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Abstract
The Frome Embayment, in the south of the Eromanga Basin, is the southernmost lobe of an intracontinental basin that formed as a result of epeirogenic motion during the Late Jurassic through to the Early Cretaceous. In the contemporary landscape, for the most part, the Mesozoic landscape has been buried by the Lake Eyre Basin. However, in the hinterland regions of the embayment, and sporadically within the embayment, remnants of the Mesozoic landscape are exposed, at least in part in their original context. Many marine shore lines, sedimentary surfaces and graded erosional terraces have remained exposed around the margins of the basin since the Mesozoic. These exposures have undergone weathering and erosion, and slight modification from contemporary regolith, such as colluvium and alluvium. Other exposures have been uplifted and exhumed such that they are now prominent features of the landscape. Localised sedimentological and structural studies indicate that the hinterland landscape at the time of basin formation consisted of erosional hills and rises surrounded by relatively flat low lying plains. In the west of the basin, shorelines, sediment profiles and structural relationships indicate uplift in access of 300 m in the basin bounding ranges during the duration of sediment deposition. Throughout basin formation, this landscape, previously thought to be a 'peneplain', was deformed by syn-depositional tectonics, which controlled the sedimentological distribution and characteristics. Localised tectonics resulted in variations in the basin evolution on different sides of the embayment, as greater tectonically controlled sediment accommodation in the west provided for deeper and more continuous sediment profiles. Regional studies across the embayment indicate that the syn-depositional tectonism was prevalent in the basin margins where episodic reactivation of structures formed localised depocentres around the Flinders and Barrier Ranges. In these areas, the tectonic offset on structures exceeded 200 m. In places where there are surficial exposures of these structures, it is evident that they have been reactivated post-dating sediment deposition, such that overall throw on the structure exceeds 500 m. In contrast, syn-deposition tectonism basin-ward at the northern edge of the embayment was calm with open folding and tectonic offset on large structures typically less than 50 m. Core and rock mineralogical analysis provides evidence of some minor syn-deposition erosion and reworking of sediments.
Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis (as listed below) resides with the copyright holders of those works.

Signature:                     Date:
Acknowledgements

Firstly, let me just say life is about perspective, I started this project with a view of the Torrens and am finishing with a view of the Yarra; and to be honest, the Yarra actually looks stunning in the ill morning light on the day you intend to submit your thesis. However, it’s like I said, that is more than likely a perspective thing.

This work was completed in the Department of Geology & Geophysics at Adelaide University and in part at the Australian School of Petroleum (ASP). This research was supported by an Australian Post Graduate Award. In-kind support was provided by the Co-operative Research Centre for Landscapes, Environments & Mineral Exploration (CRC LEME), the Lake Eyre Basin Analysis Research Group (LEBARG), Primary Industries and Resources South Australia (PIRSA), New South Wales Department of Primary Industries (NSWDPI), Geoscience Australia, Heathgate Resources and the Australian Defence Force.

Land owners: Anita from Mt Poole; Ray & Debbie from Mt Browne; Corina & Gerard from Moolawatana; Jon & Caroline from Mt Freeling/Mt Fitton; and, Doug & Marg from Arkaroola are thanked for allowing this research to be conducted on their land, and for their interest and support. David McAvaney, Rhiannon Brooke, Mike Neimanis, Guillaume Backe and Yee are thanked for assistance in the field.

Chapters from this thesis were edited for language and consistency in accordance with the ‘Editing of Research Theses by Professional Editors’ guidelines provided by the University of Adelaide in terms with the Australian Standards for Editing Practice (standard D, Language and Illustrations). The editor used was Ms Meredith Thatcher (BA, MA (Hons)(Waikato), AE (Accredited Editor), Publications Manager, Strategic and Defence Studies Centre).

I was fortunate enough to have four supervisors at different stages of this work. I would like to thank Dr Neville Alley for being a wonderful source of knowledge and for his initial enthusiasm. His stories about fieldwork and recorders made me look at geology from a different perspective. Professor Bruce Ainsworth from the ASP is thanked for his calming nature, and thoughtful comments about science and life. Dr Carmen Krapf formally from the ASP was a wonderful source of inspiration, and her zealous passion was always welcomed. And lastly Dr Steve Hill from Geology & Geophysics, who stuck out the project, is thanked for opening my world to new places and experience I probably otherwise would not have ever endeavoured to. I respect you all as scientists, but also as friends.

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Australia provides an enigma of ancient landscape remnants preserved within an evolving contemporary landscape. In central Australia, for instance, landforms from at least the Mesozoic coexist within an area transformed by recent, and in some areas still active, tectonism, weathering, denudation, sedimentation and exhumation. Central Australia's landscape is dominated by plains of Mesozoic and Palaeogene sediments, that form relics of past land surfaces, referred to as palaeosurfaces. These plains are intermittently interrupted by discontinuous mountain belts, bedrock inliers and occasionally inselbergs that both predate and post-date the plains. The magnitude of the surfaces and abundance of relics is geologically challenging considering the speculated age of these features. The preservation and exposure history of these relic landforms are in many cases poorly constrained. Ancient landscape remnants provide an insight into how past geology and environments evolved. Such evolution is important for understanding how our contemporary Earth is developing and changing, and also how environmental dynamics transpire.

Geological evolution models for Australia have typically focused on the Proterozoic and Palaeozoic development. This is primarily attributed to interest in the intense epeirogeny that the continent experienced during this time, predominantly as a result of the intense orogens that developed (for example the Delamerian, Lachlan, Alice Springs, Thomson orogens).

Contemporary geological models, that is, late to post-Palaeozoic models, for Australia have a strong focus on Australia's role in the supercontinent cycles (for example Schmidt & Clark 2000; Veevers 2004 & 2006). The focus of these studies is primarily how the continental margins separated and accreted during the dissipation of Pangea during the Permian, and then Gondwana in the late Mesozoic through to the Palaeogene (Schmidt & Clark 2000; Veevers 2006). These studies have helped to constrain the development of the morphology of the plate margins, and the progression of the continent through different latitudes throughout this time. As well as this, some studies have tried to assess the post-Palaeozoic evolution of intracontinental Australia (de Caritat & Braun 1992; Veevers 2006). However, there are inconsistencies as to how intracontinental Australia evolved throughout this time (compare Sandiford 2003 with Twidale & Bourne 1975 & Bierman & Caffe 2002). These inconsistencies are primarily based around the interpreted driving mechanism and time scale for the area's geological evolution. Two main models exist:

1. Most of intracontinental Australia was formed during the Palaeozoic epeirogeny. Since then, this part of the Australian continent has been relatively stable, with minimal tectonism and denudation (for example: Twidale & Bourne 1975; Twidale 1999, 2000; Bierman & Caffe 2002; Kohn et al. 2002; Belton et al. 2004).
2. Up until recently, central Australia was a stable, flat-lying landscape. Deformation and accretion occurred throughout the Palaeozoic; however, after this, central Australia existed as a large peneplain. Substantial neotectonic processes have reshaped aspects of it, on both a local and a regional scale. These modern processes have formed most of the continents topography (for example, localised studies: Celerier et al. 2005; Quigley et al. 2006; Quigley et al. 2007; and, regionally: Gibson & Stuwe 2000; Sandiford 2003).
One factor that both models incorporate is that during the Mesozoic and into the Palaeogene, intracontinental Australia was a stable, “inactive” part of the continent. However, throughout this time, numerous structural basins were forming (de Caritat & Braun 1992; Vevers 2006). This includes Australia’s largest intracontinental basin, the structurally controlled, mid to late Mesozoic Eromanga Basin (Zhou 1989; de Caritat & Braun 1992). The very presence of the basin indicates that this area has been an active for at least part of the continent following Palaeozoic. Despite its size, magnitude and preservation, this basin has been seldom fully incorporated into intracontinental Australia’s geological and landscape evolution models.

The poorly constrained evolution of intracontinental Australia is assumed to be an affect of the general subtlety of the landscape and expressions of the geology throughout the area, and the assumption that most of the area’s major landforms are very young, typically Neogene structures (for example Wiltshire 1989; Sandiford 2003; Quigley et al. 2007).

However, this poor knowledge of intracontinental terrain is not constrained to Australia. In general, intracontinental evolution is typically a neglected research topic. The subtleties in the rates and magnitudes of the processes and their subtle expression typically hinder recognition of important geological structures and processes. This is not helped by the lack of methodology established for analysing subtle geological terrains. While there is no set method by which plate margin reconstructions are conducted, processes associated with them are typically more obvious, making reconstructions more straight-forward.

Two key issues of Australian geology are highlighted here:

1. A post-Palaeozoic palaeogeological model for intracontinental Australia that incorporates a wide range of aspects of the area’s evolution, morphology and preservation is needed; and,
2. There is a need for a process based analysis that can work with the subtle nature of the geology in intracontinental environments to extract key information on the palaeogeology such that a better understanding of continental interiors can be developed.

The primary aim of this project is to bridge these gaps in the understanding of the geological evolution of central, intracontinental Australia. This includes generating a geological evolution model for part of central Australia that represents a typical intracontinental terrain, but also the main processes contributing to the evolution of the Australian continent during the Mesozoic and through to the Palaeogene. This will also generate a methodology and technique for constructing intracontinental geological evolution models, both on a regional and local scale.

Past attempts at understanding intracontinental interiors, particularly within Australia, have focused on one component of an area’s geology. This has then been used to extrapolate a generalised evolution for the area. This type of approach is typically fraught with error as geological processes work within the context of an environment, forming in a dynamic system, thus are not able to be type cast by one feature (e.g. climate or tectonics) in that area. To elucidate this issue, integration of techniques is needed.

Tools typically employed in successful geological reconstructions around plate margins include: regional and localised geophysical imagery and modelling; sedimentological correlation and interpretation; structural and tectonic reconstructions; and geomorphological analysis. Many of these processes have been employed within central Australia; however, they have rarely been used to generate or contribute to evolution models.

A less common tool that has been recently applied to several localised studies throughout intracontinental regions of Australia applies surficial geology and geomorphology to aid in geological reconstructions. These studies employ regolith geology, that is, “the study of everything between fresh air and fresh rock” (Eggleton et al. 2001), as a basis for understanding an area’s evolution. The general thought process associated with this is that regolith geology is a combination of the ancient geology and how it exists within the modern environment. By understanding the regolith profiles and their formation, it is possible to reconstruct not only past geology, but also past environments. The techniques involved in this type of geology are applicable anywhere as it is the study of the surface of the Earth. Interestingly, these studies have come up with a different palaeogeological conclusion to
that of the two typical models proposed above. These studies support a general model in which tectonism, denudation and other geomorphic processes have been active and significantly contributing on a regional and local scale to the Australian landscape and palaeogeological evolution since at least the Mesozoic (for example regional studies include Hill 1999; Davey & Hill 2005, 2006; McAvaney & Hill 2006; Wilson 2007).

While surficial geological approaches have proven to be a valuable reconstruction tool, they are not without problems. Regolith profiles, especially within Australia, are typically thick, blanketing profiles that can cover or modify some important palaeogeological attributes. Furthermore, while this type of geological study has been successful on a local scale, it has rarely been applied as a reconstruction tool in regional studies. Where it has been used regionally it has been a productive starting point for landscape evolution models (for example: Hill 1999). It is proposed that by using surficial geological analysis integrated with typical methodology the subtleness of the geology and the otherwise hidden aspects will all be incorporated such that a more common model can be created.

The Eromanga Basin represents a large portion of inland Australia from this time. The basin formed during the initiation of the Australia-Antarctica dissipation, such that it represents a time when the continent was undergoing considerable stress. This has lead to this Basin being chosen as the primary focus of this study.

The entire Basin area is too large for the scope of this single study, so the study area has been further refined to an embayment in the south of the basin. The Frome Embayment in south-central Australia represents a smaller analogue of inland Australia. This embayment hosts sedimentary basin margin exposures, regolith-dominated terrains, and deep basin profiles conducive to the different regions of inland Australia. Mountain belts and ridges of varying ages surround Mesozoic and Palaeogene palaeosurfaces, and relic landforms of similar ages. This area is not only important in terms of its varying terrains and its potential for developing a generalised palaeogeological methodology, but is also forms part of the Eromanga Basin, thus is well located in helping to developing the post Palaeozoic geological and environmental evolution of intracontinental Australia.

This project therefore addresses three questions:

1. How did the Frome Embayment evolve?
2. How do several traditional forms of geology incorporated into one study to generate a better evolution model?
3. Can a generalised palaeogeological technique that can be applied to other environments, be developed?
Chapter two: The Eromanga Basin, Australia

2.1 The Scientific Problem

The Eromanga Basin is a multiphase, intracratonic, Mesozoic basin within central and east-central Australia (Figure 2.1). Spaning almost 1 million square kilometres of the Australian continent, the basin is the largest of the four structural sub-basins that comprise the Great Australian Basin (Figure 2.1) (Moore 1986).

![Figure 2.1 The Mesozoic extent of the GAB, projected on to contemporary Australia](image)

As a consequence of successful petroleum exploration, and to a lesser extent mineral exploration, the basin has been the focus of many studies since the 1950s (summarised in Moore 1986). These studies have focused on attributes ranging from the basin’s structure through to the depositional environments of its sediments. As a result of these studies numerous interpretations on the basin’s formation, depositional environments and palaeogeography have been presented. More often than not, these interpretations produced considerable inconsistencies and often contradicting arguments. For example: interpretations of the depositional environment do not consistently support sediment type, location and thickness (compare Wiltshire 1989 with Veevers 1984). Surficial exposures contradict interpretations of well data. An example of this is the studies mapping the distribution of sediments within the basin. Well profiles and seismic define the extent of sedimentation of units (Truelove 1980); however, surficial exposures mapped regionally and locally contradict this (Campana et al. 1961 a, b & c). There are also lithostratigraphic variations in basin sediments between states, primarily as a result of...
sediment classification and the assigning of nomenclature; this particularly affects the basal Mesozoic unit and the transition zone in the south of the basin (Hawke & Bourke 1982; & see Table 2.1) and in the New South Wales portion of the basin where basal sediments identified throughout Queensland and South Australia are apparently not present (see Table 2.1, Cramsie & Hawke a & b 1982; Morton 1982; Van Doan 1988) significant discrepancies exist between models of basin formation and subsidence history (summarised in Zhou 1989), all compromising attempts at creating palaeogeographical interpretations.

Potential reasons for some of these inconsistencies include:

- Differences in interpretations and comparisons between critical geophysical data (primarily seismic, gravity and magnetics data);
- Lack of known exposures and inability to distinguish Eromanga Basin sediments from predecessor and successor basin sediments;
- Inconsistent nomenclature and lithological classification schemes in different states (Summarised in Table 2.1);
- Different foci and different objectives of the studies producing different and often incompatible outcomes. Many studies have had economic geology objectives, often resulting in conclusions driven by the need of the market;
- Interpreting evolution models from limited aspects of the basin’s geology when a multidisciplinary approach is required; and,
- Using localised studies to extrapolate regional interpretations and conclusions, without considering the impact of local variation.

One pertinent issue that seems to arise from all of these problems is the inability to relate different studies from different parts of the basin (Wiltshire 1989). A complex geomorphological history from both during basin formation and since then has resulted in extreme local variations (Twidale 2000; Celerier et al. 2005). This, accompanied by the many inconsistencies between the different studies has made it near to impossible to successfully and meaningfully integrate different aspects of the geology. Because of its size and complexity, regional studies are also often simplistic, so there is a great need to be able to incorporate localised more detailed studies.

Palaeogeographical reconstructions for the entire Basin have at best been broadly and poorly attempted. This is in part due to an inability to integrate different studies with different frameworks in different areas, but also because that there is no recognised manner in which palaeogeographical studies should be conducted. These studies are important in developing an understanding of the basin’s formation as they define the geological processes that occurred, and not just what is driving them. Palaeogeography incorporates all of the geological processes that are occurring in a landscape. Multifaceted geological studies like this are often difficult; incorporating subsurface deformation and tectonic frameworks into sedimentology and landscape expressions requires large amounts of data and time (Wiltshire 1989). In the past, such studies have been conducted using one facet of the landscape’s evolution such as the tectonics or eustacy or climate change. On their own, these studies lend important contributions to facets of geological and environmental evolution; however, do not typically provide the full account of the geological evolution.

This highlights the need to create an approach to palaeogeographical reconstructions for intracontinental basins that have a complex history and subtle landscape expression, such as the Eromanga Basin.

2.2 Objective of This Study

This study aims to develop a model of palaeogeographical reconstruction for a portion of the Eromanga Basin that can be used for further basin analysis. This will be conducted by integrating landscape expressions and features with subsurface sedimentology. Sedimentology can be used as a basis for interpretations of the landscape at the time of basin formation. Tectonism, sea level fluctuations, climate, landscape morphology and
surficial exposures influence sediment type and availability (Levell 1992; Allen et al. 2006). Sediment composition and sedimentary flow direction structures indicate potential sediment provenance, which relates to landscape features and morphology (Potter & Pettijohn 1963; Van der Zwan et al. 1992; Allen 2006). Variations in formation thickness, depocentres and lateral facies variations are possibly an indicator of syn-depositional landscape topography and morphology, which in itself is potentially indicative of syn-depositional tectonism and subsidence. Relationships between sedimentary facies, even where subtle, can represent sedimentary response to changes in the landscape (Allen et al. 2006).

The sediments of the Eromanga Basin have undergone substantial changes since deposition. Geomorphic processes such as uplift, weathering and erosion have changed their position within the landscape and their relationships. Weathering and induration due to regolith processes have redefined sediment characteristics. To understand the original characteristics and positions of these sediments, landscape studies have therefore been incorporated into the palaeogeography reconstructions.

2.3 Geological History

The Eromanga, Surat, Clarence-Moreton and Carpentaria basins form the Great Australian Basin (GAB) (Figure 2.1), the geological equivalent of the hydrological Great Artesian Basin. In total the GAB encompasses 1.7 million km² of inland Australia (Habermehl 1980; Cramsie & Hawke 1982a; Moore 1986; Muller 1989), making it Australia’s largest intracontinental basin. The basin hosts numerous petroleum and mineralogical deposits, as well as the world’s largest artesian aquifer.

Initial subsidence and sedimentation occurred within the basin during the Late Jurassic and continued through to the Cenomanian, when ‘grade’ equilibrium occurred in which net grain loss is approximately equal to net deposited. This resulted in the Eromanga Basin sediments no longer have prominent representation in the sedimentary record. The sediment thickness in the central region is up to 3000 m at its deepest, consisting of successions of both fluvial and marine sediments (Habermehl 1980; Cramsie & Hawke 1982a; Moore 1986; Gallagher & Lambeck 1989; Muller 1989; de Caritat & Braun 1992). There are also minor contributions from lacustrine and aeolian environments and some glacial deposits (Alley & Frakes 2003). Sediments are typically siliclastics, with minor components of volcanoclastics and localised carbonates.

Segregation between the sub-basins in the GAB complex (Figure 2.1) is thought to have occurred during the Early Cretaceous as a result of variations in subsidence (Zhou 1989). This led to isolated depocentres and subsequently as the evolution of the GAB continued, isolated basins. Despite these divides, the sub-basins are thought to be at least in part lithostratigraphically continuous.

The Eromanga Basin contains a near complete sedimentary succession of the Late Jurassic to mid-Cretaceous sedimentary cycle. It forms the largest component of the GAB, hosting the thickest and oldest sedimentary packages. It broadly consists of three different sedimentary environments controlled by the three stages of basin formation. These include: mid-Jurassic to Early Cretaceous fluvial and lacustrine sediments; Aptian to Albian shallow marine sediments; and, mid-Cretaceous fluvial sediments.

Underlying the sediments of the Eromanga Basin are rocks pertaining to several older sedimentary basins and cratons. These include sequences from the Carboniferous to Permian Arckaringa Basin, the Permian-Triassic Cooper Basin and the Triassic Simpson Desert Basin (Moore 1986). The south-eastern and eastern portion of the basin overlies metasedimentary rocks from the Cambrian-Ordovician Kanmantoo and Thomson orogens, and rocks from the Ordovician to early Carboniferous Lachlan Orogen (Cramsie & Hawke 1982a, Zhou 1989). Most of the rest of the basin overlies pre-Cambrian – Cambrian crystalline basement, including the granites and gneisses from the Musgrave Block and Mt Babbage and Mt Painter Inliers (see chapter 4).

Initial geological interest within the basin began in the late 1800s with the search for water supplies (Rawlinson 1878; Ward 1946; Forbes 1986). Geological reconnaissance in central Australia resulted in the location and mapping of mound-springs, providing encouragement for further investigations (Rawlinson 1878). Collection of
fossils and sediment samples during this time lead to the first attempts of establishing a classification and stratigraphy of the basin sediments, with the hope of better understanding where more water could be found (Jack 1925, 1930).

As well as the initial hydrogeological interest, hydrocarbon exploration within the basin began in Queensland in 1924, where ‘yellow oil’ was extracted from a well sunk to almost a kilometre deep (Mott 1952; Sprigg 1986). Following this, further exploration began around the northern margins of the basin where artesian bore waters contained oil (Sprigg 1986). The lack of commercial discoveries resulted in minimal exploration and drilling until the 1950s when it was recognised that Jack (1925) had inadvertently discovered oil in the South Australian portion of the basin (Sprigg 1958a). This renewed interest within the basin identified the need for more detailed mapping of the area, specifically the southern regions. This began with the 1961 production of the northern Flinders Ranges ‘1 mile’ map series (Campana et al. 1961a, b, c), followed by the production of numerous map sheets in the south of the basin in north-western New South Wales (Rose et al. 1967). This was followed by the production of the Maree, Wilpoorinna and Callanna additions to the ‘1 mile’ map series in South Australia (Coats et al. 1963; Forbes & Coats 1963; Webb et al. 1963). During this time, coal bearing sediments were discovered throughout the basin. The most notable were discovered in Queensland where large seams of coal are hosted in exposed Jurassic sediments (Swarbrick 1975). It was not until 1978 that economic oil was discovered (Sprigg 1986). Petroleum exploration is still active within the central regions of the basin.

Other economic resources hosted in the Mesozoic sediments include opal (MacNevin 1975; Townsend 1981; Cramsie & Hawke 1986b) and gold (Brown 1881; Cramsie & Hawke 1986b) with minor recorded occurrences of gypsum, flint-clay and uranium (Cramsie & Hawke 1982b; Forbes 1986). Current mineral exploration in the South Australian, Queensland and Northern Territory portions of the basin are focused largely on uranium, with ongoing gold and opal exploration associated with previous discoveries. Gold is the primary focus for mineral exploration in New South Wales.

2.4 Basin Formation Mechanisms

Formation of the GAB began in the eastern Australian portion of Gondwana in the mid-Jurassic, approximately 160 Ma, during the final dissipation of the super-continent Pangea (Zhou 1989; de Caritat & Braun 1992; Veevers 2006). During this time, Gondwana occupied high latitudes, such that central Australia was approximately 65 degrees south (Frakes et al. 1987), almost 35 degrees further south than its contemporary location. Sea levels fluctuated substantially on a short term scale, but in terms of general trends were on the rise (Figure 2.2).
The break-up of Pangea was driven by a sub-continental heat store that had built up underneath the large landmass (Zhou 1989; de Caritat & Braun 1992; Veevers 2006). Large continental bodies prevent natural heat release which can result in thermally induced crustal metamorphism. This deformation manifests in different ways dependent upon the amount of heat stored (Sandiford et al. 1998). Elevated sub-continental heat stores accumulated during the existence of the supercontinent Pangea were still driving epeirogenic deformation during the Mesozoic, such that it resulted in several stages of thermally induced crustal metamorphism. This deformation is in part responsible for the initiation of the Gondwana Break-up (Zhou 1989; de Caritat & Braun 1992; Veevers 2006). Crustal metamorphism was also expressed in intracontinental interiors as either stress transfer or as a direct response to localised crustal metamorphism. During the late Mesozoic, The Eromanga Basin formed as a result of three major stages of basin evolution resulting from crustal metamorphism (Zhou 1989; de Caritat & Braun 1992). These stages include:

i) Initial subsidence and rifting in Australia during the mid-Jurassic;

ii) Major subsidence during the Aptian – Albian (Middleton 1980; Zhou 1989); and,

iii) Minor subsidence and epeirogenic warping into the Ceonomian

2.4.1. Stage One: Mid-Jurassic (Callovian to Berriasian)

Fossil evidence indicates that during the Callovian through to Berriasian, the climate within central Australia was dominated by moderately warm and wet conditions (DeLurio 1995; Frakes et al. 1987). Sediment supply was abundant, following extensive weathering of the landscape since the last major period of sedimentation in the Permo-Triassic. Sea-levels were highly variant throughout this time (Figure 2.2), with short lived high-stand – low stand cycles. During this time, substantial rifting occurred along the northern and north-eastern margins of Australia and between Australia and Antarctica (Figure 2.3) (Veevers 2006).

The initial subsidence within central and north-central Australia was driven by the diffusion of the last of the sub-lithospheric Pangean heat store (Zhou 1989; Veevers 2006). The amalgamation of Pangea hindered mantle thermal convection, such that heat and hence pressure built up occurred underneath the supercontinent (Zhou 1989; Veevers 2006). Previous expulsions of the extensive heat build up during the Permian and early Mesozoic resulted in significant rifting, subduction and subsidence (Veevers & Powell 1990; Veevers 2006). As a result, numerous basinal systems formed throughout Gondwana including the Australian Cooper, Simpson, Perth and Arckaringa basins.

As a result of this thermally driven heat and pressure release, thermal metamorphism and extension resulted in subsidence within the northern and central part of Australia (Zhou 1989; Veevers & Powell 1990; Veevers 2006). The initial subsidence generated a minor warping of the continent (Zhou 1989) providing the accommodation space to support accumulation of sediment within a fluvial regime. The subsided areas were dominated by braided and high-energy river systems (Freitag et al. 1967; Wopfner et al. 1970; Norton 1983; Forbes 1986; Van Doan 1988). Minor lacustrine sedimentation occurred in areas affected by syn-depositional tectonism where uplift and warping compromised water and sediment availability.
2.4.2. Stage Two: Aptian to Albian

By the Aptian, global sea-levels had increased by almost 250 m since the Triassic (Haq et al. 1987), to levels approximately 200 m above the contemporary sea level (Figure 2.2). The climate was highly variable, with fossils and mineral assemblages indicating both near freezing conditions and warm wet climates within this period (DeLurio & Frakes 1999). The Aptian also represents the period of the highest rate and most extensive lateral subsidence within the Eromanga Basin (Zhou 1989). Initial increases in the rate of subsidence occurred during the late Neocomian, resulting in minor marine transgressive and regressive cycles in the basin via the “Eromanga Seaway” (Figure 2.4). As subsidence intensified during the Aptian, accommodation space within the basin drastically increased facilitating a major marine transgression (Frakes et al. 1987). By the mid-Aptian, the transgression extended across central and east central Australia, as far south as the northern Flinders Ranges in South Australia (Freytag et al. 1967; Wopfner et al. 1970; Norton 1983; Forbes 1986; Frakes et al. 1987; Van Doan 1988) and into northwestern New South Wales (Cramsie & Hawke 1982a). Lithologically similar sediments have been identified further south (Frakes et al. 1987; Veevers 2006); however, there is no conclusive evidence that they are part of the Eromanga Basin.
Figure 2.4 Reconstruction of the Australian Continent during the Aptian (from Veevers 2000) with the Eromanga Basin superimposed.

