gold Creek Volcanics are markedly thinner mafic successions, with thicknesses of 100 m and 180 m in the study region respectively. Furthermore, the absence of the younger mafic formations at many localities (eg. Batten and Tawallah Ranges), and their largely intrusive nature is interpreted to indicate a more localised distribution than the Seigal Volcanics (Bull, 1994). The Seigal Volcanics is also distinguished from the younger mafic formations of the Tawallah Group by lower TiO₂, P₂O₅ and other incompatible element abundances (in particular Th, Hf, La, Ce, Nd and Nb).

Ce shows the greatest concentration range of the incompatible elements, and is considered to be the most incompatible (immobile) element in the Tawallah Group mafic suite. Consequently, Ce can be used as a measure of relative change in the degree of partial (batch) melting that is required to generate the Tawallah Group mafic suite, assuming hypothetically that no Ce is retained by residual solids (ie. If D_Ce = 0, then C₀/CL = 1/F for the modal melting equation (Clague and Frey, 1982);

\[
\frac{C_L}{C_0} = \frac{1}{D_0 + F(1 - D_0)}
\]

C_L = concentration of trace element in the liquid;
C₀ = initial concentration of trace element in the source rock before partial melting;
F₀ = fraction of melt;
D₀ = initial bulk-solid/liquid partition coefficient.

Over the range of Ce concentrations shown on Figure 4.8, the Settlement Creek Volcanics and Gold Creek Volcanics are respectively enriched in P₂O₅ and La by a factor of 2 and 3 relative to the Seigal Volcanics. To generate the Tawallah Group mafic suite from a single mantle source, the degree of partial melting required to form the Seigal Volcanics is therefore 2 to 3 times greater than the younger mafic formations. Consequently, a model involving successively lower degree partial melting of a single, homogeneous mantle source can be proposed to explain the volumetric decrease of basalt or dolerite and the progressive enrichment of incompatible elements in the Tawallah Group mafic suite. Green and Ringwood (1967) suggested that 20 to 30 % partial melting of a pyrolite source is required to generate a typical subalkaline olivine-
The Seigal Volcanics were derived by 20 to 30% partial melting of the asthenospheric mantle, the enriched compositions of the Settlement Creek Volcanics and Gold Creek Volcanics may have formed by 10-15% and 7-10% partial melting of a similar source respectively.

In oceanic rift settings, magmas are generated by adiabatic decompression melting of upwelling asthenosphere in response to thinning of the overlying oceanic lithosphere (McKenzie and Bickle, 1988). In intracontinental settings, the degree of lithospheric thinning and associated upwelling of the asthenosphere is primarily controlled by the rate of tectonic extension. During rapid extension, the extensional deviatoric stress in the sub-continental lithosphere enhances the propagation of magma-filled tension fractures to the surface, allowing greater penetration of asthenospheric mantle melts (Asmerom et al., 1994). Consequently, the Seigal Volcanics are interpreted to indicate a period of rapid extension in the southern McArthur Basin, and derivation from large volume asthenospheric partial melts (Fig. 4.9a). The Settlement Creek Volcanics and Gold Creek Volcanics were probably derived from lower degree partial melting of a similar asthenospheric source, in response to slower rates of tectonic extension (Fig. 4.9b). Lower degree partial melting will result in the preferential partitioning of incompatible elements into the liquid phase and eruptive/shallow intrusive products with more enriched compositions (Clague and Frey, 1982).

The Tanumbirini Rhyolite is interpreted to have been emplaced during the final stages of Tawallah Group magmatism. Chappell and White (1974) subdivided felsic igneous rocks into those derived from igneous source regions (I-type) and those derived from sedimentary sources (S-type). These terms have been subsequently redefined as infracrustal (I-type) and supracrustal (S-type; Chappell and White, 1992). The latter subdivision infers that S-type felsic rocks were derived from source regions affected by supracrustal processes (e.g. weathering), as opposed to I-type felsic rocks whose sources were not exposed to surficial processes (Wyborn, 1992). Felsic volcanics emplaced during the Late Palaeoproterozoic of Northern Australia are predominantly I-type, and are interpreted to have been sourced from granulitic lower crustal regions (Wyborn et al., 1987). Cox (1980) suggested that deep crustal gabbroic sill complexes underplate continental crust during lithospheric extension and associated emplacement of within-plate flood basalts. The deep gabbroic complexes ultimately become metamorphosed to granulite facies assemblages due to the high geothermal gradients accompanying extension. In Proterozoic Australia, mafic material is thought to have underplated continental crust during recurrent extensional events, resulting in the progressive accretion of I-type source regions (Wyborn et al., 1987). Consequently, the Tanumbirini Rhyolite is interpreted to have been derived from the partial melting of lower crustal (I-type) source regions that were generated during underplating of the older tholeiitic magmas (Fig. 4.9b).
Fig. 4.8 Variation diagrams showing the distribution of incompatible elements in the Tawallah Group mafic formations. The range of Ce abundance indicates that degree of partial melting varies by a factor of < 2.5 to generate the Tawallah Group mafic suite.