While the initial subsidence within the basin during the mid Jurassic supports thermally driven down-warping as a result of extension (Zhou 1989; Veevers 2006) the cause of the major subsidence during the Aptian is an issue of contention. Three main models exist;

i) Continual extensional down-warping resulting from various tectonic driven processes;

ii) Thermal contraction and subsidence due to crustal cooling; and,

iii) Negative isostacy resulting from a combination of sedimentation and a transition to compressional stresses.

Extensional down-warping is the most favoured theory for the Aptian subsidence; however, the driving tectonic regimes are unknown. Seismic interpretations by de Caritat & Braun (1992) suggest that the basin is a platform basin forming as a result of subduction. This was based upon the classification system defined by Mitrovica et al. (1989) from which a 'platform' basin is characterised and identified by a wedge-like distribution of sediments that has resulted from a sub-lithospheric pressure gradient that causes subsidence (Figure 2.5). A key component of this model is a thickening of the sedimentary packages along the subducting margin that results in the formation of a foreland basin.
Chapter Two: Literature Review

Figure 2.5 Platform basin model adapted from Mitrovica et al. (1989).

The model proposed by de Caritat & Braun (1992) suggest that the Carpentaria and Eromanga basins form the ‘platform’ with the Surat Basin forming as a foreland basin (Figure 2.6).

Figure 2.6 Platform basin model interpretation of the GAB from de Caritat & Braun (1992). This model is based upon a Phanerozoic multiphase subduction (summarised in de Caritat & Braun, 1992) in a convergent margin, with the final stage (illustrated above) resulting in the GAB formation.

In the Eromanga Basin; however, the thickest and oldest sediments are hosted in the centre, such that the basin forms a synclinal structure. This sediment distribution pattern is inconsistent with the ‘platform’ model, which would require a substantial thickening of the Eromanga Basin sedimentary packages against the highlands to the east.

Whitehouse (1955) and Sprigg (1986) attribute the subsidence to extensional epeirogenic down-warping, which is supported by the overall synclinal structure of the basin, where the oldest and thickest parts of the sediments approximate the centre.

In contrast to the extensional terrain theories, a thermal change model is also proposed for the Aptian-Albian subsidence (Falvey 1974; Middleton 1980). In accordance with this model, rapid cooling of the crust resulted in a change in thermal regime in which a change in the metamorphic facies caused an increase in density of the crust (Falvey 1974; Middleton 1980). In response to this density increase, central Australia subsided (Falvey 1974; Middleton 1980). While plausible, this model over simplifies metamorphic thermal transitions and thermally driven crustal subsidence processes (Zhou 1989). It also does not account for the rapid subsidence that occurred at the start of the Aptian as crustal cooling would have been a long term process and generating a slow and steady subsidence history (Zhou 1989).

The most likely cause of rapid major subsidence would have most likely been a change in the tectonic regime from extensional to compressional (Zhou 1989). In the south of the basin, local sediment characteristics are
consistent with a compressional regime during this time. Angular unconformities between the older fluvial units and the younger marine sediments indicate a syn-depositional compressional tectonic regime. An example of this is where marine sediments infill synclinal valleys formed within folded Algebuckina Sandstone and Cadna-owie Formation around the Mt Babbage Inlier in the northern Flinders Ranges (see chapter 4). However, at this stage, evidence of syn-depositional compression has only been recognized on a local-scale, and therefore is not conclusive evidence supporting this interpretation.

The third model proposed for the Aptian subsidence is one of isostatic rebound (Zhou 1989). This model largely depends on the increase in land mass over the basin. The sedimentary record supports a post-subsidence sediment influx, so it is highly unlikely that sedimentation caused the subsidence. However, regional compression could have caused crustal thickening, and a change in crustal metamorphism, causing an overall negative isostatic response.

The differences between these interpretations highlights the need for further research into this aspect of the basin formation.

2.4.3. Stage three: Cenomanian

During the late-Albian, Australia rotated considerably as it separated from Gondwana (Figure 2.7) (Veevers 2006). Sediment accommodation space decreased and the preservation within the sedimentary record ceased as subsidence in central Australia ceased (Veevers 2006). This resulted in a temporary hiatus in sedimentation. Global sea levels had remained relatively constant since the Aptian (Figure 2.2), and climates had progressively warmed as the continent drifted further to the north.

Renewed epeirogeny during the Cenomanian resulted in further subsidence (Zhou 1991; Veevers 2006). This subsidence is attributed to a north-western extensional regime associated with the final stages of the Gondwana break-up (Veevers 2006). This subsidence resulted in the deposition of the Winton Formation, and the final stages of the major Eromanga Basin sedimentation.

Following the deposition of the Winton Formation, the top sediments were affected by a large scale weathering process that formed a thick kaolinitic profile (Senior 1976; Idnurm & Senior 1978). This weathering profile covers the south of the basin, being as wide spread as the Surat Basin (Idnurm & Senior 1978; Schmidt & Ollier 1988). Non-quartz rich sections of the weathered profile have ferruginous profiles, characterised by a pink-purple induration or staining. From the ferruginous weathered sections the apparent magnetic signature of the weathered rocks were incorporated in to dating the weathering events. From this, these profiles have been estimated to have formed in two separate weathering events that occurred during the Late Cretaceous (Idnurm & Senior 1978). The two events are referred to as the Morney and the Canaway profiles (Senior 1976; Idnurm & Senior 1978).
2.5 Sedimentology, depositional environments and palaeogeography

The descriptions and interpretations of stratigraphy within the Eromanga Basin is typically complicated and confusing as a result of different stratigraphy, standards and categorisation techniques employed by different state geological surveys. This is highlighted in Table 2.1 in which the general nomenclature and age of the primary sedimentary units for different states are compared. To overcome this confusion, the sediments will here by be referred to by the sedimentological divisions assigned to three primary units and two intermediate units, generally defined by most studies of the basin sediments within South Australia (Table 2.2). This is primarily a sedimentological division aimed at minimising confusion in nomenclature.
Table 2.1 Composite of the accepted stratigraphy for New South Wales (Cramsie & Hawke 1982 a & b; Moreton 1982), South Australia (Freytag 1966; Moore 1986; Van Doan 1989; Alexander & Kreig 1993), Northern Territory and Queensland (Cramsie & Hawke 1982).

<table>
<thead>
<tr>
<th>Jurassic</th>
<th>Cretaceous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid</td>
<td>Early</td>
</tr>
<tr>
<td>Kimmeridgian</td>
<td>Barremian</td>
</tr>
<tr>
<td>Tithonian</td>
<td>Vaalrian</td>
</tr>
<tr>
<td>Ostracocnian</td>
<td>Aptian</td>
</tr>
<tr>
<td>Neocomian</td>
<td>Albian</td>
</tr>
<tr>
<td>Lias</td>
<td>Cenomanian</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NSW</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Neals River Group</td>
<td></td>
</tr>
<tr>
<td>Marree Subgroup</td>
<td></td>
</tr>
<tr>
<td>Codina Oowie Formation</td>
<td></td>
</tr>
<tr>
<td>Toolebud Formation</td>
<td></td>
</tr>
<tr>
<td>Wilgunga Subgroup</td>
<td></td>
</tr>
<tr>
<td>Codina Oowie Formation</td>
<td></td>
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<tr>
<td>Toolebud Formation</td>
<td></td>
</tr>
<tr>
<td>Queensland</td>
<td></td>
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<tr>
<td>Blythsdale Group</td>
<td></td>
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<tr>
<td>Coddin Oowie Formation</td>
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<tr>
<td>Toolebud Formation</td>
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<tr>
<td>Queensland</td>
<td></td>
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<tr>
<td>Coddin Oowie Formation</td>
<td></td>
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<tr>
<td>Toolebud Formation</td>
<td></td>
</tr>
<tr>
<td>Northern Territory</td>
<td></td>
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</tbody>
</table>
Table 2.2 Adapted sedimentology of the Eromanga Basin, incorporating typical facies, fossils and approximate global sea-levels relative to contemporary sea level (after Haq et al. 1987). Red sea-level line is relative global level, blue is local.

<table>
<thead>
<tr>
<th>Cretaceous</th>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
<th>Depositional Environment</th>
<th>Sea level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>Late</td>
<td>Cenomanian</td>
<td>Winton Formation</td>
<td>Fluvial &amp; lacustrine</td>
<td>0 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Albian</td>
<td>Oodnadatta Formation</td>
<td>Marginal marine</td>
<td>200 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aptian</td>
<td>Bulldog Shale</td>
<td>Marine</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Hauerivian</td>
<td>Cadna-owlie Formation</td>
<td>Open marine</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Valanginian</td>
<td></td>
<td>Marine</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Barremian</td>
<td></td>
<td>Transgressive marine</td>
<td></td>
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<td></td>
<td></td>
<td>Neoconian</td>
<td></td>
<td>Fluvial</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Tithonian</td>
<td>Algebuckina Sandstone</td>
<td>Lacustrine</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Kimmeridgian</td>
<td></td>
<td>Fluvio-lacustrine</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxfordian</td>
<td></td>
<td>Fluvial</td>
<td></td>
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2.5.1 Initial sedimentation: the Algebuckina Sandstone

Initial sedimentation within the basin was dominantly in fluvial environments during the mid-Jurassic. This was a period in which small sediment accommodation space resulted in shallow meandering streams with an east-west flow axis (Ambrose 1980; Green et al. 1989). Sedimentation was dominated by inter-fingering mudstones and sandstones unconformably overlying the predecessor basins and crystalline basement (Green et al. 1989). Occasional ‘pinch-outs’ within these sediments, have acted as hydrocarbon traps, with gas and oil being trapped in the more sandy lenses.
As subsidence increased during the Late Jurassic, the fluvial environments became more widespread resulting in a greater distribution and deposition of sediments (Green et al. 1989). Facies resulting from this phase of deposition are very diverse, including: clast-supported conglomerates laterally grading into massive sandstone; mudstones and other finer grained sediments dominating marginal regions in the south; and, complex interbedded sandstones and siltstones inter-finger with claystone in the centre of the basin (Ambrose 1980; Hawke & Bourke 1982; Forbes 1986; Green et al. 1989). A thickening of this unit occurs to the north, with it being patchy or absent in the south of the basin (Green et al. 1989). The largest volume of hydrocarbons within the basin is hosted within these sediments (Green et al. 1989), possibly due to the nature of the facies variations and the traps that this has created. The facies variations are attributed to the varying depositional environments. These include: braided river systems, point bars, alluvial flood outs, fans, alluvial plains, and minor lacustrine environments (Ambrose 1980; Hawke & Bourke 1982; Forbes 1986; Green et al. 1989). This unit is widely referred to as the Hutton Sandstone (Green et al. 1989); however, is here classified as part of the basal Algebuckina Sandstone.

The variation in sediment type continued throughout the deposition in the mid to Late Jurassic sediments; however, the lateral variations are not so evident. Massive, cross-bedded, quartzose sandstones dominate the top of the formation, with beds of clast-supported conglomerates composed primarily of well-rounded quartz pebbles throughout (Day 1969, Forbes 1986). A thickening of this unit occurs to the east near the Surat Basin, where substantial syn-depositional tectonism resulted in a substantial localised increase in subsidence (Green et al. 1986). Sediment thickness variations throughout the top of this formation are attributed to the active tectonism during the mid to Late Jurassic (Ambrose 1980; Forbes 1986; Green et al. 1989).

Lateral equivalents of these sediments accumulated within the Surat and Carpentaria basins in similar depositional environments (Green et al. 1989) indicating that the differentiation between the basins had not yet occurred.

Figure 2.9 Palaeogeographical interpretation of the basal Mesozoic from Alexander et al. 2007.
2.5.2 Transition zone: the Cadna-owie Formation

The Cadna-owie Formation marks the transition from fluvial to shallow marine environments within the basin. It is a transitional unit with gradational boundaries at both the base and top of the succession. In some areas in the south of the basin this unit is distinguished from the underlying Algebuckina Sandstone by an acute angular-unconformity (Wopfner et al. 1970), despite any lithological variation between the tilted and flat lying bed. This assumption is based on there being an absolute base to the formation, which contradicts the transitional nature of these sediments. This acute angular-unconformity is mostly representative of a change in the tectonic environments during deposition, which resulted in a tilting of some of the strata, as opposed to a lithological boundary. In some areas of the basin, Cadna-owie Formation sediments directly overlie crystalline basement. Where this disconformity occurs, the age of the sediments, typically based upon fossil and palynological data, is used to classify them as Cadna-owie Formation.

In general, the Cadna-owie Formation is used to define the Early Cretaceous (approximately Neocomian) terrestrial and marine sediments that contain a variety of facies from various depositional environments. Generally this formation is the result of the basin-ward progradation of the Eromanga Sea. Thus, descriptions of the stages of the typical facies of this formation are not specifically related to depths, but rather are relative, in accordance to the transgression of the sea. The basal parts of this formation are dominated by claystone, siltstones and fine to medium sandstones with conglomeratic lenses (Wopfner et al. 1970; Byrnes 1973; Hawke & Bourke 1982; Forbes 1986). The conglomerates are generally dominated by large, well rounded clasts of white quartz, quartzite and lithic fragments. Ripple marks, shell fragments and the rounded pebbles indicate primarily paralic, braided fluvial depositional environments with some of the finer-grained facies pertaining to lacustrine and alluvial plains and flood-outs (Ambrose et al. 1986). Minor glacial units have been recognised within these sediments in the south of the basin (Alley & Frakes 2003); however, similar interpretations have not been formally made further into the basin. Secondary cementation has in-filled pods in both exposure and the subsurface within the base of this formation making it difficult to determine detail about the original depositional environments.

The bulk of the Cadna-owie Formation is defined by clayey facies containing minor glauconite and numerous calcareous layers (Byrnes 1973; Hawke & Bourke 1982). For the most part, the detrital component of the sediments is predominantly reworked quartz and minor feldspar, with varying amounts of micas (glauconite, muscovite and biotite) and locally derived lithic fragments (such as garnet, ferruginous inclusions and volcanoclastics) (Wopfner et al. 1970; Byrnes 1973; Hawke & Bourke 1982; Ambrose et al. 1986). Pyrite concretions are abundant in some sandy facies, often in cubic form (Forbes 1986).

The first major marine transgression within the area was recognised by marine fossils within claystones in the south of the basin (Alley 1987; Alley & Lemon 1988). Despite initial interpretations suggesting that these sediments were correlative with the early phases of the Algebuckina Sandstone, the micro-plankton assemblages are indicative of Neocomian fossils (Alley & Lemon 1988). Laterally equivalent sediments from the Carpentaria Basin host similar fossils, supporting the interpretation of a widespread marine transgression (Alley & Lemon 1988). Previous minor marine transgressions have been interpreted throughout the northern margins of the basin (Morgan 1980; Alley & Lemon 1988), but these are limited both spatially and temporally. Interpretations of the marine shorelines throughout the Mesozoic define the seaway that occurred around this time as only being narrow (Figure 2.10), with considerable fluvial and lacustrine environments in the surrounding areas (Frakes et al. 1987). The extent of the transgression is thought to have been structurally controlled (Frakes et al. 1987), potentially indicating the beginning of the differentiation of the GAB.

The top of this unit is defined by a friable, thin bedded, clay-rich mudstone intercalated with a massive sandstone (Hawke & Bourke 1982). Coarse-grained units are cross-bedded and mostly have minor thin layers of peat (Hawke & Bourke 1982). The intercalated nature of these sediments is indicative of a progradation – aggradation cycle, possibly driven by the substantial tectonic instability of the area at that time. This cyclic sedimentation
corresponds to the short lived period of fluctuating global sea-levels during the late Neocomian (Figures 2.2 and 2.2).

2.5.3 Marine sedimentation: the Bulldog Shale
The Bulldog Shale marks the onset of the major marine transgression within the basin during the Aptian (Figure 2.10) (Griffiths 1980; Forbes 1986; McKirdy et al. 1986; Van Doan 1988; Kreig & Rogers 1995; DeLurio & Frakes 1999). At this time, the sea extended inland via the Eromanga seaway, from the Gulf of Carpentaria in the north of Australia (Figure 2.10) (Frakes et al. 1987).

This formation was first defined by Freytag (1966) from a section south of Bulldog Creek to the east of the Peake and Denison Ranges in South Australia. Throughout the basin, the thickness of this formation is highly variable, ranging from meters near the margins of the basin to 320 m near Moomba in South Australia (McKirdy et al. 1986). This sediment package is considered to be the most laterally extensive package in the basin (Ludbrook 1966), as the marine transgression was widespread (Figure 2.10). These sediments are characterised by friable, grey to green shales, fossiliferous mudstones and bioturbated limestone with sporadic sandy lenses (Figure 2.11).

The base of the Bulldog Shale is typically defined by a thick conglomeratic layer consisting of well-rounded quartz, quartzite, siltstone and shale pebbles hosted in a sandy-kaolinitic matrix (Flint et al. 1980; McKirdy et al. 1986; Van Doan 1988). Many of these clasts have been derived from the re-working of Permian glacial sediments within the area. Devonian fish fossils within some of the quartzite and sandstone clasts indicates their provenance from the reworking of Permian glacial sediments some of which transported clasts of Devonian sediments from the Amphitheatre Group in NSW (Flint et al. 1980). In some areas in the south of the basin, the Bulldog Shale unconformably overlies the Precambrian basement. In these areas, the basal unit is characterised by a thin, matrix-dominated, heterogeneous conglomerate bed that grades into a thicker sequence of friable, kaolinitic and occasionally alunitic shale (Van Doan 1988). These conglomeratic packages are interpreted to have been deposited as low-angle episodic debris flows during the initiation of the marine incursion (Flint et al. 1980), potentially representing transgressive lag deposits.

Immediately above the basal conglomerates are successions of organic-rich, black-dark brown shales (Kreig 1982; McKirdy et al. 1986). These sequences have an abundance of opaline and pyritised petrified terrestrial wood fragments and fossilised root casts (Moore & Pitt 1985). A mineralogy dominated by pyrite and glauconite indicates alternating anoxic conditions, and from the shaly nature of the sediments it has been interpreted that these fossils have been transported and were not fossilised in situ (McKirdy et al. 1986). In the central region of the basin this facies is up to 25 m thick, has a high gamma-log response and a low sonic velocity (McKirdy et al. 1986).
Chapter Two: Literature Review

Figure 2.11 Bulldog shale sediment exposure from the west margin of the Freme Embayment (375259mE / 6682037mN). Exposure is in a small creek bed abutting the Flinders Ranges near Parabarana (see chapter 5).

Above the basal conglomerates and organic-rich shales, the Bulldog Shale has informally been divided into an upper and lower unit defined by variations in sediment characteristics (Griffiths 1980). The lower unit is characterised by bioturbated grey and black shales with sporadic silty and sandy lenses with meso-scale cross-bedding (Griffiths 1980). Mineralogy is dominated by weathered volcanoclastics (Holbrook 1966) with secondary infilling in many burrows by pyrite and glauconitic sands (Griffiths 1980, McKirdy et al. 1986). Locally, where pyrite is extensive, an abundance of secondary gypsum, predominantly in the form of selenite, is typical. Glendonites, a unique mineral assemblage of pseudomorphic calcite replacing metastable ikaite, are in some shale beds in the lower parts of this unit (DeLurio & Frakes 1999). Glendonites only form at low temperatures (-1.9 to 7°C), in alkaline marine or terrestrial waters that are rich in orthophosphates (DeLurio & Frakes 1999). The presence of the glendonites indicates that at the time of deposition, the climate was exceptionally cold, and the sediments were most likely hosted in a reducing environment. The decay of organic matter common to the shales could have contributed to the development of reducing conditions, and also the abundance of orthophosphates. These beds are hosted in the shales that contain the Mesozoic plant and wood fossils thought to have come from warm, wet environments (Van Doan 1989, Frakes et al. 1987) producing contradicting information about the palaeoenvironmental conditions. While the plant and wood fragments were not fossilised in situ, they have been categorised as being from that time and interpreted to have been derived from within close proximity to the sediments (Griffiths 1980). This evidence suggests that during the Aptian-Albian, the climate was highly variable and fluctuated regularly (DeLurio & Frakes 1999). Sediments in this sub-unit are characteristic of a low energy marine environment occasionally exposed to intermittent current activity (McKirdy et al. 1986).

The upper sub-unit is dominated by inter-bedded, grey, occasionally pallid shales and argillaceous siltstones (Griffiths 1980; McKirdy et al. 1986). Drop-stones and large clasts are sporadically distributed throughout the shales, particularly in the darker sandier units (Van Doan 1989; Alexander & Kreig 1993). Mineralogy is also dominated by volcanoclastics, with a higher abundance of glauconite and pyrite (Griffiths 1980). The vast amounts of glauconite in these sediments could be attributed to periods of slow or minimal deposition when marine digenesis was potentially occurring. Periods of slow or minimal deposition could also explain the lack of larger fragments and clasts that tend to be throughout the darker, glauconite-depleted sediments. Concretionary limestone clasts and cone-in-cone dewatering structures are common within the siltstone layers (Kreig 1986). This unit contains well preserved fossilised terrestrial plant and shell fragments (Holbrook 1966; Griffiths 1980). Sedimentary environments for this sub-unit are interpreted to have been below the wave base in shallow marine environments (McKirdy et al. 1986).
2.5.4 Transition zone: the Oodnadatta Formation

Conformably overlying the Bulldog Shale are the sediments from the Oodnadatta Formation (Freytag et al. 1967; Van Doan 1988). This formation is predominantly composed of marine sediments but contains zones of considerably variable depositional environments. The basal units are difficult to distinguish from the underlying Bulldog Shale because the sedimentary environments are very similar, but, in general, this formation is considered to be a sandier variable unit as opposed to the generally homogeneous Bulldog Shale. At the type section near Oodnadatta, South Australia the sediment package is up to 140 m thick (Freytag 1966; Forbes 1986).

![Figure 2.12 Oodnadatta Formation type section, Mt Arthur South Australia (Photo T047444 from Alexander et al. 2007).](image)

This formation is defined by three separate packages: The Coorikiana Member; Wooldridge Limestone; and, Mt Alexander Sandstone Member.

The Coorikiana Member (often referred to as the Coorikiana Sandstone (Moore et al. 1986) and the Terebratella Beds (Sprigg 1958a) grades from the Bulldog Shale in the south of the basin, often considered absent or patchy in New South Wales. Typically the sequence grades from basal sandy-siltstone to moderately sorted, fine to medium-grained, calcareous, occasionally glauconitic sandstone (Ludbrook 1966; Moore et al. 1986). In the central parts of the basin, laterally discontinuous lenses of sandstone that have their base in the Bulldog Shale penetrate the basal siltstones (Moore et al. 1986). Further north the unit is dominated by massive glauconitic sandstones with layers of calcareous cements up to 15 cm thick (Ludbrook 1966). Megafaunal associations date the base of this unit to lower to mid-Albian (Ludbrook 1966; Dettman & Playford 1969); however, uncertainties as to the differentiation between it and the underlying Bulldog Shale possibly push the age to late Aptian (Moore et al. 1986).

In the centre of the basin, predominantly in Queensland and South Australia, overlying the Coorikiana Member are interbedded black, bituminous shales and calcareous siltstones and mudstones from approximately the mid-Albian (Day 1969; Senior et al. 1975; Hawke & Bourke 1982). In New South Wales this unit boundary is marked by the uplands (Grey Range) corresponding to the Tibooburra Ridge (Hawke & Bourke 1982). The bituminous shaly facies contain abundant carbonaceous material, occasional fish fossils and calcareous shell fragments (Moore et al. 1986). The siltstones and mudstones are dominated by laminated dark-grey and grey clays and occasional limestone beds (Moore et al. 1986). This zone is typically recognised and correlated in the subsurface using gamma-log anomalies, as the contrast between the two facies produces a unique ‘saw-tooth’ signature (Ozimic 1982; Moore et al. 1986). The depositional environment has been interpreted to have been restricted marine, with a halocline below a near fresh layer of water (Ozimic 1982). The calcareous nature of the mudstone,
abundance of carbonaceous materials and the limited input from terrestrial environments has been interpreted to represent slow, low-energy deposition (Moore et al. 1986). The abundance of carbonaceous material has been attributed to an algal mat that is thought to have perched just above the sediment-water interface (Moore et al. 1986). This unit is typically referred to as the Toolebuc Formation or Toolebuc Limestone or the Toolebuc Interval (Vine et al. 1967; Hawke & Bourke 1982; Moore et al. 1986). Overlying this interval is a zone of blue-grey shales that contain abundant planktonic fossils suggesting the return to open marine conditions (Hawke & Bourke 1982). The Wooldridge Limestone Member is composed of calcareous, sandy siltstones, with minor limestone concretions (Forbes 1986). Where the Toolebuc Formation is absent, the basal Wooldridge Limestone forms the lateral equivalent. Salert facies in this unit contain ammonites from the late Albian (Ludbrook 1966; MacNamara 1980). This unit is not recognised within the New South Wales portion of the basin; however, laterally equivalent sediments consisting of pallid calcareous sandstones and mudstones of similar age are common (Hawke & Bourke 1982).

The final unit within the Oodnadatta Formation is the Mt Alexander Sandstone Member (Forbes 1986). It consists of fine-grained glauconitic sandstones and shaly siltstones (Forbes 1986). At the base of the unit, the fine-grained facies consists of blue-grey mud with thin calcareous laminations (Vine & Day 1965) similar to the sediments that mark the top of the Toolebuc Formation (Hawke & Bourke 1982). Uncertainty exists with the correlations with the Mackunda Formation, a sub-group defined within the Manuka Sub-group from Queensland (Forbes 1986) and the New South Wales Allaru Mudstone (Hawke & Bourke 1982) (Figure 2.9). This unit is a regressive unit, considered to be representative of the regression of the Eromanga Sea at the end of the Albian.

2.5.5 Final deposition: the Winton Formation
The Winton Formation marks the end of deposition within the Eromanga Basin. Following the short-lived hiatus in sedimentation at the end of the Albian, minor subsidence occurred at the beginning of the Cenomanian giving rise to the development of fluvial environments. Around the Patchawara Trough in the centre of the basin this unit exceeds 1200 m, which is the greatest thickness of any unit within the basin (Rogers 1986). This formation consists of interbedded, terrestrial mudstones, lithic and arkosic sandstones and sporadic gravely conglomerates (Whitehouse 1955; Hawke & Bourke 1982). Abundant coal and lignitic beds are throughout this formation, typically dominated by ‘banded’ vitrinite (Cook 1986). This formation contains abundant cross-bedding indicating a fluvial influence during deposition (Hawke & Bourke 1982). Across the basin, the Winton formation is characterised by a thick zone of weathering. This zone, as previously mentioned is defined by the Morney and Canaway profiles, two zones of intensely weathered sediments dominated by kaolinite and ferricretes (Idnurm & Senior 1978; Schmidt & Ollier 1988). In places the weathered profiles can be up to 100 m in vertical extent, dominated by three zones: a basal ferruginised zone with abundant ferruginous nodules and iron stones; kaolinitic profile with some ferruginous, and gypseous inclusions; and, a thin silcrete profile (Idnurm & Senior 1978). Characteristic features of the profiles include kaolinitic breccias, red and purple mottling and preserved microfossils that have been used to determine that the profiles are in fact Winton Formation.

Following the deposition of the Winton Formation, was a period of substantial sedimentary hiatus. The next major period of sedimentation did not occur within the region until the onset of the Lake Eyre Basin in the late-Palaeocene.

2.6 Economic Geology
The economic geology within the basin has typically focused on petroleum. The basin does not have the typical conditions needed to support hydrocarbon formation as it is relatively shallow and young (Pitt 1986). Despite this, the basin hosts abundant gas, oil and coal deposits (Figure 2.13). The production of hydrocarbons within the basin is attributed to elevated geothermal gradients (Pitt 1986; Gallagher 1990). This geothermal ‘kitchen’ has aided the maturation of the hydrocarbons in the basin, such that the typical burial or time factors are not needed.
The basin hosts Australia’s largest onshore oil field, the Jackson Field in southwest Queensland (Figure 2.13). The Jackson Field and associated satellite fields are estimated to host 360 million barrels of oil in place (BOOIP) from 40 fields; however, it is estimated that only 110 million barrels are extractable from the 182 oil producing wells (www.santos.com). Up until May 2008, 95 million barrels had been extracted (www.santos.com). Most of the oil within the basin, including the Jackson fields, is hosted in structurally controlled traps, many with secondary sedimentary traps. Oil is formed from three primary sources: two from the underlying Cooper Basin; and, one from the lower coaly units in the Patchawarra Formation. The marine sediments from the Bulldog Shale and the Oodnadatta Formation have been recognised as potential source rocks as well; however, this is still a contentious issue. Primary migration was into the Hutton Sandstone, with the basal units of the Birkhead Formation providing a seal. Tectonism has resulted in secondary migration into the Birkhead Formation, Hooray Sandstone and to a lesser degree the Cadna-owie Formation. The Bulldog Shale acts as a regional seal.

Gas commodities within the basin include the Moomba Zone and the Ballera Gas Zone, the two largest gas producers in Australia. Ballera, in southwest Queensland, includes 45 gas fields with 130 operational gas producing wells. The majority of the commodity extracted here gets pumped to the Moomba Facilities in northern South Australia. Moomba includes 115 gas fields with 536 gas producing wells (www.santos.com). Moomba also has a smaller oil plant, operating from 28 fields with 177 oil producing wells.

Base metal deposits are widespread, but not abundant throughout the basin. Copper occurrences are common, and few 10, 000 – 100, 000 tonne deposits are hosted in the area of the southern part of the basin and a 250, 000 to 1 000, 000 tonne deposit at Osborne in western Queensland (Jaireth & Porritt 2008). The largest occurrence is at Olympic Dam iron oxide, copper-gold deposit where copper, gold, silver and uranium are mined. The second
largest base metal deposit in the basin is the Prominent Hill deposit, where copper is one of the main ore minerals. The southern margin is host to several uranium deposits, as well as several active mines including the Beverley and Four Mile deposits, hosted in Cainozoic sediments near the northern Flinders Ranges (see chapter 5) and the Honeymoon and Goulds Dam deposits further south (McKay & Mietzis 2001; McKay et al. 2008). Small gold deposits are scattered throughout the basin (Huleatt & Jaireth 2008). Included in these deposits is the Prominent Hill deposit, in which a zone of alteration extending up within Basin sediments. The Olympic Dam deposit is hosted on the southern margin, but not within the basin sediments (Huleatt & Jaireth 2008). Other deposits are hosted around bedrock inliers in northwest NSW (see chapter 6) as well as in southern Queensland (Huleatt & Jaireth 2008). Precious gems are a rare occurrence in the basin. No recognised diamond deposits are hosted; however, diamondiferous intrusions and subtrusives crop out and underlie basin sediments (Jaques 2008). These bodies resemble, both chemically and physically, other diamond bearing intrusions from within Australia, and thus are a target of interest. Opal deposits are common throughout the southern portion of the basin, particularly around northern NSW and in central South Australia. Two main active opal provinces are within the basin, the Coober Pedy field in central South Australia, and the White Cliffs deposit in northern New South Wales. The basin is also an integral part of the recent geothermal advances within Australia. Underlying crystalline basement in the region is typically renowned for being a combination of high heat producing granites, gneisses and metasediments (Figure 2.14) (Gallagher 1990; Alexander 2004; Draper & D'Arcy 2006). The sediments within the basin form a blanket over the rocks sealing in this heat. This forms a geothermal reservoir that spans almost the entire Basin. Average thermal gradients range between 30-50°C (Polak & Horsfall 1979; Pitt 1986; Alexander 2004) with local anomalies recorded between 80-103°C (Polak & Horsfall 1979; Pitt 1986; McLaren et al. 2006).

Figure 2.14 Estimated crustal temperature at 5 km depth for Australia (Holdgate & Chopra 2004).

Current geothermal exploration is focused within the central portion of the basin, and within the South Australian portion of the Frome Embayment (Alexander 2004). These areas have been targeted because this region is
considered to have high crustal heat flow at 3 km depth (Alexander 2004). This area is also targeted as the artesian waters hosted within the basal Jurassic units have been heated to temperatures exceeding 100 °C. In 1986, a small geothermal test plant was set up at the Mulka Bore in South Australia (Alexander 2004). From this a 20 kW generator was powered. In southwest Queensland in 1999, a 90 kW generator was built powered off a 99 °C water bore heat source (Alexander 2004). In 2005 in the northeast of South Australia the Habanero project successfully flowed hot water between Habanero-1 and Habanero-2 (www.geodynamics.com.au). Cold water was pumped down Habanero-1 and flowed through the closed fractured rock system and back up through Habanero-2 at ‘super-high’ temperatures (www.geodynamics.com.au). Habanero-3 was proposed in 2007, to be the first well in Australia’s first commercial geothermal plant (www.geodynamics.com.au). The Yerila, Paralana and Callabonna wells in the south (see chapter 4) and the Savina wells are other examples of high heat producing well within the basin.

2.7 Contemporary Environments and Landscapes

Remnants of sediments from the Eromanga Basin are scattered across the landscape of central and eastern Australia (Figure 2.15). For the most part where exposed, these sediments form large undulating plains in a relatively flat landscape. In part, younger successor basins unconformably cover the sediments, such that the large plains are preserved in the subsurface, as seen in drill core and in exhumed and incised profiles. Throughout the basin, post-Mesozoic tectonism, weathering and erosion have exhumed mesas and mountains of these sediments particularly around the margins of the basin.

The most abundant Mesozoic sediments exposed within the contemporary landscape are the Marree Subgroup (and equivalents) and the Winton Formation. Exposures of both units are typically very highly weathered and altered. Marree Formation sediments dominate these exposures in the south and central regions of the basin. These sediments are often so highly weathered that they form large erosional gullies and extensive ‘pallid’ zones that have undergone extensive leaching (such as at White Cliffs in northern NSW). The Winton Formation dominates exposures northwards into Queensland. These sandstones form extensive plains that are broadly remnant of a Mesozoic land surface. For the most part, these sediments are also highly weathered; however, are typically more consolidated than the Bulldog Shale or Oodnadatta Formation.

Surficial exposures of the Algebuckina Sandstone are limited to the areas around the southern and south-western margins. However, Surat and Clarence-Moreton basin equivalent sediments crop out along the southeast margin of the GAB (Martin 1981; Chan 2009). Exposures of Cadna-owie Formation are prominent around the basin margins (however in exposures too small to map). Throughout the basin where recent tectonism has caused uplift, both of these formations have been exhumed.
Early to mid-Cretaceous sediments
Early Cretaceous sediments
Mid-Jurassic to Early Cretaceous sediments

Figure 2.15 Contemporary exposures of GAB sediments derived from the 1:1 Ma Solid Geology of Australia Geoscience Australia maps data base. Exposures are limited by scale, such that localities known to host some, but not an abundance of surficial GAB sediments, are not mapped.
Chapter Three: Methodology and Rational

This project uses a combination of geological techniques to create palaeogeological reconstructions of an embayment within an intracontinental basin in central Australia. The methodology for the project is split into two stages:

1. Palaeogeological reconstructions on a regional scale: integrating surficial geology, sedimentology and structure of the Frome Embayment.
2. Palaeogeological reconstructions of localised field areas within the region, such as in the vicinity of the Tibooburra-Milparinka Inliers and the northern Flinders Ranges.

3.1. Field Studies

The field study subdivision was made to test the effectiveness of a regional study compared to a localised study and also to assess and determine how the two approaches can be integrated to further clarify and elucidate the reconstructions. Both the regional and localised studies apply as many different techniques as possible, such that their effectiveness and ability to contribute to the geological evolution model can be assessed. As well as this, this project aims to test the ability of analysing surficial geology and processes to better understand subsurface geology.

The Frome Embayment was chosen as this is a part of the Eromanga Basin with different contemporary landscape expressions, despite many parts being covered by the Lake Eyre Basin sediments of the Callabonna Sub-basin (see chapter 4). This landscape combination allows for the potential to extrapolate the reconstructions from several different areas and into central Australia as well as providing the opportunity to test the same techniques on different terrains to determine the effectiveness and potential to develop a standardised palaeoreconstruction methodology. Furthermore, this is an area of considerable geological interest, and thus has an abundance of drillhole data, geophysics and remotely sensed imagery available.

The regional study incorporates techniques and methods typically employed in sedimentary basin reconstruction. There is a focus on combining geophysical techniques with well data and fieldwork. The localised field areas had a more detailed focus, centred around fieldwork, mapping sedimentological observations and associations.

The two local field areas were chosen based on exposure type and extent, as well as their position within the embayment. Both are marginal basin terrains, and thus in terms of landscape development, pose an interesting comparison. With the field areas being in different states, they provide an opportunity to address the shortfalls and divisions across state boundaries within regional analysis and compilation (chapter 2.1). Most importantly though, these field areas provide two different landscape settings where each contribute different aspects of a reconstruction both for reconstruction outcomes and analysis of techniques. The area of the Tibooburra-Milparinka Inliers are a regolith-dominated terrain surrounded by basin sediments, whereas the northern Flinders Ranges are a tectonically active, basin margin. The two areas also present an interesting contrast in the framework provided by the extent and detail of previous studies. The area of the Tibooburra-Milparinka Inliers have been the focus of many recent localised landscape studies (Anderson et al. 2004; Chamberlain 2001; Davey 2005; Davey & Hill 2005, 2006; Hill 2005; Hill et al. 2005; McAvaney 2006; McAvaney & Hill 2006); however, the studies on Mesozoic sediments have been limited; typically focused on fossils and formaferia
Chapter Three: Methodology

(Morton 1982) or on the authigenic processes that have affected them (Watts 1978; Stevens 1988). In contrast, the Mesozoic sequence in the vicinity of the northern Flinders Ranges have been the subject of considerable sedimentological studies. Many of these have focussed on specific detailed attributes of the sediments (Alley & Frakes 2003; DeLurio 1995; DeLurio & Frakes 1999; Norton 1983). Some more regional attempts at correlating the sediments have been conducted (Alley & Frakes unpublished; Van Doan 1988); however, these studies have also been biased towards a specific feature of the sedimentology. Landscape studies in the area have focused on Quaternary tectonism (Quigley et al. 2006; Quigley et al. 2007a); geomorphology of the ranges (Quigley et al. 2007b; Twidale 2000); and, localised geomorphology around mineralised and potentially mineralised zones (Dubinecki & Hill 2007; Hector & Hill 2007; Wilson 2007). No long-term, regional landscape history studies have been undertaken in the area. This equates to an abundance of localised landscape knowledge in different areas near the Tibooburra-Milparinka inliers, and an abundance of specific sedimentological knowledge in the northern Flinders Ranges. Neither field area has a regional landscape evolution model that incorporates both contemporary landscape and Mesozoic sediments. The Mesozoic focus and objectives of this project bases techniques around the Mesozoic sediments in the field areas.

3.2 Geophysics and Remotely Sensed Imagery

The geophysical interpretation focused on two data sets: 1. remotely sensed imagery and air-borne geophysics; and, 2. seismic surveys.

3.2.1. Remotely Sensed Imagery & Potential Field Surveys

Remotely sensed imagery and potential field surveys were used to assist with land surface, regolith lithology and materials, structure and geomorphology mapping. Imagery used includes:

- Digital Elevation Model (DEM) derived from Australia and South Pacific Shuttle Radar Topography Mission (SRTM) imagery. SRTM is a form of synthetic aperture radar (SAR) that is mounted on a space shuttle that orbits the earth. The SRTM data differs from other earth radar images as it uses bi-perspective radar or radar interferometry to collect two viewpoints of the earth during the orbit. The difference between the two images is used to calculate surface elevation changes. The data set is comprised of data sampled spatially at 3 arc-seconds, approximately 1/1200th of a degree of latitude and longitude, equating to approximately 90 meters of resolution. At the time of mapping, this was the highest resolution available for the area and for the Australian continent. The SRTM data set used was the version 2 or ‘final’ version of the 90 m resolution radar. It has been edited by the National Geospatial Intelligence Agency so that landforms such as lakes and channels are clearer than previous editions. The unprocessed SRTM was purchased from the NASA Data Base. Data was processed in Global Mapper and ArcGIS, and used to refine localised mapping, and identify aspects of the surface to be incorporated into the regional mapping. The DEM was generated by converting the world tiff file downloaded NASA ([http://www2.jpl.nasa.gov/srtm/](http://www2.jpl.nasa.gov/srtm/)) into 3D point data that was then gridded. The Frome Embayment has no data voids, wells or spikes that affect the resolution of the grid. A SRTM data set with approximately 30 m resolution was released in late 2009; however, this was too late to aid with mapping and interpretations. It is estimated that the processed data set will be available in 2010, beyond the scope of this work.

- Landsat, air photography. The Landsat-7 satellite uses a Multi-spectral-scanner to collect panchromatic, reflected, near-infrared (NIR), mid-infrared and infrared light to make pictures of the earth’s surface. These bands of light are processed to highlight specific land surface features. Three different processed images were used; these include:
  
  i. Regional, 300 m resolution, Landsat-7 imagery with averaging of brightness for multi-spectral bands with matching of scene statistics in the forward and reverse scans (NASA processing
methodology) (CIGAR 2009 electronic resource). Two versions of this data set were used: the ‘natural’ colour and the ‘pseudo’ colour images. These images are versions of the reflected light and NIR spectra processed to approximate land surface colours; that is, processed to look like actual air photographs. The natural colour image is coloured as close to true colour as possible, and the pseudo colour is an exaggerated version of this. On the pseudo colour image, the land surface is near natural with features such as water bodies exaggerated in bright colours dependent upon their reflective light signal. Examples of this are water being bright blue and salt iridescent white/pale brown.

ii. Koonenberry, western New South Wales Landsat 3-4-7 Brovey imagery courtesy of the NSW DPI. Imagery using Landsat bands 3, 4 and 7 has been processed with a Brovey Fusion cycle. This technique involves each selected band being divided into its separate channels from which they are then normalised. The layers are then multiplied with a panchromatic band to ‘fuse’ all bands together. This image was initially processed by the DPI in 2005; however, was reconstructed in 2007 using bands 3, 4, 6 and 7 to try and refine the multispectral divisions between regolith types.

iii. Multispectral Quickbird imagery with a resolution of 2 m. (multispectral bands MS Channels: blue: 450-520nm, green: 520-600nm, red: 630-690nm, NIR: 760-900nm). This image is also a ‘natural’ colour image, processed to be a near accurate image of the land surface. Procession of this data was conducted in 2006 by Heathgate Resources. This imagery was supplied by PIRSA.

- Radiometrics from the Australian Survey (Geoscience Australia). This image shows the surficial distribution of Uranium, Potassium and Thorium over an estimated 80 % of the continent. The grid is a merge of 550 airborne gamma-ray spectrometry from the national radioelement database. Gridding is conducted using minimum curvature (Minty et al. 2009). The cell size of the national grid ranges from 50 m to 800 m, with some places not covered. The average cell size across the grid is 100 m. The maps were used locally when they were of good quality.

- Isostatically corrected gravity survey: survey cell size of 0.5 min arc with Bouguer anomalies at a density of 2.67 tonnes per cubic meter. Approximately 200 m resolution (Bacchin 2008).

- High resolution airborne magnetic survey from the national survey (conducted by Geoscience Australia) comprised of a composite of shot height of 250 to 400 m with 100 m survey line spacing totalling to over 9 million line km of data (Milligan et al. 1999; Milligan & Franklin 2004 a & b). Cell size approximately 90 m (Hill 2006). Magnetic imagery used was TMI processed using Global Mapper and ArcGIS from the basic survey points from Geoscience Australia.

3.2.2. Seismic Survey Analysis

Seismic survey data were used as a means of imaging the subsurface across the embayment. Seismic data provides an extension of well data, such that in areas where there was limited well information, or where well logs were not available, the seismic data could be used to correlate and define sedimentary boundaries. The complete Arrowie Basin survey set from PIRSA and surveys from the Tibooburra seismic set from the NSW DPI were merged and loaded into Move and Petrel, which are both structural and modelling packages. In total, 323 2D seismic surveys were loaded for the embayment, totalling 3689.2 km. A quality assessment was made on the lines before interpretation to determine data quality and the lines that are adequate for interpretation (See appendix 1). This assessment was based upon the visibility of reflectors, migration attributes and processing quality, as well as scanning the quality of data that had been transcribed from paper. Four categories of quality were assigned, including:
Chapter Three: Methodology

- Good: clear reflectors, minimal survey noise, minimal migration effects - survey easily interpreted;
- Moderate: reflectors present, some survey noise, migration patterns; however, minimal interference with data - survey interpreted with minor difficulty;
- Poor: minimal reflectors, extensive survey noise, migration effects masking data visibility, parts of survey missing - difficult to interpret survey; and,
- Bad: migration patterns, noise and missing data dominate section - interpretation impossible

Only survey lines with good or moderate classifications were used. Interpretation was conducted using the basic seismic stratigraphic approach defined by Mitchum et al. (1977) and Hubbard et al. (1985). This technique analyses reflector terminations and parameters including reflector amplitude, continuity and geometry (Hubbard et al. 1985). Basic structural interpretation was also carried out on high quality lines. All lines were normalised or corrected relative to sea level, and tied to all major wells that penetrate to bedrock that had checkshot data (velocity-depth surveys) available. While correcting datum to sea-level is not a standard for onshore seismic data, it is used as a basic standardising mechanism to overcome issues associated with the age and lack of information on many surveys.

A line from the Lakes Crossing seismic Survey was used as a guide for identifying horizons throughout the embayment. This survey was used because it had been tied to several deep wells and could be easily corrected to sea level.

This line also had depth-velocity curves available. Depth velocity data availability was an integral component in choosing a standardised pick set to adhere to as it allowed for the conversion of the time seismic surveys to be associated with the depth of formation tops in the wells. These standardised picks also correspond to the standardised horizons from the Lake Stewart Seismic survey in New South Wales (Namco 1962) and from the surveys in the western margin of the basin in Queensland (Edwards 1991).

To convert the seismic data from the acoustic wave travel time of standard seismic reference units of two way time (TwT) into depth, a regional velocity function was applied. Seismic studies in the Eromanga Basin have previously used a form of interval velocities (a different depth conversion function for each horizon) for depth conversions (for example Hillis et al. 1995). Eromanga Interval velocities have been focused on applying different
functions based upon major facies variations. Three subsequent zones are defined in this methodology: 1. base fluvial (Top Cadna-owie to base Algebuckina); 2. mid-marine succession (base Bulldog Shale to the top of the Oodnadatta Formation); and, 3. the top fluvial units (Winton Formation and subsequent successor basin sediments) (Hillis et al. 1995). While it is typically better to use interval velocities, the Eromanga sediments in the embayment rarely exceed 1 second. Localised studies within the embayment that focused on the shallow basin sediments indicated that the variations in sediment facies and thicknesses are not significant enough to warrant interval velocities (Hughes & Fitzgerald 1995; Meyers et al. 2006). Because of this, a single velocity function was applied over the entire basin sequence. The merged Arrowie and Tibooburra seismic surveys were intersected by few wells. Many of these wells did not have checkshot data published or publically available. As such, limited data was available for this application. It is widely accepted that for seismic depth conversion for reflectors from 0-1.5 seconds, time approximates depth, and thus the limited velocity data can be applied across the embayment. Once expressed in depth, seismic was then tied to well data to rectify issues generated by the depth conversion, and the lack of checkshot data available.

Table 3.1 Seismic characteristics of the Eromanga Basin sediments in the Frome Embayment.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Seismic Characteristic</th>
<th>Sediment Characteristic</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Land surface not reflected on seismic</td>
<td>Poorly consolidated sands, silts, and clasts</td>
<td>Land surface not reflected on seismic</td>
</tr>
<tr>
<td>Cainozoic</td>
<td>Low amplitude, discontinuous, single loop reflector</td>
<td>Interbedded claystones, sandstones, siltstones and conglomerates</td>
<td>Occasionally too shallow to detect on seismic</td>
</tr>
<tr>
<td>Winton Formation</td>
<td>Low amplitude, discontinuous, single loop reflector</td>
<td>Sandstones and occasional siltstone</td>
<td>Generally absent</td>
</tr>
<tr>
<td>Oodnadatta Formation</td>
<td>Medium to high amplitude, continuous, single loop reflector</td>
<td>Marine shales: glauconitic shales, claystones, occasional pallid zones</td>
<td>Present across the whole Basin</td>
</tr>
<tr>
<td>Toolebuc Formation</td>
<td>High amplitude, continuous double loop reflector</td>
<td>Coaly sandstones and shales</td>
<td>Easily recognised in petrophysical logs</td>
</tr>
<tr>
<td>Bulldog Shale</td>
<td>High amplitude, continuous, single loop reflector. Patches of medium amplitude, discontinuous, double loop reflectors within unit</td>
<td>Poorly consolidated marine shales: glauconitic shales, claystones, hashy sandstones and siltstones. Abundant disseminated gypsum. Coal zones</td>
<td>Present across the whole Basin. Occasional intense zones of soft sediment deformation, make reflector appear discontinuous</td>
</tr>
<tr>
<td>Cadna-owie Formation</td>
<td>Medium amplitude, continuous, single loop reflector; wormy seismic characteristic below</td>
<td>Claystone, sandstone, occasional conglomerates</td>
<td>Thins to the south of the basin</td>
</tr>
<tr>
<td>Algebuckina Sandstone</td>
<td>Low amplitude discontinuous reflector</td>
<td>Sandstones, siltstones and conglomerates</td>
<td>Some reflectors possibly indicating coal</td>
</tr>
<tr>
<td>Bedrock</td>
<td>High amplitude, continuous reflector, up to three loops</td>
<td>In places crystalline basement. Typically metasediments from the Arrowie Basin</td>
<td>Often faulted, in places intensely deformed. Sometimes interference from migration and stacking issues (seismic smiles)</td>
</tr>
</tbody>
</table>
3.3 Surficial Geology and Mapping
The surficial geology of the field sites was characterised by mapping the areas. Scale variations resulted in the style of mapping being different between the regional field site and the localised studies.

3.3.1 Fieldwork
Because of the size of the area, extensive fieldwork was not possible on a regional scale; however, opportunistic fieldwork was conducted in March, April and August through to September in 2006, February, July and November 2007, and again in July 2008. These trips were based around areas known to host exposures of Mesozoic sediments and areas of varying landforms and morphology. For the most part, these trips were designed to assist with regional mapping in order to check specific features on remotely sensed data, and to analyse rock exposures. Major fieldwork was conducted extensively throughout the northern Flinders Ranges and Tibooburra-Milparinka Inliers as these were the areas of the localised studies. Each field area was divided into smaller target zones to better characterise Mesozoic sediments and associated regolith and structure. This division of the main areas is outlined in the Mapping Methodology. As well as the primary field areas smaller areas around the embayment were also incorporated in fieldwork for reference points in the regional studies. These areas were targeted as there were either known exposures of the Mesozoic or regolith features that needed defining for the surface mapping.

Areas targeted for the regional fieldwork included Fowlers Gap in the Barrier Ranges in western NSW, the Lake Frome chain of lakes in South Australia, basin terrains around Mt Hopeless in the northwest of the basin in South Australia, transects along the Silver City Highway in NSW and sporadic destinations within the southern part of the Strzelecki and Sturts Stony deserts. Where possible, samples from these areas were collected and analysed.

3.3.2 Mapping
Initially, the areas of the localised field areas were mapped, focusing on identifying the extent and types of exposures of Mesozoic sediments. From this initial mapping, each field area was subdivided into either major geomorphic terrains or places of interest that warrant further mapping in detail.

The recent landscape studies in the area of the Tibooburra-Milparinka Inliers provided a regional subdivision primarily based on the extent and exposure of the inliers and their margins. The four areas defined include:

- Tibooburra Inlier: the Tibooburra Inlier, and surrounding sand plains and extensive plains of Mesozoic exposures in the north (Chamberlain 2001; Hill et al. 2005).
- Warratta Inlier: the eastern rangefront of the Warratta Inlier along the Warratta Fault (Anderson et al. 2004).
- South Warratta: South Warratta and New Bendigo inliers, peak hill and the extensive plains of Mesozoic sediments up to Mt Wood (McAvaney 2006; McAvaney & Hill 2006).
- Southern Inliers: Mt Poole, Mt Browne and Gorge inliers, Mt Poole, the ‘jump ups’ and the Milparinka sand plains (Davey 2005; Davey & Hill 2005, 2006, 2008).

To assess the relevance of this previous division for use in this study, preliminary regional reconnaissance and mapping was conducted. From this it was established that these field areas would be used as the basis to define new sites for detailed study within the area. Adjustments were made to the extent of many of the field sites so that they were divided by major structural features and geomorphology (as opposed to site size and extent of the inliers) and such that the Mesozoic sediments were in focus.
Figure 3.2 Location of the Frome Embayment within Australia and DEM of the Frome Embayment. The DEM of the Frome Embayment has the approximate area incorporated within the study, incorporating areas beyond the scope of the contemporary basin, such that ranges and rises that are renowned for hosting Mesozoic sediments could be included. Main image shows fieldwork distribution throughout the embayment. Back ground image of 30 m cell size DEM.
The previous mapping from the Warratta Inlier (Anderson et al. 2004) was limited in extent, and focused on the inlier's eastern range-front fault. This excluded the western part of the inlier where Mesozoic sediments lap onto the bedrock, and the plains either side of the ranges. For this study, the area defining Warratta Inlier area was extended to include both sides of the inlier, the western sand plains and the Silver City highway plains as defined by Davey & Hill (2008). The Southern Inliers (Davey 2005; Davey & Hill 2005, 2006) and South Warratta (McAvaney 2006; McAvaney & Hill 2006) field sites were merged in to one site, as the morphology of both areas is controlled by concordant structures. The area extending between them, through the northeast of Milparinka, was previously unmapped, despite hosting important Mesozoic sediment exposures. The merged areas were remapped and termed the Milparinka Inliers as defined by Davey et al. (2008). The Tibooburra field area was left the same as the area defined by Chamberlain (2001) and Chamberlain & Hill (2002).

Preliminary regional field mapping of the northern Flinders Ranges was conducted with the intention of identifying the extent and nature of exposed Mesozoic sediments, and specifically identify areas of interest. Five field sites were selected for detailed study. These localities were chosen based upon the type, preservation and extent of exposure and landscape relationships. These areas include:

- Parabarana Well, east of Mt Neill: including near continuous exposure of Mesozoic sediments, their basal unconformity and relationships with the overlying Eyre Formation;
- Mt Babbage Inlet, north Mt Babbage Inlier: faulted, folded and uplifted basal Mesozoic and marginal marine sediments;
- Moolawatana, Moolawatana homestead: preserved shorelines, transition sediment exposures & Marree Subgroup profiles;
- Birthday Well, Terrapinna Corridor: previously unmapped fault controlled exposures of Mesozoic sediments overturned against the inlier, overlying Eyre Formation; and,
- Prospect Hill, northwest Mt Babbage Inlier: remnants of Mesozoic palaeovalley sediments.