Fig. 4.9 Partial melting model for the Tawallah Group mafic suite. Melting results from subcontinental lithospheric thinning and adiabatic decompression of upwelling asthenosphere (McKenzie and Bickle, 1988). 4.9a Rapid tectonic extension results in 20 to 30% partial melting of asthenospheric mantle and the production of large basalt volumes with 'depleted' compositions (Seigal Volcanics). 4.9b Extension occurs at slower rates following tectonic compression (D1), resulting in lower degree partial melting of the asthenospheric mantle (Settlement Creek Volcanics: 10-15%; Gold Creek Volcanics: 7-10%). Small volumes of basalt/dolerite with 'enriched' compositions and I-type granites are produced during this stage.
The change to slower rates of tectonic extension during emplacement of the Settlement Creek Volcanics, Gold Creek Volcanics and Tanumbirini Rhyolite is interpreted to have occurred following the D1 compressional event (Chapter 6). This event postdated eruption of the Seigal Volcanics, predated emplacement of the Settlement Creek Volcanics and Gold Creek Volcanics and was associated with significant intrabasinal uplift in the study region (Chapter 3). D1 compression is interpreted to have terminated the initial stage of Tawallah Group rifting, with tectonic extension occurring more slowly in the subsequent Tawallah rifting phase. Crawford and Hilyard (1990) suggested that continued lithospheric extension ultimately leads to the formation of true oceanic crust with N-MORB type compositions. The absence of volcanics with N-MORB affinities in the southern McArthur Basin can be interpreted to indicate that lithospheric extension did not proceed to this stage. Instead, the eventual cessation of rifting resulted in the deposition of the carbonate- and evaporite-dominated McArthur Group in a non-volcanic, sag-phase tectonic setting.

4.4.2 Mixed source model

Although progressively lower degree partial melting of a homogenous asthenospheric source region explains the general trend towards more enriched compositions in the Tawallah Group mafic suite, it cannot account for the immobile element variation patterns shown on Figure 4.1. Incompatible element enrichment trends and low Zr/Nb values (= 10; Fig. 4.1) for the Seigal Volcanics and Gold Creek Volcanics are consistent with the younger formation being derived from lower degree partial melting of a similar asthenospheric source. The Settlement Creek Volcanics have higher Zr/Nb values (= 20) than the Gold Creek Volcanics, which is consistent with higher degree partial melting, but are enriched in some incompatible elements (eg. P2O5 and LREE). This is inconsistent with a simple partial melting model, and has probably resulted from subtle differences in melting or source characteristics for the Settlement Creek Volcanics. The Settlement Creek Volcanics also differ from the Seigal and Gold Creek Volcanics by having generally more alkaline compositions (Fig. 4.2). A mixed source is suggested for the Settlement Creek Volcanics to account for these differences.

Spera (1987) proposed that the upper mantle has been compositionally heterogeneous for at least 2 Ga, with isotopic studies recognising a lithospheric source component variably enriched in LREE for many continental alkali basalts. A potential mechanism for the transport of asthenospheric magma through the sub-continental lithosphere is the propagation of melt-filled fractures (magma fracture conduit flow), with low ascent rates and small conduit diameters preventing adiabatic ascent (Spera, 1987). Examination of xenoliths and associated inclusions from alkaline mafic lavas has led to an interpretation that enrichment of the sub-continental lithosphere by veining or
metasomatism appears to be a direct consequence of non-adiabatic (asthenospheric) magma ascent (Spera, 1987). As a result of these processes, the sub-continental lithospheric mantle can contain domains that are anomalously enriched in K, Ti, Fe, P, LREE and large-ion lithophile elements (Menzies et al., 1987; Stolz and Davies, 1988).

Enrichment of the upper mantle by veining and/or metasomatic processes during genesis of the Seigal Volcanics is plausible, given the high degrees of partial melting inferred, and the large volumes of basalt that were erupted (Fig. 4.10a). Consequently, sub-continental lithospheric regions enriched in LREE and other incompatible elements are proposed as a possible source component for the Settlement Creek Volcanics. Menzies et al. (1987) suggested that isothermal perturbations associated with asthenospheric upwelling may trigger the production of lithospheric melts, which may in turn mix with ascending asthenospheric magmas. If asthenospheric upwelling accompanied post-D1 extension in the southern McArthur Basin, lithospheric melting may have occurred in the veined or metasomatised regions developed during emplacement of the Seigal Volcanics (Fig. 4.10b). Incompatible element concentrations in the Settlement Creek Volcanics are consistent with lower degree partial melting of an asthenospheric source. However, these asthenospheric melts are interpreted to have mixed with the enriched lithospheric melts during ascent (Fig. 4.10b), resulting in the development of basalts and/or dolerites with anomalously high P2O5, LREE and other incompatible elements relative to the Gold Creek Volcanics. In this model, the Gold Creek Volcanics parental magmas are interpreted to have had little or no interaction with the sub-continental lithosphere, allowing low-degree (7-10 %), asthenospheric partial melts to be erupted. This is to be expected as continued extension and input of asthenospheric melts would tend to chemically homogenise the lithosphere (Menzies et al., 1987).

4.5 SUMMARY

Mafic rock types in the Seigal Volcanics, Settlement Creek Volcanics and Gold Creek Volcanics have sub-alkaline tholeiitic compositions. Ti-Y-Nb-Zr relationships are typical of a within-plate tectonic setting, and immobile element compositions are consistent with the general trends defined by tholeiitic basalts and andesites of the Lower Cretaceous Paraná CFB province. Multi-element variation patterns have a Nb-Ta trough, supporting a CFB affinity for the Tawallah Group mafic formations (Thompson et al., 1983).

Although immobile element variation trends indicate that crystal fractionation was an important process in the evolution of each suite, the four Tawallah Group igneous formations are defined by distinct geochemical compositions. For similarly evolved rock types, the Seigal Volcanics are depleted in TiO2, P2O5, Y and La relative
Fig. 4.10 Mixed source model for the Tawallah Group mafic suite. Asthenospheric occurrence in response to subcontinental lithospheric thinning, upwelling and adiabatic decompression (McKenzie and Bickle, 1988). 4.10a High degree partial melting and the production of large basalt volumes (Seigal Volcanics) resulted in variable enrichment of the sub-continental lithosphere by veining and metasomatic processes. 4.10b Lithospheric melts produced in veined and/or metasomatized regions during post-D1 extension were anomalously enriched in incompatible elements. These mixed with ascending magmas derived from low degree partial melting of the asthenospheric mantle to produce basalts/dolerites enriched in P2O5, LREE and LILE (Settlement Creek Volcanics). Parental magmas of the Gold Creek Volcanics were largely derived from the asthenospheric mantle, with little or no interaction with the sub-continental lithosphere.
to the Settlement Creek and Gold Creek Volcanics. The Gold Creek Volcanics are distinguished from the Settlement Creek Volcanics by enriched Nb and depleted P$_2$O$_5$ and Y abundances.

Zr/Nb, Y/Nb and REE relationships are consistent with the Settlement Creek and Gold Creek Volcanics being derived from more enriched mantle sources than the Seigal Volcanics. This trend contrasts with other CFB provinces, where N-type MORB compositions become increasingly common as rifting progresses and a spreading centre is established (Crawford and von Rad, 1994). A generalised model involving progressively lower degree partial melting of an homogeneous asthenospheric mantle source is proposed to explain the trend towards more enriched compositions in the Tawallah Group mafic suite. However, an additional source component (enriched subcontinental lithosphere) is suggested for the Settlement Creek Volcanics to explain their anomalously high P$_2$O$_5$, LREE and other incompatible element concentrations relative to the Gold Creek Volcanics. Progressively lower degree partial melting is interpreted to have been controlled by a reduction in the rate of tectonic extension following the D$_1$ compressional event.

The Tanumbirini Rhyolite has immobile element compositions comparable to similarly aged felsic volcanic suites elsewhere in Northern Australia. Wyborn et al. (1987) proposed that the Late Palaeoprotrozoic felsic volcanics of the North Australian Craton were derived from lower crustal partial melts associated with the underplating of older tholeiitic magmas. Intracontinental extension in the southern McArthur Basin did not proceed to the stage where new oceanic crust was developed. Instead, failure of rifting is indicated by deposition of the McArthur Group in a non-volcanic, sag phase tectonic environment.
Chapter 5 - Fault Zone Textures
CHAPTER 5 - Fault Zone Textures

5.1 INTRODUCTION

The lack of a penetrative fabric or mesoscopic fold pattern in the Tawallah Group has led previous workers to regard the southern McArthur Basin as a relatively undeformed component of the North Australian Craton (eg. Pietsch et al., 1991; Davidson and Dashlooty, 1993). In the study region however, there is abundant evidence for complex brittle deformation. Under the temperature and pressure conditions typical of upper crustal regions, most constituent materials have an elastic-brittle response to stress. Under these conditions, the primary deformation-accommodating structures are faults, which represent the brittle form of shear strain concentration (Cox and Schultz, 1988). Regions dominated by brittle deformation are therefore characterised by well developed fracture and fault systems. In the study region, surface expressions of first and second order brittle structures are generally defined by narrow zones of cataclastic deformation, wall rock silicification and hydraulic breccia. In this chapter, the distinguishing features of brittle fault zones in the study region are described and the mechanisms controlling their development are discussed. To achieve this, field observations are combined with petrographic examination of fault zone characteristics to delineate the meso- and micro-deformational processes that were operative during deformation.

5.2 FAULT MORPHOLOGY

The structural architecture of the western McArthur River region has resulted from a deformational history that was characterised by complex block-faulting along regional-scale brittle structures. Major fault-zones that have strike-lengths greater than 10 km are hereafter referred to as primary faults. In general, each primary fault in the study region has a cumulative strike-length of up to 200 km. However, orientation and/or kinematic changes along strike separate each primary fault into a series of linked segments that average 30 km in length. Locally, primary fault segments define the margins of individual fault-blocks. The Tawallah Fault separates exposures of the Tawallah Group from McArthur Group in the Batten and Tawallah Ranges (Fig. 5.1). Similar stratigraphic juxtapositions occur across the Lorella and Bauhinia Faults, which bound the western Tawallah Range and eastern Scrutton Range margins respectively (Fig. 5.1).
Fig. 5.1 Simplified geology of the western McArthur River region and southern MOUNT YOUNG. Lower Tawallah Group includes the Yilyinti Sandstone, Seigal Volcanics, Sly Creek Sandstone and Aquarium Formation. Upper Tawallah Group includes the Settlement Creek Volcanics, Wolloogorang Formation, Gold Creek Volcanics, Warramana Sandstone, Tanumirrin Rhyolite and Nyangatju Formation.
Each primary fault segment is characterised by a near-linear surface expression, and is exposed as an irregular zone of localised or concentrated brittle deformation with respect to the surrounding host lithologies. Primary fault zones are typically composed of multiple anastomosing fault strands rather than a single definable trace. Secondary faults are well developed throughout the western McArthur River region, particularly in Tawallah and McArthur Group sandstones, and differ from the primary faults only in scale. They are typically exposed as linear deformation zones that rarely exceed 20 m in width. 'Mature' second order structures are defined by continuous but irregular fault traces and show cumulative strike-lengths that vary between 0.1 and 10 km. 'Immature' secondary faults, although rare, are exposed as zones of en échelon Riedel fractures less than 100 m long (e.g. southern Tawallah Range; Appendix 6). Immature secondary structures are geometrically similar to the simple strike-slip zones described by Martel et al. (1988) and the initial stages of model wrench faults produced in sandbox and clay-cake experiments (Tchalenko, 1970; Naylor et al., 1986).