Where previous detailed mapping was not available, field sites in both areas were mapped in detail, with scales ranging from 1:10,000 to 1:75,000 in accordance with the size of the field area, and the detail required to highlight important features. Mapping used remotely sensed imagery, predominantly, Brovey Landsat imagery (Courtesy of the NSW DPI) and Quickbird satellite imagery (Courtesy of Primary Industries and Resources South Australia), which has a ground resolution greater than excess of 5 m. Regional geophysics (predominantly magnetics and gravity images), Landsat7 and airborne gamma-ray spectrometry images from the regional Curnamona Data Package for South Australia and from the Koonenberry Data Package for New South Wales were used to assist where possible. The mapping used regolith-landform unit (RLU) approach defined by Hill (1995), Hill & Roach (2005), Pain et al. (2000). This approach to mapping allows for the analysis of surficial exposure of all medias of geology, without bias towards any specific aspect. Such a technique recognises exposed bedrock and unconsolidated geology with equal importance and detail. Mapping generally only accounts for one or the other, which limits the information which can be extracted from the mapping. The landform component of this technique also accounts for the relationship between specific types of geology and surficial processes, such that mapping not only recognises the presence of regolith units, but also the landscape in which the regolith exists. The landform component of the mapping shows the surface morphology, which can be related to surface processes and thus to regolith materials, distribution and accumulations. This generalized mapping approach allows for the original data set to be used as a surrogate for specific features and as a basis for further specialist refinement (Hill 1995; Davey 2005). Mapping was focused on collecting information about five main aspects of the geology, environment and landscape. These aspects were recorded to create generic regolith-landform maps such that derivative maps of any feature could be made after initial mapping. This technique is used as it records all aspects of the surface, be that geological or environmental.
The five units record include:

- Dominant regolith lithology and broad type - *in situ*, aeolian, colluvial, alluvial, lacustrine or evaporitic; abundance; distribution; and, variation or homogeneity of the profile.
- Landform: characteristics and landscape processes – erosional, depositional, anthropogenic; slope – plain (0-9 m), dune (>5 m), rise (9-30 m), low hill (60-90 m), hill (90-300 m), mountain (>300 m), channel, drainage depression (minor channel), fan or swamp. Features of landforms such as slope, shape, gradient and stability were also recorded for the different landforms.
- Minor features: regolith - *in situ*, aeolian, colluvial, alluvial, lacustrine or evaporitic; landform – drainage, fans, rises, dunes, playas, lakes, fill.
- Geohazards: incision; erosion; burrowing; stability; dispersion
- Vegetation: community, dominant species, growth patterns, health, aspect and abundance.

While many features recorded do not have apparent relevance to geological reconstructions, such as vegetation or Geohazards, associations between these features and geology can often be seen after mapping is conducted. An example of this is the recognition of subtle structure by populations of vegetation not typical to an area. As faults often act as fluid conduits, particular species of vegetation that would not normally grow in an area or that would be limited to drainage grow in plains or dune fields.

Based on these features, RLUs were classified and coded using the RTMAP codes from Pain *et al.* (2000) and Pain *et al.* (2007). These codes first define the primary regolith unit, and then the primary landform. A full copy of the code and map symbols used is included in Appendix 3. Maps were compiled using ArcMap V9.3, which is the mapping component of ArcGIS, and the industry standard geographical information and imagery program. A detailed guide for constructing maps in ArcMap is included in Appendix 3.3. Unit boundaries were traced out during fieldwork, and interpreted of aerial images. The scale of mapping defined the detail used in discriminating units, and the minimum size of features that could be defined. Where important features were too small to map, special consideration has been employed and marks indicating the feature are included separate to the RLUs. The resulting maps contained detailed attribute data, so simplified regolith surrogate maps could be extracted.

### 3.4 Structure, Tectonics and Geomorphology

As well as the surficial mapping, structural mapping and analysis was also conducted. For both field sites, regional mapping data are readily available that have a component of structural information; however, neither field area has comprehensive detailed structural mapping for the entire minor field sites studied. Selected areas throughout the Tibooburra-Milparinka field area have structural maps (Davey 2005; Brown & Vickery 2007; Greenfield & Reid 2007b); however, in the northern Flinders Ranges such maps are limited. Structural analysis focused on tracing out faults, folds and shearing, as well as obtaining structural measurements including bedding, fabric, cleavage and trend. Structural data were obtained primarily from the Mesozoic sediments, but also from the overlying younger sediments and underlying bedrock, in areas where these features had a relationship or obvious affect on the Mesozoic sediments. Data were plotted on maps, and used to correct other data obtained. Structural maps were incorporated as overlays on the surficial maps.

### 3.5 Sedimentology

Once the mapping had been conducted, the Mesozoic sediments in the area were the subject of sedimentological and provenance analysis. The sediments were mapped further in detail, and lithological and sedimentological data were collected from surficial and subsurface profiles. This was done separate to the surficial mapping such that it would not add confusion or bias to the data. In the localised studies, sedimentological analysis focused on
logging vertical profiles where exhumed or eroded and horizontal profiles where overturned; and, detailed sediment descriptions of exposed sediments within the basin and across the inlier.

3.5.1 Wells, Bores and Log

For the regional study, sedimentological analysis was conducted on core from wells, drillholes and bores that penetrate the Mesozoic sequence, that is, holes that at least extend to bedrock (see chapter 4). The holes penetrating to bedrock were chosen to ensure that the extent and depth of all packages could be analysed. Logging of the core was conducted in a similar manner to that of the vertical profiles (see 3.2.3 Sedimentology: this chapter), with a focus on general sedimentological characteristics. Due to the length of the core, the logs are not as detailed as the vertical profiles mapped during fieldwork. Instead of registering sequences, packages with special features are logged. Generalised sequence stratigraphy and depositional environments were interpreted from this logging. From this interpretation, lithological packages were assigned and general thicknesses of the packages were determined. Where core was not preserved, or unavailable, lithology descriptions and stratigraphic interpretations from well completion reports were used.

To aid with well analysis, down-hole petrophysical logs were used. Petrophysical logs are often used as tools to infer lithology, mineralogy, water content and subsurface deformation (as defined by Allen et al. 2006; for example: Spaak et al. 1992; Glidewell et al. 2008; Rezaee et al. 2008). This is done by associating specific mechanical responses of strata with physical properties (Allen 2006). Specific sediments from within the Eromanga Basin typically have very distinct signatures on down-hole gamma and occasionally on sonic logs (Ozimic 1982; Moore et al. 1986). Because of this, the gamma logs were used as aids to interpret the unconformity between the LEB sediments from the Eromanga Sediments and also, where possible, bedrock intersections, as well as to standardise formation top picks in as many wells as possible (Figure 3.3).

Figure 3.3 Example of petrophysical log characteristics of sediments from the Eromanga Basin: Gamma (GR – red curve) and Sonic (DT blue curve). Formation top picks standardised from the South Australian Government Eromanga Basin formations. Lithological interpretation added using Petrel.

Petrophysical logs are typically only available for petroleum wells. In total there are 43 petroleum wells in the Frome Embayment. Very few of these logs were available in digital format. Where possible, hardcopies of these
logs were digitised. Occasionally down hole scintillometers are used in uranium exploration wells. These well logs were avoided, as the scintillometers used in uranium wells split the signal to determine the source of the anomaly. This makes the lithological associations with the signal less accurate.

From this package, depth to top formation maps were constructed, along with, where possible, formation thickness maps. These maps were compiled using ArcGIS 3D Analyst, the structural modelling software packages 3D Move and Petrel. Gridding was bound by grid area and constructed using a minimum curvature algorithm. Minimum curvature assumes that the surface being gridded has a smooth elastic like membrane and as such the smallest amount of curvature is applied. This technique is favoured as it uses a multiphase gridding algorithm that uses a regression surface to minimise errors typically generated by gridding processes. Formation tops used are recorded in appendix 2.

Vertical profiles of Mesozoic sediments were logged in detail to obtain an understanding of the relationships between different sedimentary packages, and to determine depositional environments. These logs were also used to correlate sediment packages in different areas. Features classified during logging included: grain size; lithology; colour; primary structures; inclusions; fossils, weathering; and, induration. All logs were constructed as graphic Logs and are displayed bi-dimensionally with the primary sedimentological features in one column in the log, and authigenic features such as weathering and induration in another column. From these logs, depositional environment profiles were classified. Where logging of units was hindered by incomplete exposures of units, composite logs were compiled. From these logs, sequence stratigraphy and depositional environments were interpreted, and correlations between field sites were made. To classify the rocks and sediments, the basic Sedimentary Rock Classification Chart (Gore 2004) was used. These classifications were further refined using the general rock classification scheme defined by Allen (2006) and sequence stratigraphy defined by Levell (1992) and Van der Zwan (1992).

3.5.2 Mineralogy

Mineralogy was determined by optical analysis of polished thin sections mounted by Pontifex and associates. Rock samples were collected for reference from the different layers within the logs, or from 30 cm intervals down profile, whichever came first. Samples from exposures within the basin were also collected, such that mineralogy of the units could be determined. Each field sample collected was at least a 10-20 cm block; with care being taken to ensure all samples were collected from in situ profiles. Blocks 3 x 9 x 1 cm were cut from the centre of the samples, as to avoid the affects of direct surficial weathering, and then mounted on glass slides. Where the rock competency was minimal, the sediments were impregnated with glue before mounting to ensure the condition of the sample was maintained. The slides were then shaved such that a slither of rock approximately 0.5 mm was left. These samples were then polished down to 0.3 mm using a buffer and a cerium oxide solution. Samples that could not be polished with cerium were buffed down and covered with oil to compensate when viewing. Thin sections were viewed under plain and cross polarised light as to highlight different mineral properties (Figure 3.4). Optical magnification was 10x with lens magnifications of 10, 25, 40 and 65x.

To classify the rocks and sediments based upon their mineralogy, percentage abundances of minerals were determined using the thin sections. The classification used the same basic Sedimentary Rock Classification Chart previously outlined and mineral abundance and percentage was determined using the Charts for Estimating Mineral Percentages from Compton (1962).
3.5.3 Palaeocurrent Analysis

Palaeocurrent flow directions were measured from current generated primary sedimentary structures within the Mesozoic rocks. Both uni and bi-axial sedimentary structures were targeted including herringbone and planar cross-bedding, asymmetrical and symmetrical ripple marks, clast imbrications and pebble clusters. Cross-bedding structures were targeted due to their ease of analysis and their reputation for general consistency in determining flow direction. Cross-bedding sediments are typically deposited in environments where there is a flowing fluid such as water or wind movement. Fluid flow creates ‘internal’ inter-bedding of sediments that is deposited transverse to the main stratification plane of the sequence. Deposition is typically inclined in the direction of flow. The morphology and shape of these inclined beds, or foresets, represent the type of current motion and velocity at the time of deposition. In general, the direction of current is parallel or sub-parallel to the maximum dip direction (or the azimuth) of the foreset (Figure 3.5). Structural bedding measurements were collected from the topset and bottomset sediments, that is the planar sediments atop and below the cross-bedding (Figure 3.5), to determine any structural variation that may have reoriented the foresets. Measurements were corrected, reoriented and adjusted for any structural variations.

Measurements were collected from both vertical profiles and exposures cropping out throughout the basin. When measuring cross-bedding in exposures, at least eight individual measurements were collected from the same lithostratigraphic position, from within a maximum of 15 m radius. For measurements for vertical exposures, locating different foresets to measure within the lithostratigraphic constraints is more difficult. To compensate for this, and to ensure that there is representative expression of the current direction presented, foresets from within
the same cross-bedding set were measured and averaged. These measurements are representative of the current flow direction at that point, as opposed to representative of an area.

Figure 3.5 Cross-bedding profiles and foreset truncation examples (Potter & Pettijohn 1963).

Ripple marks were also used to determine flow vectors; however, these were only measured in basin exposures and not from vertical profiles, as vertical exposures limit three-dimensional expression needed to accurately assess and measure the ripples. Ripple marks are rhythmic undulations that form in the bedding plane as a result of moving fluids (air or water). Two types of ripple marks were analysed, symmetrical and asymmetrical. With asymmetrical ripples the long axis of the ripple is parallel to the current flow direction (Figure 3.6). By measuring the azimuth of the crests on the long axis of the asymmetrical ripple an approximate current direction can be obtained. With the symmetrical ripples the strike of the crests is approximately perpendicular to the direction of current flow (Figure 3.6). By measuring the strike and then converting it to a dip direction, the flow direction can be obtained.

Figure 3.6 Ripple marks and current flow direction analysis: a) symmetrical ripples; b) asymmetrical ripples (Levin 2002).

As with the cross-bedding, numerous readings were obtained and averaged into flow vectors using the same technique as for the cross-bedding; however, ripple marks have a greater tendency to represent eddy currents, so the area in which the measurements were collected from was increased to a 25 m radius, with at least 15 measurements being collected per location. In compressional terrains, micro-scale folding or crenulations can
sometimes be mistaken for ripple marks, or can subtly re-shape the ripple crest peaks. For areas that have undergone significant tectonic deformation, ripple marks were not used to measure flow vectors. Where present, flute casts were also used as flow indicators. Flute casts are three dimensional sole marks that are the product of infilling of scour pits generated by flowing mud and sand in laminar currents (Potter & Pettijohn 1963). They form a distinct ‘tear-drop’ shape in which shape varies depending on the intensity of the current. With flutes, the lobe of the structure points upstream of the current, with the narrow “throat” of the structure pointing in the current direction (Figure 3.7).

![Figure 3.7 Flute cast structures indicating current flow direction (Gore 2004).](image)

The azimuth of the structure is measured along the line that connects the maximum point of curvature on the bulb and the “throat” of the flute. These structures can be measured in plan and length cross section; however, when viewed in length, they can be mistaken for trough cross-bedding. Because of their ease of measurement, noted reliability and repeatability of measurements, they were preferentially measured over ripple marks. Exposures of these structures; however, typically undergo differential weathering, due to competency and resistance variations between the hosting sole, and the infilling flute mediums. This has resulted in limited or remnant exposures of these structures. To ensure precision, and minimise error, at least 8 measurements were taken at each location. To sort the data, rose diagrams were constructed from the measurements from each location, showing the dispersion of the measurements. These diagrams determine the average mode of the flow direction (Figure 3.8), that is, the frequency of flow azimuths. As the mode represents the frequency of measurements, rather than a general trend for the flow, the mean of these measurements was also calculated. The mean was plotted on maps as a single flow vector. The rose diagrams were used to determine phased or multidirectional flow, and the accuracy of the measurements, as large swaths around the primary flow direction indicates the presence of eddy currents, or error in structural corrections. The roses were used when comparing the flow vectors on a regional scale, as the swath may represent a general trend, as opposed to the calculated vector, which represents the local trend. In order to ensure comparable data, flow vectors were only compared with other vectors measured in similar lithostratigraphic positions. In vertical profiles the availability of sets of foresets to measure to obtain an average direction is limited, such that foresets within the same set are measured. These measurements reflect a more accurate flow pattern for an exact location; however, it is not possible to determine whether the flow vector represents the primary current or if it reflects a local current eddy.
When plotted on maps the vectors obtained from measuring current derived structures were coded according to the lithology they were measured in, the nature of the structure they were derived from (that is: herring bone, trough or planar cross-bedding; fluting; or, symmetrical or asymmetrical ripple marks), the axial component (uni, bi or multi-axial), and the reliability (generally determined by the number of readings obtained and the rose plot swath distribution). This allows for more accurate interpretation of the flow vectors and also helps to incorporate regional assessments.

Clast distribution patterns, dispersion and attrition were also used to determine flow directions. This technique is not as reliable as measuring cross-bedding or ripples, but provides a general flow range direction as opposed to a flow vector, in areas in which current-derived sedimentary structures are absent. Clast size is important for this technique. It is assumed that when clasts are deposited, the smaller clasts will be transported the furthest. Thus, in longitudinal profile, the direction in which the clasts get smaller is the direction that the current is flowing. As simplistic as this is, it provides an approximate directional assumption on current direction. Determining flow direction is rather simple, tracing clast size for at least 100 m to find lateral variations. In some areas, 100 m is not substantial enough to determine variations in clast size, so trace extended until clasts size variations were substantial enough to discern a direction. Unlike the other structural techniques, this method of current analysis only determines a flow range, that is a circular mean deviation, as opposed to a specific direction (such as the flow vector calculated for the cross-bedding structures). These measurements are plotted on maps as rose segments that define a multi-axial path of flow. To illustrate the distance covered to define the length of the longitudinal profile analysed to obtain the results, the rose segments are weighted differently when illustrated on maps. This allows for considerations of accuracy. Many factors must be considered when using this approach. The availability, competency, mineralogy and deposition energy largely control distribution of clasts, such that there is no definite means by which to define this technique. Furthermore, to view the distribution of clasts requires considerable continuous or near continuous, correlated exposures of sediments that corresponds to along flow direction. The deposition of younger sediments and tectonism often impedes such profiles. Thus, this is an opportunistic technique, and not particularly accurate.

3.6. Palaeogeological Reconstructions

Palaeogeographical reconstructions incorporate the different aspects of the study. Because the methodology from the different areas was not consistent, initially a reconstruction for each field study was compiled. These studies were then combined to create a regional palaeogeographical reconstruction. The reconstructions are focused on attributing factors such as sedimentology and structure and using them to reconstruct the landscape from the Mesozoic. Sediment profiles, mineralogy and petrological analysis were used to determine depositional environments, from which general topography and landforms, water availability, levels and tectonism were derived. Structural relationships and tectonic element analysis were used to regenerate Mesozoic landscapes from contemporary ones. Regolith mapping was incorporated into this process as a representation of the contemporary landscape morphology and structural architecture.
Variations in basin architecture and geomorphology are determined by a complex interplay between climate, tectonics, eustacy, sediment availability, source rock lithology and time. These factors are typically interrelated making it difficult to isolate individual evolutionary processes. In intracontinental terrains, factors such as eustacy and climate change are typically not assumed to have significant effects on basin evolution (Thamo-Bozso et al. 2002). In the Eromanga Basin; however, the environment changes from an intracontinental to a marine system as the incursion of a major seaway covered much of central Australia during the Aptian-Albian. This indicates that typical intracontinental evolutionary processes do not universally apply to the Eromanga Basin area. Furthermore, the progression of the Mesozoic extent of the Australian continent through different latitudes during the separation of Gondwana (Schmidt & Clarke 2000) has been linked to considerable climatic changes (Frakes et al. 1987; DeLurio & Frakes 1999; Frakes & Barron 2001). These climatic changes have been previously identified as a major control on sediment influx in the basin (Frakes et al. 1987; De Lurio & Frakes 1999). The formation of a large basin in an intraplate area indicates that the basin has also undergone significant tectonic contributions to its evolution, driven by large magnitude epeirogeny.

To understand the complex genetic interactions for the basin’s evolution, an area expressing exposures of important sediment contacts and relationships, tectonic interactions and the effects of climate and environmental processes is needed. Aspects of morphology, remnant tectonism and depositional trends should ideally be expressed. Such features and relationships are best exposed around the transition between the basin margin and the basinward terrain. In the Eromanga Basin, these areas are defined by the interaction between basin exposures in the marginal areas, and subsurface features extending into the basin. Basin margins typically contain the lateral extremities of the stratigraphic model, emphasising lateral changes in deposition and environmental settings. Furthermore, the exposures that typify basin margins can preserve important structural, sedimentological and mineralogical features that could otherwise only be partially exposed in core or geophysical imagery. The subsurface aspects of the basin are equally important as they help to provide the large-scale basin features such as depth, sediment thickness, basin shape and major structures. These features are best imaged in geophysical imagery and drill core.

The Frome Embayment represents a small portion of the subsidence and sedimentation from the Eromanga Basin. The embayment forms the southernmost extent of the Eromanga Basin where the contrast between basin margins and basinward stratigraphy and structure is particularly evident. The landscape within the embayment possess stark contrast between clear and abundant exposure of Mesozoic geology around and within the surrounding ranges (once basin margins) and extensive plains of younger successor basin sediments (on average 50–200 m of sediment) covering the Mesozoic succession in the central regions. Geophysical imagery is abundant and of high quality in the area, and there is an abundance of deep wells allowing for the representation and interpretation of subsurface features. Furthermore, the embayment is of mineralogical, petrological, geothermal and environmental significance, and is an important component of the economic and scientific aspects of the Eromanga Basin.
4.1. Geological Setting
The Frome Embayment occupies the southernmost extent of the GAB, forming a structurally controlled lobe that extends through northeast South Australia and northwest New South Wales (Figure 4.1). The embayment is bound to the west by the Flinders Ranges (the northerly extent of the Adelaide Geosyncline), in the east by the Olary, Barrier and Grey ranges, and to the south along the Anabana-Redan Fault Zone Scott to the Mundaerno Hills (Ker 1966; Wopfner 1969; Callen 1975; Truelove 1980; Gravestock & Hibburt 1991). In the north, the embayment is continuous with sediments that extend across a majority of the Eromanga Basin, such that the northern extent of the embayment has been defined as being 29°55'S, or equivalent to the latitude of Moolawatana Station (Callen 1975, Truelove 1980). For the purpose of this study, and for simplicity, this is redefined as the latitudinal extension from Moolawatana Station to the northern extent of the New South Wales portion of the Grey Ranges (Figure 4.1). This is the approximate area occupied by the Cainozoic Tarkaroola Embayment or Tarkaroola Basin (Callen 1975; Youngs 1978) which has recently been redefined as the Callabonna Sub-basin (Callen et al. 1995), an equivalent southern lobe of the Lake Eyre Basin (LEB) (Devogal et al. 2004; Fitzsimmons 2005).

Figure 4.1 Pseudo coloured Landsat7 global imagery mosaic of the Frome Embayment.
4.1.1 Regional Geology

Major structures that control the extent and morphology of the embayment are dominated by basement structures and regions that had surficial expression during the Mesozoic, or that were reactivated during the mid-Jurassic basin subsidence. These structures can be divided into five main tectonic zones:

- Moorowie Syncline in the west: incorporating the Poontana Fault Zone, Poontana Trough and the area abutting the east margin of the Flinders Ranges;
- Benagerie Ridge in the central area;
- Yalkalpo Syncline in the east: with the Bancannia Trough and Barrier Ranges;
- Koonenberry-Wonominta Block in the northwest: incorporating the area inclusive of and to the east; and
- Koonenberry Ranges up to and including the Grey Ranges in the north.

The Moorowie and Yalkalpo synclines both have approximately NNW-SSE trending axial plains and are open to acute folds with a northerly plunge (Figure 4.2) (Gravestock & Zang 1996). These features formed syn depositional with the Cambrian Adelaidean strata, as indicated by the thickening of the sediment packages in the north. These structures define the central and eastern morphology and sedimentation of the Arrowie Sub-basin (Broomfield 1997; Teasdale et al. 2001; Zang 2003).

The Benagerie Ridge in the centre of the area is composed of Mesoproterozoic ‘A-type’ volcanics (Williams et al. 2009). These volcanics are derived from a large sub-circular pluton that approximately corresponds to the area of the Curnamona Province (Broomfield 1997; Robinson et al. 1998; Teasdale et al. 2001; Williams et al. 2009). The contemporary extent of the ridge has been determined from deep drill holes and geophysical imagery (Williams et al. 2009). The extent of the ridge is considered to be approximate, as data are limited at depth over the area. The ridge is controlled by the younger folding that formed the Moorowie and Yalkalpo synclines (Teasdale et al. 2001; Williams et al. 2009). The Benagerie Volcanics are reported to be relatively undeformed (Teasdale et al. 2001; Williams et al. 2009), despite the overlying sediments showing deformation associated with the Delamerian Orogeny and the extent of the ridge being controlled by the open folding. A NW-SE trending shear zone extends through the area, called the Benagerie Shear Zone; however, this does not affect the volcanic pile.

The area northeast and inclusive of the Koonenberry Ranges defines the eastern extent of the embayment (Figure 4.2). A controlling feature of this area is the Koonenberry Fault, a NW-SE trending structure that is concordant to features from within the central portion of the basin (Figure 4.2). This structural trend is prevalent throughout the east of the area, including the Olepoloko Fault, which is a structure depicted to control the Wonominta Block (Neef & Bottrill 2001), and the Warratta and New Bendigo Faults near Tibooburra (see chapter 6). The north of this block forms the southern extent of the Thomson Orogen, and the New South Wales portion of the Grey Ranges. This area hosts the interpreted junction between the Thomson, Lachlan and Delamerian orogens (Davey & Hill 2009), which is assumed to be within the Grey Range in the north.

The Muloorina Ridge in the northwest coincides with the approximate northern extent of the embayment. This ridge has a continuation of the regional structure trends with a NW-SE trend. This ridge marks the approximate northern extent of the Adelaidean sedimentation and the Delamerian Orogen, and associated deformation (Alexander & Hough 1990; Paul et al. 1999). The Norwest Fault south of the ridge marks the western extent of the Frome Embayment beyond the Flinders Ranges (Figure 4.2).
4.1.2 Basin Geology

The embayment forms the southernmost lobe of the Eromanga Basin, and is approximately spatially equivalent to the Cainozoic, Callabonna Sub-basin, part of the LEB (Callen et al. 1995; Youngs 1978; Devogal et al. 2004; Fitzsimmons 2005).

The LEB sediments overlying the Frome Embayment broadly consist of three Cainozoic units (Moussavi-Harami & Alexander 1998). These units include: Palaeocene-Eocene Eyre Formation; late-Oligocene-Miocene Namba Formation (Etadunna Formation equivalents); and Late Pliocene Yandruwantha Sand (Table 4.1).

The Eyre Formation is characterised by a basal conglomerate dominated by small, rounded, highly-polished quartzose clasts. The unit is further characterised by coarse grained sands, with interbedded conglomerates, mudstones and occasional claystones. These sediments are readily identifiable by highly distinguishable sedimentary structures, including large-scale cross-bedding and bowl dewatering marks. Depositional environments are interpreted to include braided streams and other high-energy fluvial environments, such as crevasse splays, floodplains and fans (Alley 1998; Moussavi-Harami & Alexander 1998). Exposed profiles of the Eyre Formation sediments have yellow-orange-red coloured weathering patterns, representing iron oxide staining and iron oxides associated with palaeo-redox conditions. Large portions of these sediments are indurated. The most abundant induration is a massive grey silcrete that has formed around the base of the unit throughout most of the basin. Despite appearing to be a near continuous induration sheet, the silification has formed in pods. The continuity of the induration is a result of the mineralogy and chemical composition of the sediments being homogeneous, such that fluid percolation and chemical reactions within the unit are similar, and thus forming the extensive silification. Other Eyre Formation indurations in the embayment include pedogenic silcretes in the northwest, ferruginous cementation in the central regions, and occasional gypcrete formations in the south.
Chapter Four: The Frome Embayment

The Namba Formation consists of interbedded sandstones and siltstones with dolimitic beds. Sediments range from lacustrine to fluvial, with sporadic aeolian influence in the south where the sediments start to thin (Moussavi-Harami & Alexander 1998). These sands and silts host large carbonaceous zones, distinguishable by their black colour. These zones are typically associated with U mineralised zones, such as the U deposits associated with the Beverley deposits in the west of the basin (McKay & Miezitis 2001; Hore et al. 2005; McKay et al. 2008).

The Late Pliocene Yandruwantha Sand and the Quaternary sediments are comprised of the sands, silts, clays and pebbles found mostly on the low-lying plains. The LEB is considered to be contemporaneous, and therefore contemporary sedimentation is considered to be the youngest basin sediments. The Yandruwantha Sands and the Quaternary sediments are therefore considered to be part of the same depositional phase (Moussavi-Harami & Alexander 1998). Sediments are being deposited in active channels, flood and colluvial plains, evaporitic lakes and playa plains. Aeolian processes are active in the area, reworking sediments and redepositing them in large dunefields and sand plains (see this chapter 4.4).

**Table 4.1 Stratigraphy of the Lake Eyre Basin from Moussavi-Harami & Alexander (1998).**

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<th>Ma</th>
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<tr>
<td>60.0</td>
<td>Early Paleocene</td>
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<td>38.0</td>
<td>Late Paleocene and Middle Eocene</td>
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<td>Late Oligocene and Mioocene</td>
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<td>3.3</td>
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<td>0.8</td>
<td>Early to Middle Pleistocene</td>
<td>Millyera Formation and equivalent</td>
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The Mesozoic sequence in the embayment consists of the entire Eromanga Basin succession, of variable extents (Table 4.2). The sediments conform to the five primary units and the three major stratigraphic subdivisions, as defined in chapter 2. For simplicity, the same nomenclature adopted in chapter 2 will be used to describe the Eromanga Basin sediments in the embayment. This nomenclature is a simplified version of that assigned to the northern South Australian portion of the embayment (Table 4.2).
### Table 4.2 Distribution of the Eromanga Basin sediments in the Frome Embayment after Holbrook 1966; Morton 1982; Norton 1983; Van Doan 1988; Moussavi-Harami & Alexander (1998); Davey 2005.

<table>
<thead>
<tr>
<th>AGE</th>
<th>Tibooburra, NW NSW</th>
<th>Tibooburra, NW NSW</th>
<th>Fowlers Gap</th>
<th>Northern Flinders Ranges, SA</th>
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#### 4.1.3 Economic Geology

The economic geology within the embayment is focused on U mining and exploration. Two U mines are currently active: the Beverly U mine in the west; and the Honeymoon U mine in east South Australia. Both mines use hydrometurlurgic extraction processes. A mining lease has been granted for the 4 Mile U deposit west of Beverley. Uranium dominates mineralisation in the embayment, with known occurrences around Windermerta Hill, Spring Hill and Goulds Dam in the south and around the Mt Painter-Mt Babbage zone in the north (McKay & Miezitis 2001; Hore et al. 2006; McKay et al. 2008). Uranium exploration is active within the South Australian portion of the embayment with 90% of active mineral exploration applications and over 50% of active mineral exploration licences in the Frome area being for U (SARIG electronic resource 2009). Uranium exploration and mining in NSW is currently not permitted.

Gold exploration is active throughout the embayment, particularly to the southeast of Lake Frome and around the Barrier Ranges (SARIG & DIGS electronic resource 2009). Known Au mineralisation is common throughout the south of the embayment, typically associated with Cu, Ag and As. Minor Au occurrences are present within the
northeast of the embayment around the Tibooburra-Milparinka Inliers (see chapter 6). This Au was economic in the late 1800s and early 1900s; however, this is not presently the case (McQueen 2008). Other base metal exploration is also active in the area, particularly Ni and Mo. The Ni and Mo exploration is focused around the Old Telechi and Plumbago deposit north of the Olary Ranges in the south of the area. Molybdenum is also associated with known U deposits around Benagerie and Kalcaroo in the south of the embayment. Manganese mineralisation is prominent, flanking the ranges in the west and to the east of Lake Frome. Small mines have been excavated for Mn; however, they are currently considered uneconomic. Copper has limited occurrences in the embayment; however, it is present with Ba at the Mc Brides Dam and Ameroo Hill Prospects in the south.

Petroleum exploration has been active within the area since the 1940s (Evans 1948; Sprigg 1958; Gravestock & Zang 1996; Broomfield 1997; Zang 2002; O’Neil & Alexander 2007). Gas exploration in the embayment was prevalent between 1940 and 1950 when Australia was experiencing a major fuel shortage (O’Neil & Alexander 2007). Initial exploration in the embayment discovered gas during drilling in the Bancannia Trough in New South Wales (Sprigg 1958a; O’Neil & Alexander 2007). This was further supported when the execution of numerous mineral exploration wells in the south of the basin experienced blow outs when unexpected gas was intersected during drilling (Mawby 1944; O’Neil & Alexander 2007). This gas was not hosted in A-typical petroleum environments. The Eromanga Basin sediments in the south of the Bancannia Trough are typically shallow with
respect to petroleum environments and are not underlain by particularly fertile petroleum sources or ‘kitchens’. This indicates that the Eromanga Basin sediments have either been buried to depths greater than 1 km more than their contemporary existence or have been affected by the high geothermal gradients in the area. As well as the gas, minor oil was discovered around Lake Frome and in western New South Wales (O'Neil & Alexander 2007). Despite these initial discoveries, this round of petroleum exploration was, by and large, unsuccessful. Minor gas occurrences have been found in the north of the embayment where the Eromanga Basin sediments are thicker (Evans 1948). The gas is hosted within three units, including the basal Jurassic, Cadna-owie Formation and Winton Formation (Evans 1948). Gas occurrence in the Winton Formation is not yet considered economic; however, recent drilling of wells in the northwest of NSW has confirmed that the Winton Formation hosted gas deposits have potential where the basin is deeper.

In the south, petroleum exploration is focused on the Cambrian sub-basins within the Arrowie Basin (Wopfner 1970; Broomfield 1997; Zang 2002). Two zones of oil shows are present: the minor oil occurrences in the wells drilled in the south of the Moorowie Sub-basin; and the oil shows in the Wilkatana wells in a zone to the west of the Flinders Ranges (Allender & Owler 1996; Broomfield 1997). These shows are typically limited to the mid to early Cambrian Arrowie Basin sediments (Wopfner 1970; Gravestock & Zang 1996; Broomfield 1997).

More recently, geothermal exploration has been active within the area, particularly in South Australia. Because the geothermal activity in this area is so recent, minimal data obtained from this exploration is available in the public domain. Press releases by companies are indicating very anomalous gradients in excess of 50°C / km (see chapter 5).

4.1.4 Environment and Land use

Since 1980, the embayment has been part of the driest area of Australia (BOM 2009). In the past seven years this area has been affected by drought (BOM 2009). On average, rainfall is low, in the ranges of 0-200 mm fall per year (BOM 2009). Water in the area is primarily fed through creeks and channels flowing from further north. The vast dunefields and lack of water inhibit land use in the embayment. Because of this, the land is primarily used for cattle and sheep grazing and camel farming. The area also attracts a large amount of tourism, particularly focused on the Strzelecki Desert, Flinders Ranges and Tibooburra areas. Several research stations are active in the embayment, including Fowlers Gap Arid Zone Research Station in the Barrier Ranges; Gammon National Park and Arkaroola Wilderness Reserve in the Flinders Ranges; and the DHE wilderness station north of Goulds Dam. These stations are designed to monitor, rejuvenate and study the different aspects of arid environments.

4.2. Remotely Sensed Imagery

Remotely sensed and geophysical imagery were used to provide the basis for surficial and structural mapping. Images were used in conjunction with fieldwork to map the entire embayment. Fieldwork was used to register specific features of the remotely sensed imagery, such that the boundaries of landforms and regolith types could be picked with images. The fieldwork registry also allowed for regolith attributes to be assigned. Remotely sensed data used within this study included true colour and false colour SAR air photography, Landsat-7, NASA Digital elevation model (DEM) and geophysical data such as Total Magnetic Intensity and Bouguer corrected and isostatically adjusted gravity surveys. Regionally the embayment is covered by DEM, aeromagnetics, gravity and SAR. Locally Landsat-7 and Quickbird survey are available.
4.2.1 Digital Elevation Model

The DEM largely shows the contemporary and approximate original extent of the embayment (Figure 4.4). The main features of the DEM are the surrounding mountain belts encasing a low-lying basin area, with Lake Frome at the lowest part of the landscape. The similarities between the extent of Mesozoic deposition (i.e. the original extent of the embayment) and the contemporary expression of the embayment indicate that the syn-depositional landscape at least in part reflects the contemporary landscape.

![Figure 4.4 Digital Elevation Model of the Frome Embayment.](image)

4.2.2 Landsat and Synthetic Aperture Radar

Landsat and SAR imagery over the embayment were used for mapping and base maps for fieldwork. Publicly available Landsat 7 and SAR imagery cover Australia, and have a resolution within the embayment of approximately 90 m. Because of this, it was used as the basis of all mapping. Two spectra of SAR were used: (1) true-colour; and (2) pseudo-colour (Figure 4.1a). True-colour imagery typically lacked contrast in the dunefields that was instead bought out by the false-coloured imagery. Large landforms are readily distinguishable on both the natural- and pseudo-colour images. Small-scale and subtle landscape features are difficult to define on these images.

Multispectral Quickbird imagery covers the northern Flinders Ranges and surrounding basin areas in the west of the area and the Tibooburra Inlier in the northeast. The Quickbird imagery is very high resolution, with clarity down to 2 m. These data are limited in distribution, as acquisition of the multispectral imagery is very expensive, and mostly obtained for specific purposes (for example the PIRSA and Heathgate Resources acquisition over the
Flinders Ranges for U exploration). Where present, this data set was incorporated into the base maps. Quickbird was used for recognition of bedrock and saprolite exposures, dunes, channels and small drainage depressions, and channel zones of dense vegetation. Figures of the Quickbird are in chapters 5 and 6.

The New South Wales portion of the basin has publicly available Landsat Brovey 2005 version imagery as part of the Koonenberry digital resource. The Brovey image displays specific bands of the Landsat, which better defines surficial features that on the true-colour and pseudo-colour images are not visible (Figure 4.5). Fieldwork was used to match colour patterns on the imagery, such that it could be used to refine mapping.

![Figure 4.5 Landsat bands 7-4-1: Brovey Image of the Barrier and Koonenberry ranges showing features such as channels and lakes, as well as bedrock exposures.](image)

Bedrock exposures show up as purple-red features amongst the brown-yellow basins. Alluvial features (including channels and fans) are distinct with a green colouring (Figure 4.5). Aeolian-dominated landforms have a bright yellow appearance, occasionally with a red tinge. Field checking of the most intense red units indicate that these units contained a higher clay fraction than the yellower units. Lakes and clay pans have a distinct dark blue appearance (Figure 4.5).

Colluvium and, in some cases, alluvium have a purple-red colouration. This feature is often a representation of the source material, particularly indicating the presence of bedrock.
4.2.3 Potential Fields

Dominating the magnetic imagery of the embayment is a large circular zone of high magnetic intensity (MI) (Figure 4.6). This zone corresponds to the extent of the crystalline basement of the Curnamona Province, which is defined and underlain by a large Mesoproterozoic pluton (Teasdale et al. 2001). The regional magnetic imagery over the embayment defines limited features because of the high signature of the Province. The metasedimentary and metaigneous suites that form and underlie the Province contain an abundance of magnetic minerals, which typically have a heterogeneous distribution (Williams et al. 2009). This results in a high MI, with limited variation in the regional imagery. A Mesoproterozoic pluton called the Moolawatana Pluton has been previously attributed to generating the majority of this anomaly (Teasdale et al. 2001).

When focused at a localised scale, subtle differences emerge. One of the most prominent features on the localised imagery is a zone of high MI variation to the south. This zone corresponds to the Olary Domain and the Broken Hill Domain. The NW-SE trending lineaments that cross the Province correspond to the structures from the trans-lithospheric Benagerie Shear Zone (Figure 4.2). The minor changes in this zone correspond to Neoproterozoic intrusions, namely from the Moolawatana Suite (see chapter 5). Other features on the magnetic survey are the NW-SE trending lineaments that define the Bancannia Trough. The Tibooburra-Milparinka Inliers have slight expressions on the magnetic imagery, with the Tibooburra Granodiorite appearing as a slight rise in MI within a zone of relatively low MI. The magnetic survey closely reflects bedrock features in the embayment. Similarly orientated structural features are present to the east of the province, controlling the Bancannia Trough, and approximate expressions of the Koonenberry and Olepoloko faults.

Figure 4.6. Total Magnetic Intensity image of the Frome Embayment. Image courtesy of Geoscience Australia (electronic resource).

The gravity image is compiled based on a coarse grid of 0.5 arc seconds (approximately 800 m spacing). As a result of this, the image is limited to expressing regional features. The gravity image shows the same general trends as in the magnetics in the east of the embayment around the Bancannia Trough (Figure 4.6). It also has a large area of high values in the centre of the embayment and one in the north. The Flinders Ranges are also prominent on the image as a gravity low in the west (Figure 4.6).
4.3. Surficial Geology

Regionally, the embayment can be divided into five morphological zones. These include:

- Flinders: Chace/Druid highlands in the west;
- Discontinuous eastern highlands: Grey Ranges in the northeast; Barrier and Koonenberry ranges in the southeast;
- Central low-lying basin, typically populated by longitudinal dunefields, small swale and salt lakes;
- Colluvial fans and plains surrounding the dunefields, shedding off the ranges; and
- The lake system in the west of the basin, including Lake Frome, Lake Callabonna and Lake Blanche

The ranges and bedrock inliers that encompass the embayment are dominated by rounded rises and low terraces, steep hills and mountains, and stepped rangefronts (see chapters 5 & 6). For the most part, these landforms are exposures of bedrock. The Flinders Ranges in the west are the highest part of the landscape, with elevations typically 500–600 m ASL (see chapter 5). The ranges that form the eastern margin of the embayment consist of three mountain belts, including the Barrier Ranges in the south; Koonenberry Ridge in the southeast; and the Grey Ranges in the north. For the most part these ranges are
Chapter Four: The Frome Embayment

Frome Embayment field points

CHfs1: elongated sheet flow fans, dominated by subrounded bedrock and Mesozoic clasts

CHfs2: broad sheetflow fans, dominated by rounded to subrounded bedrock clasts, sporadic Mesozoic & Eyre Formation exposures

Figure 4.7. Regolith landform map of the Frome Embayment

Cfc1: elongated, moderately steep colluvial fans, dominated by angular to subrounded colluvium shedding off the ranges

ACah1: Active ephemeral channel, dominated by channel sediments

Afa1: Alluvial fan dominated by red-brown sands and silts with minor subrounded clasts

Lpp1: playa plain dominated by lacustrine sediments, occasionally incorporating a narrow lunette.

ISul1: longitudinal dunes dominated by red-brown fine sands and silts

ISul2: longitudinal, parabolic and transverse dunes

ISul3: longitudinal dunes dominated by red-brown fine sands and silts, with clay pans, salt lakes and ephemeral streams

ISps1: Sands plains dominated by red-brown sands & silts with minor, rounded quartz clasts

Chfs1: broad sheetflow fans, dominated by rounded to subrounded bedrock clasts, sporadic Mesozoic & Eyre Formation exposures

Figure 4.7. Regolith landform map of the Frome Embayment
The oldest rocks within highlands and also the embayment are the late Palaeoproterozoic Willyama Supergroup metasediments and metaigneous rocks from the Broken Hill and Olary domains (Stevens et al. 1988; Williams et al. 2009). These rocks form the southern and southeastern margin of the area (Figure 4.8), and underlie much of the basin sediments to the east of the Benagerie Ridge (Broomfield 1997; Williams & Betts 2009; Williams et al. 2009). Mesoproterozoic and Neoproterozoic rocks from the Radium Creek Metamorphics and Moolawatana Suite, and also metasediments from the Cambrian Adelaidean Suite, dominate the mountains in the west (Teale 1993 a & b; Robertson et al. 1998; Williams et al. 2009). The northeast side of the embayment is constrained by discontinuous bedrock inliers. These consist of Ordovician Wonominta Phyllite (Neef et al. 1995; Neef & Bottrill 2001) which are the approximate stratigraphic equivalent to the Cambrian to Ordovician metasediments of the Easter Monday Group (Rose et al. 1967; Thalhammer et al. 1998; Davey 2005; Hill 2005; Greenfield & Reid 2007 a & b) (see chapter 6).

In places these ranges incorporate Mesozoic and Cainozoic sediments that have been recently uplifted (see chapters 5 & 6).

The low-lying basin area bounded by the ranges forms the southern part of the Strzelecki Desert (Fitzsimmons 2005). This area has extensive longitudinal dunefields, clay pans and salt lakes (Figure 4.7). In the south of the
embayment, longitudinal dunes are orientated WSW-ENE. The equivalent dunes in the north of the embayment are orientated almost N-S (Figure 4.7). This anti-clockwise rotation is a representation of the changes in prevailing wind directions in that area. Longitudinal dunes form parallel to the dominant wind direction (King 1960; Wasson 1983; Wasson et al. 1988; Devogal et al. 2004). The rotational pattern in the Strzelecki indicates the intracontinental ‘whirl’ or rotation of prevailing winds. The dunes are made of accumulations of red-brown sands and silts, with occasional small grains and clasts of quartz scattered throughout, presumably from colluvial and alluvial processes acting at the same time as dune formation. Dating of these dunes indicates that there are three stages of dune formation, ranging from 100 ka through to the present day (Fitzsimmons 2003). In places, the dunefields are so extensive that they form ergs. The dunes are populated by open woodlands, hosting shrubs such as needlewood (*Hakea* spp.), emu bush (*Eremophila* spp.), saltbush (*Atriplex* spp.) and bluebush (*Maireana* spp.), as well as larger woodland species such as whitewood (*Atalaya hemiglauca*), rosewood (*Heterodendrum oleifolium*), sandhill wattle (*Acacia ligulata*) and mulga (*Acacia aneura*). The dunes also host an abundance of grass species such as hard Spinifex (*Triodia intans* and *Triodia basedowii*).

![Figure 4.9. Small, densely vegetated sand dune at the edge of a clay pan in western New South Wales (568144mE / 6720814mN).](image)

In the central part of the embayment, and sporadically in the east of the area, the dune swales are dominated by large clay pans and small salt pans. Both these features are indicative of a high water table (Fitzsimmons 2003). In wet seasons, these areas typically become water-logged, such that the localised depressions become ephemeral lakes. In the dune swales and clay pans, vegetation is more diverse, with species such as coolibah (*Eucalyptus microtheca*), ironwood (*Acacia excelsa*), black box (*Eucalyptus largiflorens*) and lignum (*Muehlenbeckia cunninghamii*). In the east of the area, where small salt pans and lakes are nestled within the dunes in wider swales, species such as prickly wattle (*Acacia victoriae*) and bimble box (*Eucalyptus populnea*) dominate.

Around the edge of the embayment, parabolic and transverse dunefields surround the ranges and bedrock inliers. These dunes are typically orientated perpendicular to the longitudinal dunes. Localised variations in wind patterns produce these landforms, which are typically of locally-derived detritus.

Colluvial sediments surround the dunes and ranges. These sediments are hosted in sheetflow plains and fans, flanking low-angle rises. Two types of colluvium are hosted within the different landforms. These include: proximally sourced sheetflow in the west and surrounding the ranges in the east; and gibber plains in the east. The proximally sourced sheetflow occupies large fans, plains and low rises surrounding the northern Flinders Ranges and to the south of the Willouran Ranges in the west. The origin of the clasts was loosely determined.
based upon lithology and attrition. Exposures of bedrock and the Eromanga and Lake Eyre Basins were studied in detail within chapter 5, and thus were easily recognisable.

In the west of the area the landscape is dominated by large colluvial plains that are shedding detritus from the Flinders Ranges. In total, three generations of large fans spread across the landscape, feeding into Lake Frome (Figure 4.7). The basal fan system is dominated by broad fans that extend across from the ranges to the dunefields and lacustrine plains that surround Lake Frome. These fans are overlain by a smaller set of fans, recognisable by a change in clast lithology from quartz and granites in the larger fan, to a mix of quartz, sandstone, silcrete, and lithics off the ranges. The attrition of the clasts in the fan has also changed from sub-rounded to sub-angular–angular. A younger, elongated set of fans overlie both sets of fans. A closer investigation of these fans is conducted as part of chapter 5.

In places, clasts that appear to be foreign or exotic to the area dominated the sheetflow plains. These clasts indicate partially concealed exposures or sub-crop. An example of this is in the plains surrounding Mt Hopeless. Here the landscape is dominated by vast sheetflow plains, hosting bands of sub-angular, highly ferruginised sandstone and mudstone, amongst bands of red-brown sands and silts (Figure 4.10). These plains are nestled in between the extensive sand plains and the fans shedding off the ranges, and thus appear to be out of place. The clasts are sourced from discrete exposures of basin sediments that crop out at the top of very slight rises. These sediments are lithologically similar to Mesozoic sediments around the Mt Babbage Inlier (chapter 5). The ferruginisation of these sediments is not as prevalent around Mt Babbage (see chapter 5).

This is also a characteristic of the landscape around the bedrock inliers in the northwest, where quartz colluvium signifies localised bedrock exposures, while sandstone clasts signify Mesozoic exposures.

Gibber plains dominate the landscape in the east of the embayment, particularly surrounding the Tibooburra-Milparinka Inliers. These plains consist of undulating clay and silt pans armoured with rounded, highly-polished silcrete and quartz clasts (Figure 4.11). The rounded, highly-polished silcrete surface is attributed to the ubiquitous weathering of clasts that are constantly exposed to the elements and environment, often referred to as a ‘desert varnish’. The silcrete clasts are predominantly sourced from the pisolithic silcrete that has formed within the middle part of the sequence of the sediments equivalent to the Eyre Formation, and silcretes formed within the Mesozoic sediments equivalent to the Bulldog Shale or Oodnadatta Formation. These plains form the southern part of the Sturts Stony Desert. The plains are intermittently bisected by ephemeral erosional drainage, channels, small mesas and sand dunes. Vegetation on the gibber plain is sparse and is dominated by chenopods and forbs, including bladder salt bush (Atriplex vesicaria) and kerosene grass (Aristida contorta).
Lakes Blanche, Callabonna and Frome in the west of the embayment form a discontinuous, contemporary endoreic lake system within the dunefields. Lake Frome is the largest of the lakes, forming a lacustrine playa occupying approximately 2600 km² within the Lake Frome Regional Reserve. This lake is characterised by a fan or tear-shaped playa (for the most part below sea-level), surrounded by smaller lakes that have formed in the lacustrine plains. The main lake pan is covered by a thick crust of salt (Figure 4.12). In places the crust is stable enough to walk on (being up to 50 cm thick); however, most of it is very unstable, cracking, breaking and sinking underfoot. Below the salt crust is a thick, black-brown and rancid ooze-like mud. During fieldwork, shallow water covered the northern part of the lake, while, further south, small puddles of water were common in localised depressions.

Figure 4.12. Salt accumulations at Lake Frome: (i) thick salt pan (373112mE / 6578961mN); and (ii) salt accumulation surrounding a local topographic high (375049mE / 6579751mN).

Throughout the southeastern side of the lake, small islands crop up amongst the salt pans (Figures 4.13 & 4.14). These islands are surrounded by shallow dipping shorelines that grade into small erosional rises and mounds. Exposures of sandstones are common on these rises, with one of the southern islands having a minor sandstone cliff exposure. The west of the lake is bound by a large lunette that in places has exposures of lithified rock. This lunette has accumulations of saltbush (Atriplex ssp.) and bluebush (Maireanna spp.) species growing on and around it, with minor woodland species growing on the less consolidated parts of the lunette. The water in Lake Frome is derived from the ephemeral creeks and channels flowing from the Flinders Ranges. In seasons with high rainfall, water also sheds off the Olary and Barrier Ranges and from the Strzelecki Creek.
Figure 4.13. Landsat 7 imagery of the Southern lobe of Lake Frome, with field data points superimposed.

- Lpl1: Lacustrine sediments in a lacustrine plain. Ephemeral lake with muds, silts and salt accumulations
- Lpd1: Lacustrine sediments depositional plain. Active crevasse splay and channels with channel sediments, associated with lacustrine spill points
- Epl1: Evaporitic sediments in a lacustrine plain. Thick salt crust with ephemeral channels and fans
- Epp1: Evaporitic sediments in a playa plain. Salt accumulations atop fine-grained sands and silts; very low relief
- ISul1: Aeolian sands hosted within longitudinal dune field. Red-brown fine sands and silts hosted within rounded, asymmetrical dunes. Clay pans and small lakes forming in the lower parts of the landscape
- ISu1: Aeolian sands in a lunette. Fine-grained sands and silts hosted in a parabolic dune. Some partially lithified sediments exposed
- ISps1: Aeolian sediments in a sands plain. Low-relief landform with coarse to medium grained, red-brown sands, with minor clay pans and salt lakes forming in the low relief plains
- Apd1: Alluvial sediments in a depositional plain. Fine-grained sands, silts and minor salt accumulations hosted in ephemeral channels, fans and floodplains
- ACah1: Channel sediments hosted within an active channel
- Afa1: Alluvial sediments within an alluvial fan; sands and silts with small erosional drainage
- CHEp1: Sheetflow sediments on an erosional plain; sub-rounded granite, silcrete, sandstone and quartz clasts scattered amongst red-brown sands and silts
- CHER1: Sheetflow sediments on an erosional rise; sandstone and siltstone overburden on buff-yellow fine sands and silts
- SSep1: Slightly weathered saprock on an erosional plain; slightly silicified sandstones and mudstones with minor calcrete accumulations
Figure 1: 150,000 surficial geology map of the southern lobe of Lake Frome highlighting the intricacies of the lake system. Points of interest include the lobe shaped islands with lithified sediments forming small ridges, and the alluvial fans shedding into the lake in the south.

Figure 4.14. Regolith landform map of the south of Lake Frome. The map highlights the different generations of lake sediments and the small rises of partially silicified sediments that crop out as small islands in the centre of the lake.
Lake Callabonna is linked southwards to Lake Frome by Salt Creek, a near N-S trending ephemeral channel. Lake Callabonna is a dry salt lake that occasionally floods with brackish water flowing off the ranges and occasionally flow from Strzelecki Creek (Tate 1893). The lake is encompassed within a fossil reserve, which limits access to most of the landform. The fossil reserve was erected around the area to preserve the environment where a near-complete diprotodon skeleton was found in the late 1890s, after which numerous diprotodon and dromornithidae skeletons were found (Tate 1893; Murray & Vickers Rich 2004) (Figure 4.15).

Lake Blanche in the north occupies 1700 km² and forms the southwest margin of the Strzelecki Regional Reserve (Puckridge & Drewien 1992; Morelli & Drewien 1993). Unlike the other two lakes, it is fed from eight main tributaries, including the Strzelecki, Petermorra, Serpentine and MacDonnell creeks (Reid & Gillen 1988; Morelli & Drewien 1993). The lake itself forms in the floodplain of the Strzelecki Creek, and subsequently is the only lake in the chain not dominated by salt pans. The lake is typically shallow and is surrounded by fluvial channels and alluvial fans. Natural springs flow around Lake Blanche, occasionally charging the lake itself.

### 4.4. Sedimentology

As evident from the regolith mapping, Mesozoic exposures in the embayment are typically limited to the basin margins. These exposures are not only limited in extent; they are also characteristic of marginal sediments and not necessarily indicative of the sediments in other areas of the embayment. Therefore, sedimentological analysis within the embayment focused on subsurface geology obtained from wells, bores and down hole geophysical imagery, such as gamma logs. A minor component of sedimentological analysis was gathered from the marginal exposures obtained during mapping.
In total there are 294 geothermal, minerals, petroleum, stratigraphic and water wells and bores that intersect at least one sequence of Mesozoic sediments in the embayment (Figure 4.16). Sixty-five of these wells and bores penetrate the Mesozoic sequence through to basement (Figure 4.16).