The absolute width of a fault zone appears to be controlled by the prevailing sense of displacement and attitude of the fault plane (Fig. 5.2). For example, the southern Tawallah Fault segment (Batten Range) records evidence for dextral strike-slip displacement during the final phase of tectonic compression (see Chapter 6), and is defined by a narrow deformation zone (≈ 100 m wide). In the Batten Range region, the Tawallah Fault is steeply inclined (70 - 80°W) and intersects present bedding surfaces at an oblique angle (60 to 80°; Fig. 5.2). The northern Tawallah Fault (Tawallah Range), Bauhinia Fault and southern Lorella Fault segments in contrast, have all preserved evidence for oblique-reverse motion during the final compressional phase (see Chapter 6), and are exposed as relatively wide deformation zones (up to 500 m across). All of these primary faults are steep to moderately dipping (50-80°) and strike approximately parallel to the strike of bedding (Fig. 5.2).

The relationship between fault plane attitude, sense of displacement and fault-zone width is interpreted to be a function of the distribution of strain in the immediate hangingwall or footwall during deformation. Layer parallel slip in the immediate hangingwall is suggested to have been more prevalent for reverse or oblique-slip faults that were orientated with strike near-parallel to bedding. A greater proportion of the bulk strain was accommodated in the hangingwall, and lateral development of the deformation zone less confined. In contrast, steeply inclined strike-slip faults orientated at high angles to bedding (> 70°) were associated with restricted layer parallel slip, and strain partitioning into adjacent host rocks was low. In consequence, bulk strain was concentrated along relatively narrow zones.
5.3 MESOSCOPIC FAULT ZONE TEXTURES

To characterise the brittle deformation textures in the study region, mesoscopic structural features of brittle fault zones exposed in Tawallah Group and lower McArthur Group stratigraphy are described. It is important to note that the fault zone textures described below are the end-products of prolonged and/or multiple brittle deformation episodes.

5.3.1 Cataclastic fracture and brecciation

The primary response to brittle fault zone development in Tawallah Group and lower McArthur Group stratigraphy is the generation of cataclastic sandstone (Plate 5.1a). Throughout the study area, mesoscopic cataclastic textures preserved in sandstone lithologies are typically defined by narrow zones of concentrated fracturing (Plate 5.1b). In general, a preferred fracture orientation parallel to the main fault trace was recognised. However, narrow and irregular zones of fault breccia define the primary deformation zone in some cases.

Breccias are generally clast supported, monomict and comprise angular quartz sandstone wall rock fragments contained within a fine- to medium-grained sand/clay matrix (Plate 5.1c). Coarse crystalline barite, calcite or quartz may occur between clasts (Plate 5.1d), suggesting that the development of breccia-induced permeability created favourable sites for late stage hydrothermal fluid migration and mineral precipitation. Engelder (1974) suggested that this type of fault breccia can develop in quartz aggregates during severe cataclastic grainsize reduction, subsequent to fault zone formation.
Plate 5.1 Mesoscopic fault-zone textures in the study region.

a) Mesoscopic cataclastic sandstone texture preserved along a secondary strike-slip fault zone in the Masterton Sandstone (Tawallah Range; 5642E - 82210N).

b) Narrow zone of concentrated, zone-parallel fracturing and hematite mineralisation along a secondary strike-slip fault zone in the Sly Creek Sandstone (Tawallah Range; 5678E - 82145N).

c) Attrition breccia comprising angular wall rock clasts of Wollogorang Formation sandstone set in a fine- to medium-grained sandstone matrix (Scrutton Range; 5628E - 82077N).

d) Coarse-crystalline barite occurring between attrition breccia clasts in the Settlement Creek Volcanics (Scrutton Range; 5626E - 82081N).

e) Hydraulic fault breccia preserved in the Bauhinia Fault Zone. Angular Sly Creek Sandstone clasts occur in a jig-saw fit pattern, and are separated by a quartz-hematite matrix (Scrutton Range; 5609E - 82163N).

f) Hydraulic fault breccia preserved in the Tawallah Fault Zone. Angular, randomly orientated Sly Creek Sandstone clasts are supported by quartz-hematite matrix (Batten Range; 5829E - 81856N).

g) Hydraulic fault breccia preserved in a secondary strike-slip fault zone. Angular Sly Creek Sandstone clasts occur in a jig-saw fit pattern, and are separated by bladed hematite (Batten Range; 5800E - 81884N).
initiation and the generation of a through-going structure. A fault rock generated by cataclastic grainsize reduction is termed attrition breccia, and is characterised by a low volume of surviving host rock fragments surrounded by a fine-grained matrix of crushed grains (Sibson, 1986). To be defined as an attrition breccia, the fault rock must contain more than 30% original fragments or grains (less than 30% constitutes fault gouge; Engelder, 1974).