![Figure 4.16. Well distribution within the embayment, with the wells that penetrate Mesozoic sediments and also intersect basement highlighted. Select wells are named for reference purposes.](image_url)

Mineral holes dominate the wells and bores in the embayment, most of which are U exploration holes. Since the early 1970s U exploration in South Australia has focused significantly on the embayment as a result of the Beverley and Honeymoon mineralisation. Uranium exploration is currently not permitted in the New South Wales portion of the embayment; however, during the 1980s, U exploration was prevalent in the northwest. Wells around New South Wales are dominated by Au holes. Au exploration has been prevalent since the early 1900s following the Tibooburra-Milparinka gold strike (McQueen 2008). However, these wells are specifically focused in either the Eyre Basin sediments or a section of the Mesozoic and therefore do not always penetrating the entire sequence.

Petroleum wells are scattered around the south-central portion of the embayment and in the north. In the southern and central parts of the embayment, these wells are typically focused on the metasediments from the Cambrian Arrowie Basin, subsequently penetrating the entire Mesozoic succession. However, because of the Cambrian focus, these wells often do not have core, cuttings or chips for the Mesozoic succession. Because of this, any analysis of these wells relies heavily on lithological logs from drilling, down hole petrological logging and
any other data recorded during drilling. In the north of the embayment, petroleum wells intersect complete or near complete successions of the Mesozoic sequence. These wells target the lower Mesozoic sandstones, predominantly the transition zone between the Cadna-owie Formation and the underlying Algebuckina Sandstone equivalents where gas accumulations are common in the central part of the basin (Evans 1946; Etheridge 1985). Natural artesian springs are common in the south of the Eromanga Basin. In places these springs flow naturally at surface, while in other places the water is harvested through bores. As the water is hosted within the basal Eromanga succession, these bores are crucial sources of information for the Mesozoic sediments. Stratigraphic wells also benefit the Mesozoic sediments, as they log everything as opposed to a specific portion of the subsurface.

4.4.1 Basal Jurassic Sediments
Basal Jurassic sediments equivalent to the Algebuckina Sandstone are limited in distribution in the embayment. Further, the basal sediments come in many forms, and thus are also hard to identify. The Mesozoic-basement unconformity is typically marked by a basal conglomerate. This conglomerate is present in exposures in places around the margins of the Tibooburra Milparinka inliers as well as in the subsurface.
Au drilling surrounding the Tibooburra-Milparinka Inliers target this conglomerate as it is the source of the gold nuggets (Pittman 1901; McQueen 2008; also see chapter 6). The DD88TB wells surrounding the Mt Browne Inlier near Milparinka have 15 wells that intersect the conglomerate, along with another 4 further north around Tibooburra. In this area the conglomerate is dominated by rounded milky quartz, metasediments, minor granite and basalt clasts (Figure 4.17).

Figure 4.17. Clasts sieved from the basal Mesozoic from the east of the Mt Browne Inlier intersected at 67.5 m in the J13-4 well. Clasts include milky quartz, metasediments and minor granite fragments.
Surficial exposures of this conglomerate are located around the Barrier Ranges in the southeast, the Tibooburra-Milparinka Inliers in the northeast and the Flinders Ranges in the west. The basal Mesozoic atop the conglomerates, equivalent to the Algebuckina Sandstone, is rarely intersected within the embayment. Occasional mineral wells to the north of the Flinders Ranges and petroleum wells in the north of the embayment encounter at least in part the basal Jurassic. Petroleum wells of Lake Stewart-1 in northwest New South Wales intersect the complete basal Jurassic succession. At the top of the basal Jurassic, Algebuckina Sandstone equivalent intersects at 1194.65 m (TVD). The total unit is 46 m thick, encountering three distinct sequences (Figure 4.18):

1. **Top**: fine to medium-grained sandstone with minor thin beds of dark grey-black claystones and mudstones.
2. **Mid**: medium to coarse-grained, grey, quartzose sandstone with interbedded matrix supported conglomerate and siltstones.
3. **Base**: coarse-grained sandstone with basal conglomerate (as previously described).

These sediments are typical of the Algebuckina Sandstone / basal Jurassic sandstones in the central regions of the basin (see chapter 2). Wells Lake Stewart-1, Paxton-1, Fortville-3 and Weena-1 all intersect the complete succession defined in Binerah Downs-1. Other wells in the embayment intersect part of the basal Jurassic; however, all wells that intersect the Algebuckina equivalents are in the north of the area.
Lenses of fine to medium-grained quartzose sands amongst a dark-grey silty claystone. Lenses range from cm to several m in width. Larger lenses show thin foresets herringbone cross-bedding.

Cross-bedded fine-grained sandstone and claystone interbeds with occasional white, calcareous mottles.

Fine to medium-grained sandstone. Grey and buff coloured layers, defined by a quartz dominance and a layer with more lithic fragments. Fining upward sequences repeated throughout the fine succession.

Sporadic pink, white and yellow mottles and clay pods.

Thin interbeds of claystone and sandstone. Claystones are dominated by black-dark grey clays. Sandstones contain abundant lithic fragments and small cross-bedding foresets.

Medium-grained, buff to grey sandstone. Goethite and haematite staining around the base of the sequence. Sporadic siliceous indurations are common. Some small (less than 1 cm) quartz pebbles scattered throughout.

Coarse-grained, white-yellow coloured, siliceous sandstone with a calcareous matrix. Occasional conglomerate beds. Clasts are typically proximally sourced, dominated by local volcanics, metasediments and granites.

Lithic, medium- to coarse-grained sandstone.

Basal conglomerate. Initially clast supported grading into a matrix supported conglomerate, eventually grading into the above sandstone.

Initial high-energy fluvial environment.

Bedrock or Cooper Basin sequence in the far north

Low energy fluvial deposit. Lenses are typical of channel deposits.

End of Mesozoic basin sediments

Low-energy fluvial deposit. Lenses are typical of channel deposits.

Sediments characteristic of channel sands. Fining upward sequences are typical of a meandering channel profile. Mottles are alteration and weathering of lithic fragments, namely feldspar and volcanic fragments.
4.4.2 Cadna-owie Formation

The Cadna-owie Formation marks the transition from the fluvial to marine environments within the basin. Exposures of the unit crop-out around the basin margins, especially around the northern Flinders Ranges in the west and the Tibooburra-Milparinka Inliers in the northeast. In the north of the area, the Cadna-owie sediments grade from the underlying Algebuckina Sandstone equivalents over a period of up to 20 m. This zone is characterised by thin interbeds of claystone, siltstone and fine-grained sandstone that form a rhythmic sequence (Figure 4.20). Sporadically, in the lower parts of the succession, the profile is littered with pebbly beds, intercalated with siltstone. In places the transition zone is abruptly ended by a thick conglomeratic layer consisting of matrix-supported granite, metasediment and silcrete clasts. In other places, the top of the transition zone is hard to define, as the whole Cadna-owie Formation has repetitive zones of rhythmic sedimentation representing transitional sedimentation of varying types. The zone exhibits considerable amounts of planar and herringbone cross-bedding (Figure 4.20). This zone of sedimentation represents an environment consistent with a periodic change in base level and, subsequently, periodically changing depositional environments.

In several wells across the embayment, artesian water was intersected in this transition zone. This was typically intersected at the top of the Algebuckina Sandstone equivalents, where the sandstones still dominate the sequences. Lake Stewart-1, Binerah Downs-1, Lake Frome-1, Fortville-3 and Paxton-1 all encounter the artesian aquifer in a stratigraphically and lithologically similar sand unit. In the south of the basin, the Cadna-owie Formation unconformably overlies bedrock. Where this occurs, the base of the unit is dominated by a matrix-supported conglomerate, with up to 10 m of fine-grained sandstone atop (for example Yalkalpo-2 well as seen in Figure 4.27). This unit is recorded in the Lake Frome Wells to the south of Lake Frome. Here, 64 m of Mesozoic sediments are intersected, including 50 m of Cadna-owie Formation capped by a thin Marree Subgroup. The base of the Cadna-owie Formation has 2 m of conglomerate with 11 m of sandstone atop. The conglomerate is dominated by small sub-angular to sub-rounded granite, quartz and
sandstone clasts interpreted to be proximally sourced. The matrix is a fine-grained, buff-coloured, silty sandstone. The conglomerate grades into the basal sandstone over approximately 1 m. The basal sandstone is dominated by fine-grained, rounded quartzose sands with mica visible in samples. Bands of pale brown to buff coloured, fine-grained sediments, approximately 1 cm thick, are interbedded with the sandstone. These bands effervesce when exposed to dilute HCl, and thus are interpreted to have a calcareous component in the matrix of the sandstone. Lake Frome-1 and Lake Frome-2 both intersect water in the basal sandstone (McGowran & Harris 1968; Kapel & Martin 1968), similar to the aquifers intersected in the base of the Cadna-owie Formation in the north of the area.

The top of the Cadna-owie Formation is also hard to define, as it represents a cyclic transgressive-regressive environment in the final gradational stages from fluvial to marine deposition. Sediments are characterised by fine to coarse-grained sandstones interbedded with siltstones and claystones. In the south of the embayment, these sediments have a higher content of sand and, in places, are dominated by sandstones. Occasional depositional structures are preserved in core and exposures around the margin of the basin. These include herringbone cross-bedding, sole and flame casts and ripple marks. In the embayment, the top Cadna-owie Formation-base Marree Subgroup is dominated by fluvial sediments with a tidal influence. Samples from core in the north have a stronger marine signature, with thicker zones of what is interpreted to be the shell hash, more slumps and flame casts and dominance in the finer-grained sediments. These areas are defined to be dominated by coastal marine plains, in which have formed small estuaries, lagoonal type ponds and shallow marine environments.

![Figure 4.21](image)

**Figure 4.21. Core from the top Cadna-owie Formation from Lake Stewart-1: rhythmic claystone-sandstone interbeds and small pebbles. Primary sedimentary structures include ripple marks and cross-bedding.**

Exposures of the Cadna-owie Formation around the basin margins have a higher sand content than those encountered in the wells (as seen in Figure 4.21). Sediments are characterised by fine- to medium-grained sandstones with layers of siltstone, pebble beds and thin conglomerates. These sediments are best preserved where they have been indurated, particularly where they have been silicified or ferruginised (Figure 4.22). The change in sediments represents the change in depositional environment from the basinward to the landward environment.
Around the Barrier Ranges in the southeast of the embayment sediment exposures are characterised by pale-yellow buff-coloured, fine-grained sandstone locally referred to as the Telephone Creek Formation. This sandstone has interbedded claystone and siltstones and is often preserved within the landscape as highly silicified (Figure 4.23) or ferruginised sediments. Where fresh, the sediments are highly friable, in places poorly consolidated, and typically host abundant lithic fragments. These sediments are atypical Marree Formation sediments; however, they have abundant marine trace fossils and marine signatures (Gibson 2005).

The Telephone creek formation also has abundant conglomeratic units which are characterised by rounded to sub-rounded clasts of quartz, quartzite, sandstone and quartz, metasediments, silcretes and various volcanics and granites (Figure 4.25). The metasediment clasts in the conglomerate are particularly distinctive. The Devonian Nundooka Sandstone that forms the Nundooka Ridge in the Barrier Ranges has distinct calcite pitting that forms nearly-perfect sphericular voids in the sandstone/psammite. Clasts of the Nundooka Sandstone form a major component of the conglomerate in this area. In places surrounding the Barrier Ranges, the beach pebbles have been silicified (Figure 4.24).
Figure 4.24. Silicified conglomerate at the approximate top of the Cadna-owie Formation from the edge of the Bancannia Trough, off the edge of the Barrier Ranges (576254mE / 659761mN).

In the southeast of the area in the Bancannia Trough the clast lithologies are highly variant, including rounded. Other clasts within the colluvium rounded quartz pebbles and dolomitite slate clasts are also common. These are sourced from the Adelaidean metasediments that also crop out in the ranges. Silcrete clasts are identified as being re-worked Mesozoic sandstone eroded before the deposition of the Marree Subgroup. Unusual clasts around the Barrier Ranges include graphitic pegmatite, garnet and fluorite rich granites, dacite and rhyolite. These clasts are distally sourced.

The distally sourced pebbles are all highly rounded and elongated, and show considerable wear patterns such as striations and pitting. The lithologies of these pebbles are typically very distinct and often host minerals rarely, if ever, found within the bedrock in the surrounding landscape. The mineralogy of the granitic pebbles is also very distinct. The granites have large concentrations of garnet (typically the lustrous purple-coloured spessartine) and pale, glassy-green minerals interpreted to be fluorite. Spessartine and fluorite are primary components of the granitic assemblages of the Willyama Block; that is, the Broken Hill area (Burton 2006). The graphitic pegmatite pebbles are also a common intrusive around Broken Hill and in the ranges further south (for example: Burton 2006). While the Barrier Ranges host abundant pegmatite veins, these are typically micaeous and have no recorded of graphitic inclusions.

In places the pebbles from the conglomerate have been weathered out into the surrounding landscape (Figure 4.35). This is most common in the plains that surround the Nundooka Ranges, where the Mesozoic sediments are exposed along the rangefront. These clasts are distinct from the colluvial clasts shedding off the metasedimentary ranges as there is an abundance of ‘exotic’ clasts in the mix, including the rocks interpreted to be from Broken Hill.
The transition from the Cadna-owie Formation to Marree Subgroup is marked by the interbedded claystones and sandstones. This transition is associated with a depositional environment characterised by an oscillation between marine and terrestrial environments, with the sandstones being from the terrestrial and the claystones from the marine. The repetitive nature of the transition succession is a rhythmic sequence.

Distribution of the Cadna-owie Formation is constrained to the north and the west of the area. Exposures of the Cadna-owie Formation and its equivalents are common around the west and northeast edges of the embayment. In the northeast of the area and in the far west the Cadna-owie Formation is exposed in profiles that have been uplifted by recent tectonism. Subsurface, the Cadna-owie Formation is intersected at >900 m in a basin depocentre in the northwest of the area (Figure 4.26). A similar depocentre intersection is present in the far northeast (Figure 4.26). The two depocentre lobes are separated by NW-SE trending bedrock high in which the sediments are intersected at < 100 m.

Parts of the distribution pattern are controlled by the limits in the extent of the available data. In the south-central portion of the embayment, as no wells penetrate past the Marree Subgroup, it is unknown from this data whether the Cadna-owie Formation is present. Trends from the surrounding wells support an absence of the Cadna-owie in the southeast, and a thin succession in the southwest. The furthest south wells that intersect the Cadna-owie Formation are the Lake Frome 1 and 2 wells drilled at the base of Lake Frome. However, Mudguard-1 (70 km northeast of the Lake Frome wells) does not intersect the Cadna-owie Formation (Figures 4.26 & 4.27). Yalkalpo-2 17 km southeast of Mudguard-1 intersects a thin succession of the Cadna-owie Formation (Figures 4.26 & 4.27). Other wells in the south-central part of the embayment, including LT-6, EAR-10 and TD92-09, also intersect basement, while Marree Subgroup does not intersect the Cadna-owie Formation. This represents an elongated zone trending approximately N-S in the south-central embayment that despite having no Cadna-owie Formation sediments is surrounded by them. Further northeast (130 km from Lake Frome wells), the TD wells in western New South Wales also do not intersect the Cadna-owie Formation. The Cadna-owie Formation is not intersected in the very south of the area or in the Bancannia Trough. This is confirmed by the fact that Bancannia North and South, as well as Jupiter-1 in the Bancannia Trough and in the EAR wells in the south of the central

Figure 4.25. Conglomerate pebbles within the contemporary landscape from the margin of the Barrier Ranges in western NSW (576201mE / 6597124mN).
basin, penetrate to bedrock and intersect Marree sediments, although there are no sediments from the Cadna-owie Formation.

Figure 4.26. Contemporary distribution of the Cadna-owie Formation cropped to the limits of data.
4.4.3 Marree Subgroup

Grading from the underlying sands, clays and conglomerates of the Cadna-owie Formation are the shales, silts and muds of the Marree Formation. These sediments represent the onset of the major marine incursion in the embayment. As previously mentioned, determining boundaries between the Cadna-owie Formation and the grading units is hard. However, between the Cadna-owie and Marree a conglomeratic layer is present near the top of the gradation across the entire embayment. This is picked as the base of the Marree. The conglomerates are initially clast-dominated, and grade to a matrix-dominated sequence. These sequences are prevalent in the wells drilled in the centre of the embayment atop the Benagerie Ridge and the flanking synclines. To the east of Lake Frome, several stratigraphic wells were drilled to assess the pre-Mesozoic strata of the Arrowie Basin. Therefore, they intersect the full succession of Mesozoic sediments. In Mudguard-1, a well 45 km due east of Lake Frome, 88 m of Mesozoic sediments were encountered below a succession of Eyre and Namba formations. Of this 88 m, a 32 m succession of Cadna-owie Formation is capped by a conglomeratic sequence (up to 1 m thick) conformably overlain by a dark-grey-black clay. The conglomeratic unit consists of quartz and small granite clasts, with some sandstone clasts in the lower units. A similar unit is present in Yalkalpo-2, a well drilled further east in the Yalkalpo Syncline. Yalkalpo-2 showed a considerable thickening of the Mesozoic sediment pile from the Mudguard-1 well. The 192 m of Mesozoic sediments intersected in Yalkalpo-2 is also dominated by Marree Subgroup sediments, with a 51 m thick succession of Cadna-owie Formation, followed by 11 m of conglomerate and pebbly sandstones. Other wells that encounter the conglomerate include the Lake Frome-1 and 2 and Bancannia South-1 in the south of the area and Pincilly-1, Fortville-3 and Paxton-1 in the north. The conglomerate is interpreted to be a transgressive lag deposit, deposited in the initial high-energy flux before the major marine incursion. Sub-areal exposures of these sediments are common around the Grey and Flinders Ranges.

Figure 4.28. Silicified conglomerate at the approximate base of the Marree Formation from the edge of the Flinders Ranges (363429mE / 6697753mN).
Chapter Four: The Frome Embayment

Figure 4.27. Gamma log profiles with sediment interpretation for the Basal Mesozoic. Wells flattened from the top Cadna-owie Formation, determined from the top shale unit and basal Marree conglomerate. Well profile shows the transition from the north to the south of the area with the absent Cadna-owie unit in the Mudguard-1 well, and the absent Algebuckina Sandstone in the Mudguard-1 and Yalkalpo-2 wells. The wells show the vertical and lateral variance in sediment type, particularly within the Cadna-owie Formation. The northernmost wells (Binerah Downs-1 and Tinga Tingana-1) have dominance in sandstone in the Algebuckina, with beds of silt and clays throughout. Lake Stewart-1 shows an abundance of the finer-grained sediments, indicating a change in the depositional environment progressively south. The basal Algebuckina in all wells is marked by a succession of fine-grained sediments. This relates to the southerly progression in which initial basin sediments were 'spill' sediments from the main basin's fluvial environments. A top these sediments the typical Algebuckina sediments are present in varying amounts.
Conglomerates in the northwest of the area surrounding the Flinders Ranges are dominated by quartz, granite and various metasediments, volcanics and intrusives. Granites around the Flinders Ranges are very distinctive, as are the metasedimentary units. Because of this, determining provenance of many of the clasts is relatively simple. However, a selection of clasts are exotic, and do not appear to be locally sourced. Some clasts are distinctly recognisable. These include the Gawler Ranges Volcanics; laminated metasediments; feldspathic psammite; and mafic volcanics rich in tourmaline and hornblende. These clasts are all very rounded, and often striated. The striations would indicate a glacial origin; however, the conglomerate is not typical to a tillite. The clasts are all sourced from within a Cambrian tillite from the Adelaidean Metasediments (for example Young & Gostin 1989). The clasts have been re-worked from the thick tillitic sequence and, thus, are a second generation, proximally sourced (see chapter 5).

In the northeast of the area surrounding the Grey Ranges exposures of the conglomerate are dominated by rounded quartz pebbles and metasediments. These lithologies are readily identifiable as being the local Cambrian bedrock. In the south of the ranges, granitic boulders and clasts are also common. The clasts are typically moderately to highly weathered, impeding identification. Photomicrographs indicate some of the granite clasts have a similar mineralogy to the granite and granodiorite of from the Tibooburra Suite pluton in the north of the ranges; however, some contain abundances of exotic mineralogies uncommon to the area (see chapter 6). The location of the granites was not identified and is a possible feature for further investigation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Lithology</th>
<th>Provenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Flinders Ranges</td>
<td>Quartz, metasediments, granite and volcanics, including clasts of Gawler Ranges Volcanics</td>
<td>Locally sourced granite, metasediments and quartz. Exotic rocks re-worked from local Adelaidean tillitic unit</td>
</tr>
<tr>
<td>Grey Ranges</td>
<td>Quartz, metasediments, granite</td>
<td>Locally sourced quartz and metasediments, Tibooburra suite granite, and unidentified granite</td>
</tr>
<tr>
<td>Benagerie Ridge</td>
<td>Volcanics, quartz, metasediments</td>
<td>Adelaidean Metasediments, Benagerie Volcanics</td>
</tr>
<tr>
<td>Poontana Trough</td>
<td>Granite, quartz, volcanics, metasediments, silcrete, quartzite</td>
<td>Flinders Ranges granites and metasediments, reworked Adelaidean tillites</td>
</tr>
<tr>
<td>Northern Embayment</td>
<td>Quartz, metasediments, various igneous</td>
<td>Adelaidean Metasediments, Benagerie Volcanics</td>
</tr>
<tr>
<td>Yalkalpo Syncline</td>
<td>Volcanics, quartz, metasediments</td>
<td>Adelaidean Metasediments, Benagerie Volcanics</td>
</tr>
</tbody>
</table>

Table 4.4. Lithologies and provenance of clasts hosted within the transgressive lag conglomerate unit.

The main succession of the Marree Subgroup sediments consists of shales, claystones and sporadic sandstones. These sediments are the most laterally extensive across the embayment (Figure 4.29). The sediments change from the north of the embayment to the south as terrestrial influences impact sedimentation as sedimentation migrates landward in the south.
Figure 4.29. Gridded top Marree Formations intersected in wells. Bedrock exposures clipped for increased gridding accuracy.
The Marree Formation crops out around the Flinders Ranges in the west and the Grey and Barrier Ranges in the east. The exposures are dominated by beach sediments; however, occasional profiles of the marine Marree sediments have been exposed along fault traces and in creek beds. Beach sediments consist of casts similar to the conglomerate clasts and pebbles from the base of the formation; however, these pebbles have a different morphology. The beach profiles, or shore lines, are preserved within the landscape as a pebbly lag (Figures 2.28 & 2.30). These lags differ from the conglomerates and are dominated by pebbles and clasts that are rounded and flattened. The rounded and flattened nature of the pebbles are typical of marine rolled pebbles, usually formed in the wave break zone at a shore line. Contemporary colluvium and alluvium are often mixed in with these sediments. However, the two units are very easily distinguished, as the beach pebbles have the characteristic round and flat attrition, whereas the modern attributes are typically angular, fragmented or of specific proximal source. The lithologies of the pebbles and clasts from the beach lags and gravel vary greatly across the embayment. Lithologies are typically comprised of rocks that can be identified as being proximally sourced as well as rocks that are readily identifiable as being distally sourced.

Exposures of the beach pebbles and lags around the Flinders Ranges in the west and the Grey Ranges in the East are dominated by quartz clasts (Figure 4.30). Components of the local geology are also incorporated into these exposures.

![Figure 4.30. Quartz beach pebbles perched atop a mesa of Cadna-owie Formation uplifted by recent tectonism from the northern Flinders Ranges (369308mE / 6696245mN).](image)

Pebbles around the Grey Ranges also incorporate silicified and ferruginised clasts of older Mesozoic sediments particularly Cadna-owie Formation equivalents, occasional granite and basalt clasts. These all coincide with local lithologies within the bedrock inliers. The beach sediments in the northern Flinders Ranges have large components of shell hash and fragments, and in places actual shells (see chapter 5).

Table 4.5. Lithologies and provenance of clasts hosted within the beach pebbles and lags.

<table>
<thead>
<tr>
<th>Location</th>
<th>Form</th>
<th>Lithology</th>
<th>Provenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bancannia Trough</td>
<td>Gravel and lag</td>
<td>Quartz, metasediments, silcrete, some mafic volcanics, granite, pegmatite</td>
<td>Broken Hill Willyama Super-group</td>
</tr>
<tr>
<td>Northern Flinders</td>
<td>Gravel and lag, lithified conglomerate</td>
<td>Quartz, granite, metasediments</td>
<td>Flinders Ranges granites and metasediments, reworked Adelaidean tillites</td>
</tr>
<tr>
<td>Tibooburra</td>
<td>Gravel and lag, lithified conglomerate</td>
<td>Quartz, metasediments, granite, diorite, silcrete, quartzite</td>
<td>Tibooburra Inlier, Easter Monday Metasedimentary group</td>
</tr>
</tbody>
</table>
In the north of the embayment, the Marree Subgroup can be divided into three different marine units. This segregation is similar to the division in the central basin region (see chapter 2). The basal unit, the Bulldog Shale, consists of grey-green, clay-rich shales with beds of black carbonaceous clays in the top of the unit. The shales are typically poorly lithified. Where exposed at the surface, these shales are highly friable, with an abundance of disseminated gypsum, glauconite and, in places, iron concretions. In places the shale has abundant micaeous fragments, dominantly muscovite and phengite. The micaeous beds are typically the sandy layers near the top of the shale.

Dividing the two primary marine units and grading from the shale over a very small zone is a succession of fine-grained sandstone with interbedded clay beds. This unit is highly distinctive on the gamma logs, forming a tight peak in amongst the relatively unresponsive marine sediments. The unit is classified by quartzose sands, muscovite, biotite, various mafic grains (lithic fragments) and zircons. Attrition of the grains is highly variable, ranging from sub-angular to very well-rounded. At the base of the sandstone the grains are well sorted and form a grading upward profile. In the centre of the sandstone this changes in that the grains are very poorly sorted. Here the sediments have abundant mica, zircon, feldspar, plagioclase and mafic grains. Some small quartz pebbles are scattered throughout this sequence. In places this unit has a very intense zone of black clays. These clays are haloed by pallid clays, indicating a possible zone of reduction. The top of the unit returns to a well sorted grain alignment, with the quartzose sediments. The top Marree Formation consists of shales, claystones and sporadic coal seams. These sediments are distinguished from the basal unit by a change in the dominant clay component in the shale units. The basal unit consists of glauconite and smectite; all of which combine to give the distinct green-grey colour typical to the Bulldog Shale. The top marine unit is dominated by kaolin, illite with minor smectite. These units are often pallid, pale grey or white, occasionally affected by a secondary staining where they have been exposed to water. This staining is typically a yellow and red colour indicating oxidised and hydrolysed iron (primarily goethite). The top unit also has an abundance of mica (typically muscovite and phengite). Minor coal seams are present in the top unit; these are typically thin and relatively discontinuous.

In the south of the basin the Marree Subgroup is simply represented as a thick succession of grey-black clays and shales. Data from well logs, core and chips show that the divisions clear in the north of the embayment are not obvious in this formation in the south. In these areas the Marree Subgroup has large disseminated and vugular selenite, and very small carbonaceous bands of typically < 3 cm. Some opal is found in these sediments.

Around the margins of the embayment, exposures of the Marree Formation are common in uplifted profiles and occasionally in incised valleys and drainage depressions. These sediments are dominated by the grey shales common to both the Bulldog Shale and the Oodnadatta Formation. This, accompanied by the lack of the sub-Marree marker units, makes it hard to distinguish if the sediments are Oodnadatta Formation or Bulldog Shale. In places around the northern Flinders Ranges, the landsurface is dominated by moderately weathered Marree exposures. The undulating and low-lying plains of the shales and more the common silty-clays surround the Mt Babbage Inlier in a zone of non-deposition of the Eyre Basin (see chapter 5). Places around the Tibooburra-Milparinka Inliers have similar contemporary landscape exposures, with the Wittabrena Shale, the local equivalents of the Marree Subgroup sub-cropping in the undulating plains surrounding the Mt Browne, Mt Poole and Warratta inliers (see chapter 6). In places these sediments are as shallow as <1 m below surface, as shown in channel and drainage profiles. In these areas, vertical exposures are also common along fault traces.

Depositional environments in the Marree Subgroup are dominated by marine conditions. The basal conglomerate is interpreted to be a transgressive lag deposit resulting from the initial high-energy influx as the major marine incursion occurs within the embayment. This phase of the basin development marks the onset of the major Eromanga transgression continuing on from the episodic transgression-regression cycles that mark the Cadnaowie to Marree transition. Atop the conglomerate, the basal unit, dominated by the Bulldog Shale in the north and the dark clays and shales in the south, is characteristic of a shallow marine environment. The slight changes in
facies with the interbedded clay and shale indicate a very slight change in base level, in which the depositional environment becomes slightly deeper. These sediments correspond to the Aptian period, in which there occurred no major eustatic sea-level variations (see chapter 2). The base-level changes are interpreted to be a response to tectonic oscillations similar to those that occurred during the late Neocomian, when the rhythmic sediments from the Cadna-owie Formation were deposited. The sandy sequence from the intra Marree marker unit indicates that the depositional environment intermittently returned to a higher energy environment. Although rapid, this change was conformable (as is evident by the very small gradational contact between the shales and the sandy unit). The sediments contain features associated with terrestrial and marine environments, with a marine dominance. The high gamma peak is formed by the abundance of carbonaceous material, including woody fragments (terrestrial), marine plants and algae blooms.

Within the basal Oodnadatta Formation equivalents, a free-flowing artesian aquifer is present. An example of this is the Montecollina Bore in the north of the embayment, east of Lake Blanche. Artesian water flows from the Montecollina Bore forming an oasis in the Strzelecki Desert (Figure 4.31). At Montecollina, a large pond of brackish water is surrounded by transverse dunes and sand plains comprised of white-buff, siliceous sand. Montecollina was drilled in 1897 as a water source bore to supply the pastoralists in the Callabonna area (Sheard & Cockshell 1992). Since then the bore has not stopped flowing, maintaining the Montecollina lakes even during the extensive drought periods experienced in recent times (Figure 4.31). Because of the continuous flow from the bore, the area is highly vegetated, and the home to many rare Australian fauna.

Figure 4.31. Artesian sourced Montecollina Bore west of Lake Blanche (401892mE / 6747289mN). East exposure of the lake looking north (Photo: Martin Luerssen).

The 777 m bore intersected the water in a silt unit at the base of the Oodnadatta Formation around the zone where the Oodnadatta formation grades into the Bulldog Shale. Water is also intersected lower down in the sequence in a siliceous sand unit in the basal Cadna-owie at the top of the Algebuckina Sandstone area. It has been previously suggested that the basal aquifer is feeding the Oodnadatta Aquifer; however, this is unsubstantiated (Vaughn 1920). The bore is drilled along the Lake Blanche Lineament, a structure commonly associated with subsurface water migration and occasional spill point of the natural hydraulic head of the basins artesian waters (Vaughn 1920). Lake Frome-1 and Skeleton-1 are examples of other wells that have the multi-layered aquifer system.
Marree Subgroup Composite Log

Facies

Oodnadatta Formation

Silty claystone. Pallid sediments with occasional yellow-red iron staining. Dominated throughout by clays with small amounts of silt. Zones of grey shales present.

Interbedded black clays and dark-grey shales. Some yellow mottles in the clay bands.

Interbedded shale and very fine-grained sandstone-siltstone. Shale typically black and very clay rich. Sandstone has thin beds (up to 2 cm) of kaolinite.

Carbonaceous grey-green shale. Abundant disseminated gypsum, some quartz pebbles (up to 3 cm), and zones of intense ferruginisation.

Clast supported conglomerate with fine-grained matrix. Clasts include vein quartz, sandstone, volcanics, granite, and reworked clasts from the Adelaean sediments exposed within the Adelaean Geosyncline.

Terrestrial

Shallow marine.

Coastal plains and shelves, estuaries, and shore platform sediments.

Figure 4.32. Composite log of the Northern Marree Subgroup sediments.
Figure 4.33. Gamma log profiles with sediment interpretation for the Marree Subgroup sediments. Wells flattened from the top Marree Subgroup, determined from the unconformity and, in places, the disconformity. In the southern wells the basal unit is characterised by a fine-grained succession with sands and silts throughout. The top unit also has zones of variation in two of the wells (Bumbarlow-1 and Mudguard-1). The sand unit in Bumbarlow-1 is dominated by very fine-grained sands with silts and clay interbeds. The Skeleton-2 well shows the typical homogenous sequence for the typical basin sediments; however, the typically notable intra-Marree unit is not particularly obvious on this unit.
4.4.4 Winton Formation

Winton Formation sediments are limited in distribution in the embayment. Deep wells in the north of the intersect Winton sediments below the Lake Eyre Basin sediments. At Binerah Downs-1 in the northwest, the Winton Formation is at surface. The shallowest intersection is encountered in the subsurface, at 75 m below surface in the Lake Stewart-1 well. Other intersections range from 110 m to 240 m below surface. Thickness varies between 200 m and 460 m, with the deepest profile (462 m) intersected in the Tinga Tingari-1 well in the central north.

Exposures of the sediments have been recorded cropping out in the northeast of the embayment around the Tibooburra-Milparinka Inliers (Morton 1982; Hawke & Cramsie 1984). However, in the areas surrounding the inliers, exposures of the Winton Formation are limited to the Bulloo-Bancannia Basin to the east and around Olive Downs in the north near the Binerah Downs-1 well. Other exposures of the Winton Formation are present to the northwest of the embayment near the town of Marree.

Limited exposures and preserved core samples of the Winton Formation from within the embayment inhibit detailed descriptions of the formation. Petrological logs (such as gamma logs) are not useful with respect to the Winton Formation, as many intersections occur within the top part of the cased well. Casing impedes petrological logs as it forms a barrier that many recording devices cannot penetrate. Core logs and photos from the Binerah Downs-1 and Lake Stewart-1 wells indicate that the formation is characterised mainly by coarse-grained, quartzose sandstones interbedded with claystones and occasional conglomerates and siltstones. Facies indicate a return to fluvial environments, with the variations in lithologies indicating variations in fluvial regimes.

### Table 4.6. Wells containing Winton Formation Sediments across the embayment. Wells are typically confined to the north of the area, where the embayment grades up into the main basin sediments. The furthest south the Formation is intersected is in the Coonanna Bore.

<table>
<thead>
<tr>
<th>Well</th>
<th>Top (m)</th>
<th>Base (m)</th>
<th>Thickness (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binerah Downs-1</td>
<td>0.00</td>
<td>426.40</td>
<td>426.40</td>
<td>Thick package, dominated by different sand sequences</td>
</tr>
<tr>
<td>Cherri-1</td>
<td>198.10</td>
<td>446.50</td>
<td>248.40</td>
<td>On a par with Gurra-1 with respect to the difference between the thickness from Tinga Tingana</td>
</tr>
<tr>
<td>Coonanna Bore</td>
<td>120.60</td>
<td>193.70</td>
<td>73.10</td>
<td>Furthest south intersection, 18 km north of the closest well which does not intersect the Winton Formation</td>
</tr>
<tr>
<td>Fortville-3</td>
<td>121.92</td>
<td>401.42</td>
<td>279.5</td>
<td>Approximately 100 m thickness variation over 3 km to Paxton-1</td>
</tr>
<tr>
<td>Gurra-1</td>
<td>179.83</td>
<td>441.96</td>
<td>262.13</td>
<td>18 km due east of Tinga Tingara-1 with more than 200 m difference in Winton thickness</td>
</tr>
<tr>
<td>Lake Stewart-1</td>
<td>75.00</td>
<td>277.00</td>
<td>202.00</td>
<td>Relatively shallow intersection</td>
</tr>
<tr>
<td>Lake Crossing Bore</td>
<td>129.40</td>
<td>255.80</td>
<td>126.40</td>
<td></td>
</tr>
<tr>
<td>Mt Hopeless Well</td>
<td>136.60</td>
<td>179.83</td>
<td>43.23</td>
<td>Thinnest succession, 14 km SW of Lake Crossing, indicating a trend toward the edge of the basin at Winton time</td>
</tr>
<tr>
<td>Paxton-1</td>
<td>205.00</td>
<td>381.00</td>
<td>176</td>
<td>Approximately 100 m thickness variation over 3 km to Fortville-1</td>
</tr>
<tr>
<td>Ticha Tingana-1</td>
<td>118.80</td>
<td>328.30</td>
<td>209.5</td>
<td></td>
</tr>
<tr>
<td>Weena-1</td>
<td>234.70</td>
<td>499.87</td>
<td>265.17</td>
<td>Deepest intersection of the top of the sediments</td>
</tr>
</tbody>
</table>

General sediment distribution in the embayment has the thickest succession in two pods—one in the northeast to the west of the Grey Ranges and the other in the northwest north of Lake Blanche. In the northeast, the thick succession is identified by the Binerah Downs-1 well. In Binerah Downs-1, the Winton Formation is exposed at surface, and continues down 420 m until it intersects the marine unconformity (Figure 4.34). Both of these areas
are defined by well profiles which have Winton Formation sediment accumulations dominated by stacked successions of sands (Figure 4.34). The stacked successions are comprised of sequences of white-buff coloured, quartzose sandstones that fine upwards. In some of the sequences the coarser sands have abundant feldspar and sporadic micaceous grains. In places the sequence grades into clays dominated by kaolinite. Occasionally the base of the unit is marked by a thin conglomerate band or pebbly sandstones. However, the main part of the sandstone is dominated by the fine- to medium-grained sandstones. Clasts in these sequences are typically less than 4 cm and include sub-rounded top sub-angular quartz, silcrete and sandstone.

The stacked successions common to the Winton Formation sediments are representative of channel profiles. The grading profile is indicative of meandering profiles, in which the part of the stream profile at that location changes over time. The stacked nature of the sediments indicated that there were intermittent changes in base level, such that the channel reformed or re-migrated to that location.

Other features of the formation include interbedded claystone, siltstone and mudstone successions. The clay sequences are typically pallid clays, possibly kaolinite, with occasional smectite bands in some wells. The claystones are dominantly interbedded with siltstones. The siltstones are dominated by thin (less than 2 cm thick), red to orange, quartzose sediments that are often associated with minor regolith carbonate accumulations (Figure 4.35). The finer grained sediments dominate the top of the Winton Formation with some occurrences towards the base of the formation (Figures 4.34 & 4.36). These successions are typically less than 20 m thick. However, in Binerah Downs-1, two of these interbedded successions exceed 40 m in thickness.

In places the Winton Formation sediment distribution patterns vary considerably over small distances (Table 4.6). In the far north of the embayment the greatest thickness variation occurs where the 465 m of the Winton Formation intersects in the Tinga Tingara-1 well drops to 262 m in the Gurra-1 well and to 248 m in the Cherri-1 well. Cherri-1 (16 km southeast of Tinga Tingara-1) and Gurra-1 (17 km due east) have similar sediment profiles, with the typical sandy dominance with abundant silty and clay beds. In contrast to these two wells, the Tinga Tingara-1 well is dominated by medium- to coarse-grained sands with gravelly pebble beds. The change in sediments between the wells indicates a change in the depositional regime. The sands are typically of a higher energy system than the sediments in the Cherri-1 and Gurra-1 wells. This is interpreted to be a result of the Tinga Tingara-1 well intersecting a succession of the Winton Formation which is dominated by a channel profile. The cyclic or stacking nature of the sediments indicates episodic base level changes in which the channel regenerates periodically.
Figure 4.35. Winton Formation sediments: i) small interval of interbedded sandy siltstone and claystones; ii) interbedded quartzose sandstone and clayish-siltstone. Very little core is preserved or even collected for the Winton Formation sediments, and as such minimal sub-surface samples are available.

An another example of this is the 100 m thickness variation between Paxton-1 and Fortville-3 near the South Australia–New South Wales border. The wells are located 3 km apart, aligned NE-SW of each other, and are drilled within the dunefields of the Strzelecki Desert (Figure 4.36). The dunes inhibit recognition of surficial structure that might account for the change. While this is not a particularly large variation over a small distance, it is uncommon in the embayment to see such sediment changes without there being a structural feature or a considerable change in basin morphology.
4.4.5 Sedimentary Elements

The complete Eromanga Sequence is present across the embayment in varying distribution. The basal succession ranges from the Algebuckina Sandstones in the north to the Cadna-owie Formation in the central area and the Bulldog Shale equivalents in the far south. The change in basal sediments represents the grading of the basin margin landward and further south over time. Profiles in the south are dominated by Marree Subgroup sediments with occasional thin Cadna-owie Formation beds at the base (Figure 4.37). In contrast, profiles in the far north of the area have complete successions of Mesozoic (Figure 4.37), which is often capped by a thick succession of Eyre Basin Sediments. Lateral variations in formations are also common (Figure 4.37), reflecting different depositional environments conducive to the landscape at the time and stage of basin development.
Figure 4.37. Composite logs of the Eromanga Basin succession from the different areas of the Embayment. Algebuckina Sandstone sediments are typically sandstones and conglomerates with some interbedded siltstones and claystones. This transitions into the Cadna-owie Formation, as noted by an increase in finer-grained sediments. The Cadna-owie Formation has the greatest variance across the basin, primarily as a result of the transitional nature of the sediments. The Marree Subgroup sediments fluctuate between the shales and claystones with the basal conglomerate or sandy units. The Marree Unconformity is ubiquitous across the Embayment. Around the margins this also marks the final Eromanga Basin deposition. In the north the Winton Formation is dominated by interbedded sandstones and claystones with some shale.
4.5. Tectonic Elements

Tectonic elements within the embayment were analysed using a combination of subsurface and surficial data sets. Surface interpretations were conducted from the fieldwork and also from mapping. The mapping component of the interpretation used a combination of the landsurface maps on both a regional and local scale. While this interpretation defines the approximate lateral extent of structure, it neglects to define the vertical extent. Surface interpretation can miss structure that does not radiate to surface or that has been capped by unconformable sediments and erosional phases, and occasionally that which has only subtle expression within the landscape. To account for this, the Frome seismic data set was used to define structure in the subsurface. Magnetics and gravity surveys were also incorporated to help with correlations and basin trends.

4.5.1 Structure at surface

Structural trends and attributes are often expressed at surface in landforms and sediment distribution patterns. For most of the embayment, these trends are masked by the thick cover sequence of dunes and other aeolian features. However, around the embayment and basin margin several generations of structure are exposed at surface. These exposures are not always obvious; sometimes they are exposed as subtle topographic variations that are best recognised in changes in regolith and landforms. The most prominent exposure of structure at surface is within the highlands surrounding the Embayment and the intra-basin highs. One of the most extensive trends seen at surface is the NW-SE trending structures that bound the ranges in the east of the Embayment. These structures include the Warratta and Mt Poole faults that define the major trends and bound several of the bedrock inliers in the Grey Ranges in the northeast (Figure 4.38). The Warratta Fault is the approximate northern extent of the Olepoloko Fault.

Figure 4.38. Eastern rangefront of the Warratta Inlier in the Grey Ranges. The eastern extent of the inliers is bound by the Warratta Fault, an approximately NW-SE trending reverse fault that has a component of overturned sediments in the north of the structure.

These structures control most of the uplift associated with the mountain ranges in this part of the embayment. Many of the faults have a stepped fault plain indicating that the structure has been reactivated. This indicates that there have been episodic ‘forced’ base level changes within the east of the embayment. In the north of the area this fault set deforms basin sediments from both the Eromanga and Eyre Basins. This deformation has resulted in large vertical exposures (in places over 50 m) of the Mesozoic sediments, as well as small mesas and ‘pop-up’ structures that expose the contacts between the Mesozoic and Palaeocene sediments. These relationships are explored further in chapter 6.

Other obvious surficial expressions include the Paralana Fault, a range bounding structure that defines parts of the eastern extent of the Flinders Ranges. This fault forms the abrupt boundary of the basin in the west. Uplift and deformation associated with it are relatively young, as there are parts of the fault in which the Palaeozoic bedrock
Chapter Four: The Frome Embayment

is thrust over the top of the Palaeogene sediments (Figure 4.39). The Paralana Fault is an approximately NE-SW trending structure with an eastern fault dip. The fault corresponds with the primary uplift of the Mt Painter Inlier. While this structure has a young component to it, sediments from the Mesozoic succession abruptly abut the fault and are seen both at surface and at depth (see seismic interpretation in this chapter). The abrupt nature of this structure and the thickness variations surrounding the area are an indication that the fault had at least some uplift at the time of deposition.

Figure 4.39. Paralana Fault exposure at the Lady Buxton Mine, northern Flinders Ranges (348302mE / 6651034mN). Metasediments pertaining to the Adelaidean Metasediments thrust atop the younger sandstones and siltstones. This fault is locally referred to as the ‘Lady Buxton Fault’.

Aerial imagery of the Paralana Fault shows where younger structures with an approximate E-W trend displace it. These structures, which also control the major drainage systems and morphologies of the younger fans shedding from the ranges, cause rotation in the ranges and thus a slight reorientation of the fault (see chapter 5). Smaller fault exposures are also common throughout the Barrier Ranges. These structures define the extent of the Nundooka Ranges, the prominent mountain range that cuts through the Fowlers Gap Arid Zone Research Station. These ranges are controlled by the Nundooka Fault, a structure that also displaces a series of reactivation zones. It controls the primary exposure of Devonian sediments in the Barrier Ranges. This structure has at least been reactivated post Mesozoic as, in places, it deforms the Telephone Creek Formation sediments. The more subtle expressions of structure within the embayment occur within the low-lying plains between the extensive dunefield and the bounding ranges. Landforms and often their distribution are commonly associated with subtle structure. Occasionally the expressions are actual exposures of a structure that is present at surface, and sometimes expression of subsurface structure that has had an adverse effect on features such as sedimentation and regolith profiles.

Alluvial and fluvial systems in the embayment are often controlled by structure. The lake chain surrounding Lake Blanche is an example of this. This lake and the small playas and salt pans that surround it are controlled by the Lake Blanche lineament. The structure trends approximately NW-SE along the southwest side of Lake Blanche down to Lake Callabonna (Figure 4.40). The Moppa-Collina Channel between lakes Blanche and Callabonna conforms to this trend, as does the series of small evaporitic lakes between Lake Blanche and Lake Gregory further north. The lineament has created a slight change in landscape relief, such that the northeast side of the lineament is lower (potentially a footwall), causing the playas that form the lakes and defining that extent of the Moppa-Collina Channel.
Figure 4.40. Quickbird imagery of the northern part of the Frome lake chain in the west of the area, highlighting the linear nature of the Lake Blanche system and the tributary channels feeding into it. The smaller lakes around Lake Blanche also comply with the linear trend, forming a ‘chain’ extending to the northwest and the southeast of the main lake along the Lake Blanche Lineament. The Northern Flinders Ranges in the southwest of the area.

Another example of structure controlling water distribution in the embayment is the large series of alluvial fans that spill from the mouth of the Terrapinna Corridor in between the Mt Babbage and Mt Painter inliers. Here the main active channel (Hamilton Creek) flows through the corridor and spays out into a large fan. The fan in general is quite broad (Figure 4.41), with a very small transition from the throat to the lobe of the fan. The fan extends from a point 4 km east of the end of the corridor out 17 km east into the basin, with a typical wedge-shape profile. The apex of the fan is dominated by sandy gravel and cobbles that are typically all locally sourced. The gravel component of the sediments consists of sub-rounded to rounded quartz gravel (<3 cm), sub-angular to sub-rounded lithic fragments (<5 cm), and occasional exotic clasts (such as garnets and fragments of a green mineral possibly fluorite). After the apex of the fan the sediments change laterally across it, from a coarse-grained sand and gravel mix around the throat of the fan extending down approximately 13 km to where the fan bulge reaches maximum curvature, and then to a mix of silts and clays around the very base of the fan lobe. The fan follows the approximate direction of the basin portion of the channel flowing from the corridor (Figure 4.41). This channel flows through the landscape down to the Moppa-Collina Channel and the associated evaporitic lacustrine plains that surround the Frome lake chain (Figure 4.41). Other smaller channels flow through the fan. These channels are characterised by braided and anatomising patterns. The channels are up to 2 m deep and as wide as 3 m. The ephemeral nature of the channels has formed flood and alluvial plains (Figure 4.4) that are characterised by very fine-grained sediments, with some gravely profiles around the edge of the channel.

Surrounding the fan channels is an area of dense vegetation, dominated by a canopy of woodland species such as *Acacia spp.* and emu bush (*Eremophila spp.*). The understory featured several chenopod species as well as
sprouts of Sturt desert pea (*Swainsona formosa*) and a selection of small lilies (*Liliaceae spp.*). The fan is a contemporary landscape feature, with seasonal flooding occurring in the rare wet periods. The apex of the fan forms at a point in the landscape 5 km southeast of the corridor mouth, at a point that coincides with the trend of the Paralana Fault. As previously discussed, obvious exposures of the Paralana Fault terminate at the Parabarana Bore; however, this termination is a result of structural junctions and not necessarily as a result of fault termination. At Parabarana, expressions of the fault show that the structure still has large displacement (as seen at the Lady Buxton Mine, which is in very close proximity to the Parabarana Bore). Because of this the fault is interpreted to dissipate off into the basin, such that the deformation is expressed differently in the basin sediments which are typically less dense and more ductile than the crystalline basement that forms the Mt Painter Inlier. From this detail the fan is interpreted to be a subtle expression of uplift from the fault. This uplift at this point is subtle, being expressed as a slight bump or rise in the landsurface. While this feature is subtle, it is enough to cause a change in the river profile whereby the river drops down in the landscape to the east of the structure. This is a further explored in the seismic interpretation in this chapter. Another fan has formed along this trend further south than the one at the Terrapinna Corridor. A large gully-like flow off the Mt Painter Inlier feeds a fan system that stretches 11 km wide and has a lobe breadth of just over 5 km at its greatest. These fans are characteristic of a radial fan profile (Blair & McPherson 1994).

Underlying the contemporary Terrapinna fan is a subtle expression of an old fan that spills from the mouth of the Terrapinna Corridor. This fan splays out from the apex to the toe approximately 37 km to Lake Callabonna, where it grades into the lacustrine plains and evaporitic lakes that form the north of the Frome lake chain. The fan is comprised of a similar base sediment pattern to that of the contemporary fan; however, there is considerable overburden that has washed over since its initial deposition. This overburden is dominated by bands of rounded silcrete pebbles, sandstone and granite clasts, as well as minor angular quartz and granite fragments. Occasional clay pans have formed, which sometimes host small water ponds when it has rained in the area. The morphology of the fan is characterised by a long, broad profile with minimal topographic affect within the fan itself and one main feeder channel (assumed to be the Terrapinna Corridor channel). There is minimal to no definitive fan bulge or gradual declination into the lobe. The fan sediments are mixed in with contemporary regolith features, particularly sheetflow sediments dominated by clasts shed off the inliers. Incised stream profiles show small vertical profiles of the fan succession with different parts of the fan exposed. The base of the fan sediments cap sandstones and in places siltstones from the basin successions. These sediments are primarily pebbles and clasts with a fine- to coarse-grained sand matrix. Clasts include sub-angular to very highly-rounded sandstones, brecciated metasediments, granites volcanics and some quartz-haematite crystalline rocks identified as sinter rocks from Mt Gee. Atop the basal unit is a thin coarse-grained sand unit. The sands are quartz-dominated, but also have an abundance of feldspar and micaceous grains. The upper unit of the fan is dominated by coarse-grained sands and gravel that grade out laterally to a succession of fine-grained sands with a halo of clay. Unlike the contemporary fan, the halo of finer sediments surrounds the entire fan profile.

The fans form an uncommon morphology called a low-sinuosity or meandering fan in which a succession of factors cause a multiphase alluvial ‘spilling’ (Stanistreet & McCarthy 1993). These fans begin as a distal fan in which a very low angle but large ‘mega fan’ forms, typically in an arid environment from one main high-powered ephemeral channel feeding out from a mountainous environment (Stanistreet & McCarthy 1993; McArthur 1995; Harvey 2005). These fans typically flow into a lacustrine environment (Stanistreet & McCarthy 1993), as does the system in the embayment. A sudden change in base level around the spill point or the apex of the fan results in the formation of a new fan (Stanistreet & McCarthy 1993). This new fan forms in response to the degree of change in the base level; that is, to the amount of displacement caused by the activation of a structure. In this instance the new fan has formed along the trend of the Paralana Fault, potentially reflecting one of the many recent reactivation phases of the fault.
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SSeh1: erosional rises, low hills, hills and mountains, dominated by bedrock exposures

Aap1: Alluvial sediments in an alluvial plain. Fine-grained sands, silts and minor salt accumulations hosted in ephemeral channels, fans and flood plains.

Cah1: Active ephemeral channel, dominated by channel sediments, fine-grained silts and quartzose sands with granite, metasediments, sandstones and quartz clasts. Occasional exposures of moderately weathered sandstones and conglomerates. Vegetation dominated by woodland species with abundant chenopods.

ISul: longitudinal, parabolic and transverse dunes

ISul2: longitudinal dunes dominated by red-brown fine sands and silts, with clay pans, salt lakes and ephemeral streams

ISps: Sands plains dominated by red-brown sands & silts with minor, small, rounded quartz clasts. Small, elongated, low lying clay pans that occasionally fill with water.

Lpp: Lacustrine sediments in a lacustrine plain. Ephemeral lake with muds, silts and salt accumulations

Lpl: Lacustrine sediments depositional plain. Active crevasse splays and channels with channel sediments, associated with lacustrine spill points

Epl: Evaporitic sediments in a lacustrine plain. Thick salt crust with ephemeral channels and fans

CHer1: Sheetflow sediments on an erosional rise. Sub-rounded granite, silcrete, sandstone and quartz clasts scattered amongst red-brown sands and silts. Chenopod shrublands dominate vegetation profiles.

Afa1: Alluvial fan dominated by red-brown sands and silts with minor subrounded clasts

Afa2: Alluvial fan dominated by red-brown sands with a large component of sheetwash sediments as a transported overburden consisting of rounded silcrete, angular to sub-rounded quartz, sandstone and granite clasts.

ACah1: Active ephemeral channel, dominated by channel sediments, fine-grained silts and quartzose sands with granite, metasediments, sandstones and quartz clasts. Occasional exposures of moderately weathered sandstones and conglomerates. Vegetation dominated by woodland species with abundant chenopods.

Aap1: Alluvial sediments in an alluvial plain. Fine-grained sands, silts and minor salt accumulations hosted in ephemeral channels, fans and flood plains.
Several fan profiles similar to this fan are present around the embayment. Several large fans have formed around the Barrier Ranges, particularly around Nundooka where the Nundooka Creek flows through the ranges and spills out into the trough (Figure 4.42). The fan here is similar to the one at the mouth of the Terrapinna Corridor in that it has the two distinct lobes and a migrating apex which follows the different phases of tectonism in the area.