5.3.2 Hydraulic fracture and brecciation

In the study region, hydraulic breccia is generally restricted to the brittle structures exposed in Tawallah and lower McArthur Group sandstone formations. However, the greatest proportion of hydraulic breccia is associated with faults that propagate through the Yiyintyi and Sly Creek Sandstones. Hydraulic breccias are typified by monomict, millimetre to decimetre sized, angular wall rock fragments (usually quartz sandstone) set in a matrix of fine to coarse crystalline hydrothermal quartz and/or hematite (Plate 5.1e, f and g). The majority of constituent quartz grains in breccia clasts show intense intragranular microfracture concentrations that are always defined by planar secondary fluid inclusion trails (see Chapter 7). Breccia matrices are characterised by simple mineral assemblages, comprising some combination of quartz and hematite. Breccia clasts supported by 100% quartz or hematite have been preserved in some fault zones. Accessory minerals in hematite-bearing breccias include hydrated ferric oxides such as goethite, limonite and leucoxene. These are interpreted to represent hematite alteration products developed during late-stage supergene fluid circulation. Infilling of breccia matrices by hydrothermal mineralisation is a distinguishing feature of hydraulic brecciation and enables the distinction from attrition breccia (Sibson, 1986). Although both breccia types contain highly angular wall rock derived fragments, hydraulic breccia clasts show little evidence for frictional attrition.

Hydraulic breccias are defined by two main end-member textures. The most common texture is typified by clast-supported breccia with angular clasts arranged in a jigsaw fit pattern (Plate 5.1e and g). Less abundant are matrix-supported breccias with random clast orientation (Plate 5.1f). Hydraulic fracture occurs where the pore fluid pressure exceeds the least principal stress by a magnitude equal to the tensile strength of the material (Knipe and McCaig, 1994). Hydraulic breccia represents an extreme case of hydraulic fracture and forms by the implosion of wall rock into cavity space generated during rapid slip (Phillips, 1972; Sibson, 1986). The genetic relationship between the two breccia types is suggested where hydraulic brecciation has developed along a narrow zone. Highly fractured sandstone or jigsaw-fit breccia generally occurs along the zone margins and grades laterally into the more chaotic matrix-supported breccia at the zone centre (Plate 5.2a). This geometry would suggest that rapid dilation
occurred along linear zone, resulting in a sudden fluid-pressure reduction, hydraulic brecciation, fluid influx and hydrothermal precipitation (Sibson, 1986). The gradation from chaotic breccia to zone margin hydraulic fracturing most likely reflects the progressive equilibration of fluid pressure in adjacent wall rock lithologies following dilation.

5.3.3 Veining

Quartz-hematite veins and tension gashes are commonly associated with hydraulic fracture and/or brecciation in the western McArthur River region (Plate 5.2b). Where tension gashes cross-cut an earlier formed breccia, quartz or bladed hematite mineralisation is primarily controlled by the local host rock composition. Quartz is developed in veins or tension gashes adjacent to the more silicic wall rocks, hematite forms in veins adjacent to hematite-rich wall rocks. This suggests local remobilisation of SiO₂ and Fe from fault breccias during late-stage dilational fracturing. Stockwork veining also occurs within hydraulically fractured and brecciated fault zones (Plate 5.2c), and is typically associated with larger faults such as the southern Tawallah Fault segment.

5.3.4 Wall rock silicification

The most common lithological characteristic observed in the brittle fault zones that are hosted by Tawallah and McArthur Group sandstones is localised silicification of footwall and hangingwall lithologies. An important consequence of wall rock silicification is that fault traces remain exposed as resistant linear ridges or scarps in otherwise recessive host rocks (Plate 5.2d). In general, the absolute width of any primary or secondary fault zone in the study region is defined by the lateral extent of the associated silicification. Wall rock silicification in the study region is interpreted to have resulted from the localisation of high fluid mobilities during fault zone rupture.

In low grade metamorphic terranes, the principal mechanism responsible for the mobilisation, transport and precipitation of mineral species is mass transfer (Cox et al., 1986). Removal of material by mass transfer involves either bulk transport of dissolved species in a migrating fluid or solute diffusion in a static fluid system (diffusive mass transfer; Knipe, 1989). Precipitation of the removed material occurs at sink sites such as microfractures, veins or interstitial pore space. This mineralisation may form locally or at large distances from the original source, depending on the degree of fluid mobility (Cox et al., 1986). For large-scale fault zones (eg. the Lorella Fault, where associated silicification extends for approximately 500 m into the Yiyintyi
Plate 5.2 Mesoscopic fault-zone textures in the study region.

a) Zonation of hydraulic breccia textures, from jigsaw fit, clast-supported breccia at the zone margins to chaotic, matrix-supported breccia at the zone centre (Scrutton Range; 5609E - 82163N).

b) Quartz-hematite tension gashes cross-cutting an earlier-formed hydraulic breccia. Bladed hematite vein (hm) segments occur adjacent to hematite-rich (red) wall rocks, whereas quartz vein segments occur in the more silicic wall rocks (Batten Range; 5829E - 81856N).

c) Example of stockwork veining in a Sly Creek Sandstone exposure from the Tawallah Fault Zone (Batten Range; 5834E - 81888N).

d) Typical surface expression of a secondary fault trace associated with silicification of surrounding (Masterton) sandstone wall rocks during deformation (Tawallah Range; 5642E - 82210N).

e) Silicification zone (S.Z.) associated with the NW-striking Lorella Fault segment in central Tawallah Range.

\[ \text{scale} \]
Sandstone hangingwall; Plate 5.2e), wall rock silicification was probably related to high fluid mobility during rupture and silica transfer over a large lateral extent.

5.4 MICROSCOPIC FAULT ZONE TEXTURES

To compliment the descriptions of mesoscopic brittle deformation textures, petrographic features of the Masterton Sandstone have been examined within a secondary strike-slip fault zone exposed in the Batten Range. The fault zone has a strike-length of approximately 2.0 km, attains a maximum width of 20 m, and is typified by cataclastic fracture deformation textures in outcrop.

5.4.1 Undeformed Masterton Sandstone

Adjacent to the main deformation zone (silicification zone), the Masterton Sandstone is a clean, fine- to medium-grained and well sorted quartz sandstone. Sub- to well rounded quartz grains comprise approximately 80 % of the formation, with original grain boundaries defined by a faint dusting of hematite (Plate 5.3a). Interstitial pore space has been mostly occluded by quartz overgrowths that occur in optical continuity with parent grains and comprise the remaining fraction of observed samples (Plate 5.3b). In some cases, multiple quartz overgrowths were observed at grain margins. Early overgrowths are rimmed with a fine hematite dusting (Plate 5.3c), suggesting that they formed part of original detrital grains. Although quartz overgrowths are a characteristic feature of Masterton Sandstone samples within the silicification zone, many grains remain in primary or secondary (sutured) contact with adjacent grains (Plate 5.3d). Intragranular microfractures are rare, and are restricted to isolated quartz grains where they internally link grain boundaries and cease abruptly in surrounding overgrowth material. Quartz grains showing undulose extinction comprise approximately 25 % of the detrital rock fraction (Fig. 5.3).

Within the main deformation zone, petrographic features of the Masterton Sandstone define three principle microstructural-domains: 1) intact quartzite, 2) narrow zones of concentrated deformation and 3) microbreccia/cataclasite.

5.4.2 Intact quartzite

Intact quartzite domains are superficially similar to the undeformed Masterton Sandstone, but are distinguished by a dramatic increase in the number of sutured grain margins (Fig. 5.3a; Plate 5.3e). Sutured margins are commonly irregular and, in places, are defined by 'flame-like' quartz bulges (Plate 5.3f). Small recrystallised grains (nuclei) also occur along grain margins throughout intact quartzite domains (Plate 5.3g).
Plate 5.3 Microscopic fault-zone textures in the Masterton Sandstone.

a) Adjacent to the main deformation zone (silicification zone): photomicrograph of the well-sorted, sub- to well-rounded texture of the Masterton Sandstone (plain light; sample 92-17f).

b) Adjacent to the main deformation zone (silicification zone): photomicrograph of interstitial pore space occluded by quartz overgrowths (crossed polars; sample 92-17e).

c) Adjacent to the main deformation zone (silicification zone): photomicrograph of an early quartz overgrowth (q₁) rimmed with a fine hematite dusting (detrital grain margin) and succeeded by a later phase of quartz cement (q₂; crossed polars, sample 92-17e).

d) Adjacent to the main deformation zone (silicification zone): photomicrograph of sutured grain margins (crossed polars; sample 92-17f).

e) Intact quartzite domain: photomicrograph showing the increased abundance of sutured grain margins in the deformation zone (plain light; sample 92-17c).

f) Intact quartzite domain: photomicrograph of irregular 'flame-like' quartz bulges occurring along grain margins (arrows; crossed polars, sample 92-17b).

g) Intact quartzite domain: photomicrograph of grain boundary nuclei (crossed polars; sample 92-17c).

h) Intact quartzite domain: photomicrograph of a quartz grain containing deformation lamellae (crossed polars; sample 92-17d).
Most of the constituent quartz grains in intact quartzite domains show faint undulose extinction (Fig. 5.3b), with deformation lamellae and deformation bands occurring locally (Plate 5.3h). Abundant intragranular fractures are generally less than 1 \( \mu \text{m} \) in width, confined to a single grain, annealed and/or defined by secondary fluid inclusion trails. Many intragranular fractures do not extend across an entire grain diameter and appear to have nucleated from a grain boundary, become narrowed and ultimately arrested within the grain (Plate 5.4a). In a few cases however, intragranular cracks are linked (Plate 5.4b), forming a through-going fracture that may extend for up to four grain diameters in length and displace individual grains by up to 5\( \mu \text{m} \).

### 5.4.3 Concentrated deformation zones

Concentrated deformation domains are narrow zones that contain one, or a series of through-going microfractures that link intragranular and intergranular fracture segments (Plate 5.4c). Most through-going fractures (1 to 50 \( \mu \text{m} \) wide) have been annealed or filled by microcrystalline quartz (Plate 5.4d), and many are defined by fluid inclusion trails. Nuclei occur along most narrow microfractures as a series of discrete grains (Plate 5.4e). Larger through-going fractures (50 \( \mu \text{m} \) to 0.5 mm wide) enclose discreet zones of granular, fine-grained quartz (average grain-diameter: 40 \( \mu \text{m} \); Plate 5.4f). A small proportion of the fine-grained quartz grains appear to have angular morphologies. This observation is tentative however, as the majority of clast margins are sutured to each other and to the adjacent through-going fracture plane.

The largest observed through-going fractures (0.5 to 3 mm) are planar in nature and enclose domains of quartz microbreccia (Plate 5.4g). Quartz grains at the margins of these fractures appear to have been disaggregated by zone-parallel intragranular fractures, suggesting that they were progressively assimilated into the microbreccia-
Plate 5.4 Microscopic fault-zone textures in the Masterton Sandstone.

a) Intact quartzite domain: photomicrograph of intragranular fractures that appear to have nucleated from a grain boundary and terminated within the host quartz grain (crossed polars; sample 92-17d).

b) Intact quartzite domain: photomicrograph of intragranular cracks that have linked to form a through-going microfracture (crossed polars; sample 92-17c).

c) Concentrated deformation zone: photomicrograph of a through-going microfracture linking intragranular (arrow) and intergranular fracture segments (crossed polars; sample 92-17b).

d) Concentrated deformation zone: photomicrograph of a narrow through-going microfracture annealed by microcrystalline quartz (crossed polars; sample 92-17b).

e) Concentrated deformation zone: photomicrograph of nuclei occurring along a narrow through-going microfracture (arrows; crossed polars, sample 92-17c).

f) Concentrated deformation zone: photomicrograph of a larger through-going microfracture enclosing a zone of granular, fine-grained quartz (crossed polars; sample 92-17b).

g) Concentrated deformation zone: photomicrograph of planar through-going microfractures enclosing a quartz microbreccia domain (crossed polars; sample 92-17a).

h) Concentrated deformation zone: photomicrograph of a quartz grain at the margin of a through-going microfracture disaggregated by zone-parallel intragranular fractures (grain spalling). In this example, some of the disaggregated quartz fragments contain grain boundary nuclei (arrow; crossed polars, sample 92-17b).
cataclasite (Plate 5.4h). This process of progressive grain fragmentation and incorporation into a developing microbreccia-cataclasite zone is termed ‘grain spalling’, and is characteristic of brittle deformation zones (Lloyd and Knipe, 1992). Spalled quartz fragments may contain grain boundary nuclei (Plate 5.4h), indicating that microbrecciation occurred during or post-dated grain boundary nucleation. However, many quartz fragments within cataclasite zones are sutured together, with adjoining margins representing sites of nucleation (Plate 5.5a). Consequently, the process controlling the formation of grain boundary nuclei must have also been operative subsequent to microfracture and microbreccia development.

A second mechanism of fragmentation occurs where a linked microfracture segment has propagated through a large deformed quartz grain. In these situations, intragranular fractures were developed parallel to the through-going zone along internal deformation bands (Plate 5.5b). These fractures either extend a short distance into the deformed grain, or continue across it to link opposing grain margins. In places, minor displacement has occurred along the deformation bands, resulting in progressive grain segregation and incorporation of grain fragments into the microbreccia-cataclasite zone (Plate 5.5c). Intragranular microfractures in deformed quartz are commonly healed, and the fracture trace complicated by nucleation.

5.4.4 Microbreccia-cataclasite

Microbreccia-cataclasite domains occur as narrow zones of pronounced grainsize reduction (Plate 5.5d). Breccia clasts include deformed and non-deformed, sub-angular to sub-rounded quartz fragments set in a siliceous microcrystalline matrix (Plate 5.5e). The size and number of breccia clasts rapidly decreases adjacent to zone margins (Plate 5.5f), and many neighbouring clasts are sutured, or display nucleation developed along mutual grain boundaries (Plate 5.5g). Quartz grains bordering microbreccia-cataclasite domains show an increased intensity of intragranular microfractures, deformation lamellae/bands, grain boundary suturing and nucleation relative to adjacent intact quartzite domains.

5.4.5 Discussion of microstructures

Petrographic features of the Masterton Sandstone suggest that low temperature, cataclastic deformation mechanisms were the primary response to strain accumulation in the fault zone. Cataclasis is a friction-dependant mechanism that operates during deformation of aggregate rocks in upper crustal regions, and involves the granulation of individual grains by microfracture and rigid body rotation (Engelder, 1974). The nucleation, propagation and displacement along microfractures during deformation can
Plate 5.5 Microscopic fault-zone textures in the Masterton Sandstone.

a) Concentrated deformation zone: photomicrograph of grain boundary nuclei occurring along a sutured grain contact in a quartz microbreccia domain enclosed by planar through-going microfractures (crossed polars; sample 92-17b).

b) Concentrated deformation zone: photomicrograph of intragranular microfractures formed parallel to internal deformation bands (arrows; crossed polars, sample 92-17c).

c) Concentrated deformation zone: photomicrograph of grain segregation resulting from minor displacement along deformation band-parallel microfractures (arrows; crossed polars, sample 92-17c).

d) Photomicrograph of a typical microbreccia domain (crossed polars; sample 92-17a).

e) Microbreccia domain: photomicrograph of deformed and non-deformed breccia fragments in a siliceous microcrystalline matrix (crossed polars; sample 92-17a).

f) Microbreccia domain: photomicrograph of the decrease in size and abundance of breccia clasts adjacent to a microbreccia zone margin (crossed polars; sample 92-17a).

g) Microbreccia domain: photomicrograph of nuclei occurring along mutual grain boundaries within a microbreccia domain (crossed polars; sample 92-17a).
result from a number of individual mechanisms. Intragranular fractures may nucleate at points of highest stress along grain boundaries and with low general plasticity, propagate from existing flaws (Lloyd and Knipe, 1992). Continued fracture propagation is dictated by the tensional stress trajectory that connects a second point of high stress on an opposing grain margin (Blenkinsop and Rutter, 1986). In this case, cataclastic failure is initiated once a critical crack density is attained (Krantz and Scholtz, 1977). In the Masterton Sandstone fault zone however, microstructures such as (minor) deformation lamellae/bands and grain boundary (bulge) nuclei indicate that some degree of crystal-plasticity had accompanied deformation.

Bulge nuclei occurring along grain margins can be attributed to strain-induced grain boundary migration or to pressure solution along stylolitic surfaces (Vernon, 1976). The random orientation of bulge nuclei in the Masterton Sandstone is inconsistent with a pressure solution mechanism, as dissolution should only occur on the grain margins orientated perpendicular to the principal tectonic compression (Law, 1986). A grain boundary migration mechanism, whereby grains of lesser dislocation density grow at the expense of those which are more highly deformed (Barber, 1985), is therefore proposed for bulge nucleation in the Masterton Sandstone.

Spry (1969) suggested that homogenous plastic deformation of a quartz aggregate is unlikely at low temperatures, with the limited intracrystalline slip ability of quartz promoting grain boundary migration and grain boundary sliding. Furthermore, grain boundary sliding in a polycrystalline aggregate of crystals with limited slip behaviour must lead to the formation of voids and resultant fracture (Spry, 1969). In consequence, cataclasis in the Masterton Sandstone is interpreted to have largely controlled by grain boundary sliding and associated grain fracturing. The paucity of intracrystalline deformation microstructures such as deformation lamellae and deformation bands in the Masterton Sandstone is consistent with a grain boundary sliding mechanism for cataclasis.

Grain boundary sliding and bulge nucleation have been observed in coarse-grained quartzite during relatively low temperature deformation experiments (≤ 500°C), and generally occur at temperatures below those required for dislocation climb and subgrain formation (Vernon, 1976). However, the abundance of crystal-plastic deformation mechanisms in the Masterton Sandstone fault zone is surprising, given that depth estimates for quartz-hematite mineralisation in nearby brittle fault zones is constrained between 200 and 500 m (Chapter 7). A potential mechanism for the formation of bulge nucleation during low-temperature brittle deformation of the Masterton Sandstone is pervasive influx of local fluids. Knipe and McCaig (1994) proposed that cataclastic flow results from repeated episodes of fracturing and grain size reduction, and that these brief deformation pulses will induce dilation along the zone, enhancing local porosity and permeability. In consequence, the through-going
fracture network 'opens', local fluid pressure is reduced and fluid flow rates increase. Intragranular microfractures in the Masterton Sandstone fault zone that are annealed by, or filled with microcrystalline quartz (Plate 5.4d) are interpreted to indicate that bulk fluid mass transfer (and local diffusive mass transfer; Knipe, 1979) processes had operated during deformation. The abundance of hydraulic fracture and brecciation textures, veins and wall rock silicification in fault zones exposed throughout the study region provide further evidence for fluid influx during deformation. Fluids can dramatically influence the behaviour of rocks undergoing brittle deformation by reducing the deviatoric stress required for microfracture propagation (Knipe and McCaig, 1994), and by providing the medium for diffusion processes which assist grain boundary sliding (Stel, 1981) The introduction of fluids during low-temperature brittle deformation can also facilitate plastic deformation by aiding intracrystalline dislocation movements (Paterson and Kekulawala, 1979), and therefore increasing the probability for grain boundary (bulge) nucleation. In conclusion, the abundance of bulge nucleation microstructures in the Masterton Sandstone fault zone can be explained by invoking fluid influx during brittle fault zone development.

5.5 SUMMARY

Microstructural features of a brittle fault zone exposed in the Masterton Sandstone are consistent with a grain boundary sliding mechanism for cataclastic brecciation. The introduction of large fluid volumes during brittle deformation is considered to have assisted grain boundary sliding and the formation of nuclei by bulge nucleation (normally associated with crystal-plasticity). Mesoscopic fault zone textures developed in response to large fluid influx during deformation include hydraulic fracture, hydraulic brecciation, veining and wall rock silicification. Hydraulic fractures, veins and breccia matrices are all filled by hydrothermal quartz and/or hematite. Fault zones that did not act as conduits for large fluid volumes during rupture probably continued to deform cataclastically, producing characteristic features such as cataclastic sandstone textures and attrition breccia.

The Tawallah Group contains abundant evidence for widespread upper crustal deformation. Brittle fault zones of varying magnitude are well developed throughout the study area and are associated with an spectrum of low-temperature deformational processes. The complexity of southern McArthur Basin deformation becomes more apparent when considering the hierarchical development of structures with respect to the present day structural geometry. These problems are addressed in the following chapter.