As well as the alluvial fans, several generations of colluvial fans are present within the embayment. As with the alluvial fans, these fans provide constraints on the age and relative timing of some uplift. Colluvial fans are useful in recognising stages of tectonism, particularly modern tectonism. Colluvial fans form by the gravitational movement of loose rocks and particles. They dominantly form at the base of slopes or ranges, accumulating at the base of the landform and building up against it. The morphology of the fan varies depending upon the gradient, height and lithology of the elevated landform. When a change in base level occurs (dominantly uplift), factors such as slope gradient, height and structural stability change. This is reflected in the resultant fan morphology. Recognising the styles, size and composition of a fan can define evolutionary features such as tectonism. Because fans are an erosional landform, they are also affected by climatic affects. Climates define the amount of meteoric water, wind and seasonal temperature variations. Meteoric water attributes to mass sediment movement, generating regolith profiles such as sheetflow. Water also attributes to chemical and physical weathering and subsequent erosion. Temperature meanwhile contributes to physical erosive processes, as it can dictate the stability of bonds. An example of this is the build-up of granite fragments around the Mt Babbage Inlier in the north of the Flinders Ranges, which has shed off the large granite tors as a result of shrink-swell or onion-skin weathering (see chapters 5 & 6).

Colluvial fans (predominantly sheetflow fans) dominate the basin margins. Shedding off the Flinders Ranges in the east has seen at least three generations of fans. These fans range in size from small (<20 m wide) steep talus cones to low-angle broad fans that shed across to the Frome Lake chain. Each fan represents a recent reactivation of the range bounding faults, indicating that at least some of the uplift associated with the ranges is recent. There are similar fans shed off the Mt Babbage Inlier in the north (see chapter 5). Other colluvial fans in the embayment include the multigenerational fan shedding off the Nundooka Rangefront in the Barrier Ranges. The ranges here are characterised by general rolling rises, steep hills and occasional sheered rangefronts. As with the fans shedding off the Flinders Ranges, these fans form layered profiles (Figure 4.42). The first set comprises long broad fans that shed down the slopes of the rangefronts. The second set also shed off the ranges, with the apex forming around a clear break in slope where the gentle incline of the hills and mountains increases to a steeper, high-angle incline.

Other subtle landscape features that correspond to structural trends include channels and lake chains. A common landform that forms around basin margins are structurally-controlled channels. The main channels that shed off the Flinders Ranges run along the trends of the tear faults that have caused the rotation and reactivation of the Paralana Fault. While these structures have minimal expression in the basin landscape, the channels follow the trends defined by the fault planes in the Mt Painter Inlier. Similar trends are found in the Grey Ranges, in which fault planes in the bedrock inliers are almost all associated with contemporary streams (Figure 4.43). In the surrounding basins, the channel profiles express where there has been recent uplift. The profiles in the blocks that have been uplifted are typically straight, while in the down-thrown blocks the channels anastomise and anabranch forming complex alluvial systems. The difference in profiles is based upon the stream reaching base level. In the uplifted blocks, the stream energy is dissipated in incising to reach base level. In the down-thrown blocks, where the stream is at or near base level, the stream energy is dispersed laterally such that complex profiles form. This is addressed further in chapter 6.
SSeh1: erosional hills, dominated by bedrock exposures, very steep gradient

SSel: low hill, dominated by bedrock exposures

SSer: erosional rise, dominated by bedrock exposures

SSeh: erosional hills, dominated by bedrock exposures, abundant colluvium and minor drainage depressions

SSep: erosional plain, dominated by bedrock exposures, abundant incised channels and small drainage depressions

CHfs1: sheetflow sediments on a sheetflow fan: sub-angular to angular metasediment clasts

CHer2: sheetflow sediments on an erosional rise; angular to sub-angular metasediment clasts, unstable slopes, and abundant small drainage depressions. High angle landform

CHer2: sheetflow sediments on an erosional rise; sub-angular metasediment clasts with minor sub-rounded quartz clasts scattered amongst red-brown sands and silts; chenopod shrublands dominate vegetation profiles. Abundant slightly-weathered bedrock exposures

Afa1: Alluvial fan dominated by red-brown sands and silts with minor sub-rounded clasts

ACah1: Active ephemeral channel, dominated by channel sediments, fine-grained silts and quartzose sands with metasediments, sandstones and quartz clasts; vegetation dominated by woodland species with abundant chenopods

Aap1: Alluvial sediments in an alluvial plain; fine-grained sands, silts and minor salt accumulations hosted in ephemeral channels, fans and flood plains

Figure 4.42. Regolith landform map of the mouth of the fans shedding off the Nundooka Ranges, with the multi-generations of colluvial fans shedding off.
SSeh: Highly cleaved, slightly weathered psammite, phyllite and slates with minor quartz, diorite, basalt and rhyolite intrusives hosted on an erosional high with a minor component of localised colluvium accumulating in breaks of slope and in amongst changes of cleavage profiles.

SSer: Highly cleaved, slightly weathered psammite, phyllite and slates with minor quartz and basalt intrusives hosted on low to steep rises with a minor component of localised colluvium accumulating in breaks of slope and along fault planes.

SSep: Highly cleaved, slightly weathered psammite, phyllite and slates with minor quartz and basalt intrusives hosted on undulating plains, with occasional incised drainage depressions. Minor component of localised colluvium, rounded quartz pebbles and red-brown, fine-grained sands and silts. Sparse vegetation, dominated by Eremophila ssp.

SMep: Moderately weathered sandstones, siltstones and conglomerates hosted on undulating plains, low rises and in incised drainage systems in which cliff profiles are up to 20 m high. Dark purple-red ferruginisation with some liesegang weathering pattern. Minor component of colluvium, fragmented hardpan calcrete and red-brown sands and silts.

CHer: Sheetflow sediments on an erosional rise. Sub-rounded granite, silcrete, sandstone and quartz clasts scattered amongst red-brown sands and silts. Chenopod shrublands dominate vegetation profiles.

CHfs: Sheetflow fan sediments on a low-angle, broad fan shedding of the Mt Browne Inlier. Clasts dominated by sub-rounded to sub-angular metasediments, rounded quartz, minor silcrete, sandstone and quartz clasts. Small exposures of sandstone in small incised drainage and contemporary channels red-brown sands and silts. Chenopod shrublands dominate vegetation profiles.

Cfc: Fan sediments on a high-angle, narrow fan shedding of the Mt Browne Inlier. Clasts dominated by sub-angular to angular metasediments, rounded quartz, minor silcrete, sandstone and quartz clasts. Small exposures of sandstone and conglomerates. Vegetation dominated by woodland species with abundant chenopods.

ACah1: Active ephemeral channel, dominated by channel sediments

ACah2: Active ephemeral channel, incised into Metasediments. Bound by steep valley walls, often controlled by large structure such that valley walls are fault planes.

Aap1: Alluvial sediments in a depositional plain. Fine-grained sands, silts and minor salt accumulations hosted in ephemeral channels, fans and flood plains.

Figure 4.43. Regolith landform map of the north of the Mt Browne Inlier in the Grey Range in NW NSW. Fans shedding off the western range front where the Mt Browne Fault forms the boundary of the inlier.
4.5.2 Potential Fields

Potential field surveys in the area are somewhat limited due to scale. Despite this, both the magnetics and gravity imagery show regional features of varying importance. As previously outlined, the magnetics is limited in definition because of the strong signature of the magnetic minerals that form the diapere from the Curnamona Province. When the magnetics is refined and processed at a local scale, more features become obvious. The sub-circular Curnamona Province is still the most noted feature in the image (Figure 4.44). Other features of interest include the structures in the Thomson Orogen, particularly the NW-SE trending faults, and the Bancannia Trough. Underlying the trough is a mafic intrusive. This feature presents as an anomaly on the magnetics and therefore defines the trough. The approximate expression of the Koonenberry and Olepoloko Faults are also present, although they are limited in response. The Wonominta Block is also defined, as it presents as a magnetic low (Figure 4.44).

Several features are present on the magnetics, albeit none specifically relevant to the Mesozoic sediments. Despite this, it provides a basis for correlation of some structures from other data sources such as seismic and surface mapping.

The gravity imagery is not as hindered by the Curnamona Province as the magnetics. However, the survey is very coarse and thus generally limited to the regional structures; it does not show much detail. Like the magnetic imagery, the gravity imagery highlights the Bancannia Trough in the east of the area. This trough is clearly...
marked by two sharp boundaries and a gravity high in between. The Benagerie ridge is also present as a gravity high. This is the first image to have provided an approximate on the dimensions and approximate morphology of the ridge. While not defining the physical high or the vertical component, it provides an estimate as to the location of the ridge-forming volcanics. This approximation can be tied into seismic mapping over the area to help refine the intra-basin high, and to attribute features of the seismic. The gravity also shows expressions of the Flinders Ranges and even the Terrapinna Corridor. The corridor shows up as a regional gravity low. As with the magnetics, the gravity imagery does not show distinct features associated with the Mesozoic; it shows only basic features of the basin morphology.

Figure 4.45. Gravity image of the Frome Embayment with the Bancannia Trough and the potential expression of the Benagerie Ridge.

4.5.3 Seismic Interpretation

In the Eromanga Basin seismic surveys have been used to detect stratigraphic variations in the different units and to extrapolate interpretations from wells (for example Wake-Dyster et al. 1983; Edwards 1991; Sheard & Cockshell 1992). For the Frome Embayment, detailed subsurface, relatively deep seismic reflection profiles are interpreted with the aid of synthetic seismographs so as to develop a complete understanding of the area’s sedimentary and structural evolution. The coverage of publically-available seismic is limited in distribution and quality in the New South Wales portion of the basin. Here, surveys are typically limited to image files, not digital wiggle traces. These surveys can still be interpreted; however, they cannot be included in the software used to interpreted and model the subsurface.

The limitations imposed by the data format and distribution of surveys in the east inhibit the inclusion of the seismic interpretation into the gridding compiled from the well data. However, the seismic in the embayment
displays a clear representation of structure. This data is used to compensate for the limits within the gravity and magnetic surveys generated from the presence of the high-response bedrock features. By combining interpretation of structure of the gravity, magnetic and seismic surveys, as well as incorporating the surficial map, a tectonic elements map can be constructed for the embayment. In total, 325 2D seismic lines were interpreted for the embayment; totalling 5172.7 km (Figure 4.46).

Interpretation of the 2D seismic lines was conducted at 2 Eromanga horizons: top Marree Subgroup and top Cadna-owie Formation. These horizons are picked regionally because the reflectors are prominent on most lines in the basin. Where possible the top Toolebuc and top Bulldog Shale were selected, highlighting the divisions in the Marree Subgroup. Bedrock and occasional subdivisions in the Lake Eyre Basin (Willorwortina, Namba and Eyre Formations) were also interpreted, as was the Winton Formation in the north of the embayment (Figure 4.47).
Structure was interpreted at two different levels: shallow ‘thin skin’ deformation; and deep ‘thick skin’ structure that penetrates bedrock, as well as the Mesozoic succession.

**Seismic Quality**

For the most part, the seismic lines are of good quality, with the Mesozoic stratigraphy reflecting well. Lines within the seismic project are predominantly in SEG-Y format. This means that the data is stored digitally as individual wiggle traces. These lines can be altered and modified such that each line can be viewed in its optimal condition and minor features (such as amplitude and clarity) can be adjusted where necessary. With SEG-Y lines, most lines can be interpreted as adjusting contrasts whereby amplitude balancing and scale can be uniquely defined. These lines can also be loaded into seismic interpretation software where the navigation of the line defines where in space the line sits, and allows for all of the seismic to be tied to one another. However, SEG-Y data sets are not available for all lines. In places, 2D lines are only available in TIFF (picture) format. These lines are typically very old and often of very poor quality (Figure 4.48). Surveys in the New South Wales portion of the basin are predominantly TIFF files, as digital formats of files are either not publically available or have not been preserved. TIFF files have been converted to pseudo SEG-Y format such that they can be uploaded as images with navigation files into the Move project and interpreted and tied to surrounding lines. Despite this, the lines are still of poor quality, often with little or no reflectors being present (Figure 4.48).
Geological factors affecting survey quality include homogenous facies profiles, shallow lithologies that represent as high amplitude reflectors (for example volcanics or clays), and poorly consolidated sediments. In places where the Mesozoic sediments are thin, subcropping or at surface, the top part of the Mesozoic sequence appears attenuated or absent. In the south of the embayment shallow attenuation of the seismic signal is also common (Figure 4.49). This shallow attenuation is typical in areas where basin sediments are covered by a thin, poorly-consolidated sandy regolith profile overlying the clay-dominated Willorwartina Formation from the top part of the Lake Eyre Basin.

The Willorwartina clays form a highly compacted zone that has undergone a considerable degree of shrink-swell, resulting in the formation of micro-fracturing and shatter-cones (Meyers et al. 2006). This clay package has resulted in a high amplitude reverberation of the signal, which has subsequently masked underlying reflectors that would otherwise be very prominent in the subsurface (Figure 4.49 compared with Figure 4.50). Because the Willorwartina clays are at the top of the succession, the entire line is often unreadable, with prominent reflectors.
absent (Figure 4.49). This problem is particularly obvious in the west of the Poontana Sub-basin where the Eyre Basin sediments are thick.

**Structure**

The seismic surveys best expose subsurface structure and morphological features that have evolved since the Proterozoic. Four of the major bedrock geomorphological zones are identified within the seismic. These include:

- The Poontana Trough in the east of the embayment
- The Yalkalpo Syncline to the west of the Barrier Ranges
- Bancannia Trough in the southeast
- Intra-basinal high associated with the Benagerie Ridge

Several other geomorphic features are also identifiable, including the aspects of the basins southern margin, the features controlling the variations in Winton Formation thickness and other general features within the basin. Within these zones, the seismic shows four distinct generations of structure as being common across the embayment. Many of these features are not obviously present at surface. The structural sets are dominated by

- Reverse fault set that deforms the basement and Mesozoic succession
- Large-scale inversion structures
- Marree Subgroup intraformational structures
- Pre-Mesozoic normal faults that define the minor aspects of the bedrock fabric

The most prominent of the tectonic relationships in the seismic is the fault zone between bedrock and the top Mesozoic. The structure within this zone has a high tectonic aspect and irregular throw relationships. The largest of the structures in this zone is a set of high-angle, reverse faults that deform the basal and part of the marine sequences in the Mesozoic succession as well as basement. These faults are prominent on NE-SW, N-S trending lines. Correlating on succussing seismic indicates that these structures have a typical trend of NW-SE to E-W and have throw ranging from <10 m up to 100 m in the basin sediments and up to 200 m in the bedrock. The difference in throw along the structure is interpreted to represent the fault dying out as the structure radiates up through the marine sequence. In the north of the embayment, where the sediments represent a more basinward succession, these faults occasionally penetrate into the base of the Winton Formation (Figures 4.50). Another smaller structure within this zone is the high-angle reverse faults that deform bedrock and the basal Mesozoic. The displacement associated with these structures is typically less than the larger structures previously described. Offset ranges 10–50 ms in TWT—the approximate equivalent of 10–60 m in depth. The orientation of these structures ranges from NE-SW to NW-SE, and are visible on almost every line. The orientation of the structures and their size classify them as synthetic and synthetic-antithetic structures. In places within the seismic, the displacement of these structures is so small that it represents as flexure rather than as distinct breaks in reflectors.

Shallow structures are also evident across the embayment, but are typically denser around the basin margins. These structures are high-angle reverse faults. Structure displaces the youngest sediments within the basin, indicating that this is a recent structural feature. In the north of the embayment, this structure penetrates through the Winton Formation, but does not intersect the Marree Subgroup. In the south, where the Winton Formation is not present, the faulting displaces the top Marree Subgroup (Figure 4.50).
Figure 4.50. TWT seismic line 84-SWy. 84-SWy shows the different structural levels within the Embayment. The largest fault set penetrates bedrock up to Winton Formation, however typically dies off in the Marree Subgroup, as a result of the rheological change from the sandstones in the Cadna-owie Formation to the Bulldog Shale. Some smaller structures within this set only displace the Section also shows the smaller structure at the top of the sequence that deforms the sediments from the Lake Eyre Basin and the Winton Formation.
Intraformational faults are present within the Marree Subgroup. In this fault set the structure is small, more often than not only deforming the transition zone between the Bulldog Shale and the Oodnadatta Formation (Figure 4.51). The offset from these faults is both normal and reverse, with very irregular throws ranging from <10 m up to 80 m. These structures do not coincide with the major tectonic driven fault system seen within the seismic. The abundance, angles and throw are all unique to the small zone in the marine succession. Furthermore, the variation between normal and reverse structuring is not conducive to a particular stress regime or to any of other recognised tectonics. The lack of continuity between any major structural trend, and the random patterns and nature of the sediments being deformed, is indicative of a gravitationally driven deformation as compared with a typical tectonic regime. Gravitational instability arises from low density, often poorly-consolidated sediments that undergo loading (typically sediment loading). Because these sediments are poorly-consolidated and irregularly packed, when loading occurs they have some freedom to migrate laterally and vertically. The resultant structure is a soft-sediment deformation in which the resultant displacement occurs when the burial misplaces enough fluid during dewatering and compaction of the sediments to at least partially lithify and stabilise the sediments. In the denser sediments, Mesozoic sediments dewatering and compaction resulted in lithification rather than deformation.

Figure 4.51. TWT seismic surveys 84-SPK and 84-SPG showing the soft sediments deformation intraformational faults in the Marree Subgroup sediments.
The basin is dominated by high-angled to sub-vertical reverse faults. Many of these structures can be seen at depth as well as exposed at surface, for instance the Paralana Fault (Figures 4.39 & 4.41). However, the basin formed as a result of extension (see chapter 2). Few extensional structures are evident in the seismic lines. In places some low-angled structures are present indicating thrusting. Synthetic-antithetic normal faults occur within the intraformational soft sediment deformation zone. As these structures are a result of a gravitational displacement rather than a tectonic event, they are only normal in displacement sense and not in terms of deformation regime. In many places within the basin, the reverse structures do not control the regional or large-scale morphology. Indeed, in many places the reverse structures go against the grain of the general morphology. One example is in the trough bounding the Flinders Ranges in the west. Here, the main structure present in the seismic is a series of reverse faults that have a minor degree of deformation and shortening. The reverse structuring is seen to be creeping up the sides of the trough and forming ramp and flat-thrust structures (Figure 4.52). These trends are conducive with the ramping going against the grain of the regional structure, with the hanging-wall component of the structure remaining undeformed and in situ such that the foot wall forms a ‘flat’. Many such structural features are common within the embayment. The ramp structures are relatively small as the structures controlling them are very high-angle and, in places, sub-vertical. Despite the lack of lateral deformation, the structures are indicated to be vertically extensive, deforming at least the bedrock, Mesozoic and occasionally the lower Lake Eyre Basin sediments.
The sediment’s relationship, size and association with the major basin morphology indicate that the structures are minor, and have formed post Mesozoic deposition. The contemporary stress state for the southern portion of the basement is an E-W compression (Clarke & Leonard 2002). Localised studies have shown that this stress regime has been active since the Eocene (Davey 2005; McAvaney 2006). This regime is conducive to the dominant structures present within the embayment. In many places the structures have been reactivated, potentially having the sense of displacement reversed.

While the transpressional structures form the dominant deformation phase shown in the seismic and in structure at surface, the basin was formed by a dominant extensional deformation (see chapter 2). The contemporary stress regime and the deformation associated with it dominate the seismic primarily because many of the transpressional structures are reactivated, such that the original throw or deformational regime is potentially compromised.

In the north of the embayment, where the structure is generally broader and deformation is less (i.e. tectonic displacement is considerably less than it is around the basin margins where the tectonic displacement can exceed 200 m), some normal subsurface displacement is preserved within the bedrock and lower Mesozoic sequence. Structures with normal throw include high-angle strike-slip, normal faults that deform bedrock only, and larger structures that at depth have a normal displacement, but have reverse offset in the shallow subsurface. The change in strike-slip throw direction along a fault is more common in the lateral sense of the fault than the vertical (Rowland et al. 2007). In the vertical sense, the change in orientation or throw of a fault at a unique point is typically driven by renewed stress exerted on the structure, with the change in direction of throw being due to a change in the form of this stress. This is called a scissor structure or fault hinge. In the embayment, the ‘scissor’ point occurs at the unconformity between the bedrock and the Mesozoic sediments (Figure 4.53).

These structures preserve evidence of the transtensional deformation in the embayment; however, they are small structures that typically only affect the pre-Mesozoic structural fabric and do not define the mechanisms by which...
the basin formed. In the west of the area the seismic flanking the ranges images an elongated depocentre that corresponds with bedrock structure previously identified as the Moorowie Syncline. The Phanerozoic extension of the syncline is the Poontana Trough in which has formed a large depocentre of Mesozoic and Palaeocene sediments. The seismic that cross-cuts the trough (predominantly the E-W oriented lines) shows sediment profiles which thin against the Benagerie Ridge in the east and thicken considerably against the Flinders Ranges in the west. The wedge sediment profiles are not concordant with the typical nature of a syncline, as the bedding profiles in the seismic indicate that the sediments have not been folded. Rather, they maintain a smooth dip preserved along major lithological and formational boundaries. The sediments have; however, been tilted at least 25° and, in places, up to 50-60° (Figure 4.55) since deposition, with the degree of tilt varying with depth (Figure 4.55). Sediment wedging profiles are typically an indication of syn-depositional growth patterns in which a growing fault creates ‘forced’ accommodation space in graben structures. The vertical variations in tilt are indicative of the ubiquitous nature of the structure; that is, the continual creation of a new base level throughout time. This structure does; however, indicate that the initial landscape at the time of Mesozoic deposition had some relief in the ranges, as the sediments wedge against the edge of the ranges (for example Figure 4.52).

The northern extent of the trough, near the Mt Babbage Inlier, is no longer bound by the ranges. Here the trough is bound by a subsurface high that trends along an approximate extension of the Paralana Fault. This Fault, as previously discussed loses surface expression at Parabarana, where it cross-cuts two other structures. Surficial traits such as the formation of the large alluvial fan and associated synthetic fans along a concordant apex lineament indicate that the structure continues in the north. However, the fault is not as large or as prominent in the northern extension. In the seismic, trough effects that in the east are very obvious (for example Figure 4.52) are almost negligible in the north (for example Figure 4.54).

Figure 4.54. TWT seismic 70-CFT. 70-CFT extends from the mouth of the Terrapinna Corridor across the Lake Blanche Lineament and into the central area in the embayment. This line shows the bedrock high in the east near the ranges, with the major Paralana structure and synthetic faults.
Figure 4.55. Stages of Basin subsidence in the Poontana trough schematically represented from the seismic interpretation, and the progression of the initial base level throughout the basin history. The Neocomian image shows the initial subsidence in the basin, with the unconformity between the basin sediments and the bedrock expressing the approximate landscape at the time of initial deposition. The landscape has an expression of the ranges in the west of the embayment and the intra-basin high associated with the Benagerie Ridge in the east. The Aptian representation shows how the basin has undergone further subsidence. The controlling factor is the structure that bounds the ranges that drops the base level on one side of the basin, resulting in a wedged profile against the Benagerie Ridge. The dashed line represents the original location of the unconformity. In the contemporary profile, the image shows the drop in base level throughout time, and the progression that was controlling the drop in the base level. The Benagerie ridge structure remains a high-point throughout time, eventually succumbing to a thin profile of the Marree sediments. The controlling structure along the east has continued with subsidence.
The thinning of the trough in the north is potentially indicative of minimal effect of the Paralana Fault at that location during the deposition of the Mesozoic. The sediments do thin over the high with no considerable erosional presence in the seismic reflectors, indicating that it is probably a depositional feature. The tilting and displacement of the sediments packages present over the high indicate that there has been post-depositional uplift. The more subtle expressions of the trough are images to the north of Parabarana (for example Figure 84-SPG).

A similar trough has formed in the west of the area atop the Yalkalpo Syncline to the east of the intra-basin high. The basin sediments here form a similar trend to that of the wedged sediments against the Flinders Ranges (Figure 4.54 & 4.55).

The two troughs are separated by an intra-basinal high previously identified as the Benagerie Ridge (Gravestock & Hibburt 1991; Conor 2004; Zang 2003; Williams et al. 2009). Seismic profiles identify the intra-basinal high in the south of the area, where it inhibits the deposition of several units of Mesozoic. The Cadna-owie Formation sediments are shown to lap up onto the ridge in both the east and west of the area (Figure 4.56). The base of the Marree Formation (Bulldog Shale equivalents) laps up onto and, in places, forms a very thin veneer covering the high (Figure 4.56). In the north, the top Marree Subgroup (Oodnadatta Formation equivalents) covers the ridge such that it no longer has expression within the sediment profile. In the south of the area, the ridge has a slight expression in the top Marree; however, this is minimal. This feature was also recognised in the well profiles where there was consistently an absence of Cadna-owie Formation in bore holes across a region in the south-central part of the embayment. The way that the sediments lap up onto the ridge, and in places partially cover it, indicates that the ridge was a prominent feature of the landscape at the time of deposition of the Mesozoic sediments.

Seismic lines in the south of the basin also show morphology and edging effects of the sediments and the associated structure. The southern margin shows as a shallow gradient, bedrock high that has been formed by small displacement along several major and synthetic structures (Figure 4.57), with an approximate E-W trend. The basal Mesozoic sequence, identified here as the Cadna-owie Formation, laps up onto the bedrock high. The gradual dissipation of the Cadna-owie sediments occurs over approximately 30 km where the sediment profile decreases from 200 ms down to a very thin wedge of <10 ms in TWT (Figure 4.57), equating to an approximately 200–250 m thickness variation in depth. The Marine sequence also decreases in thickness across this zone;
however, this is less prominent. The Lower Marree Subgroup sediments and Bulldog Shale equivalents decrease in profile across this zone by 100–150 m. The upper Marree Formation and Oodnadatta formation equivalents also have a slight thinning, of typically < 30 m. The basin profile at this point shows a dip in the bedding structures to the north, indicating that the sediments have undergone a slight deformation post deposition.

![Figure 4.57. TWT seismic 84-SPL. 84-SPL extends through the central embayment down to the southern margin between Lake Frome and the Barrier Ranges. This line shows the bedrock high in the south where the basal Mesozoic sediments lap up onto and end along the bedrock. The profile also shows a slight thinning of the marine sediments; however this is not as prominent as the basal Mesozoic profile tapering out.](image)

The northern margin of the embayment is an arbitrary zone where it grades into the main basin. There are therefore no definitive structural or sedimentological boundaries. However, some geomorphic features are still present. Wells in the north indicate considerable thickness variations in Winton Formation sediments, some of which are not consistent thicknesses within the Mesozoic sediment profile. The most prominent example of this is the area around the Tinga Tingana-1 well where there is a >200m difference in thickness from the Winton Formation sediments in the surrounding wells. From the well profiles alone, it was impossible to identify the cause of the thickness variation. A seismic line connects Tinga Tingana-1 and the Cherri-1 wells. This survey shows the profile between wells where there is a ‘sag’ in the Marree Subgroup sediments. This sag is not evident in the Winton Formation. The Winton sediments infill the sag and plain out to form a near-horizontal top surface (Figure 4.58). There is unconformity between the Winton Formation and the top Marree Formation.
4.5.4 Structure of the Frome Embayment

To create a structural model for the embayment, the interpretation from all three methodologies were combined to create a structural elements map. This map compiles the structure that can be seen at surface with the subsurface features so as to define the different tectonic models and fabric. The following three clear areas are defined in the elements map:

- The intense deformation, tear-faulting and contemporary uplift surrounding and within the Flinders Ranges in the west;
- The NW-SE dominance, a large and typically older structure with phases of reactivation in the central embayment; and
- Regional trends that define the Wonominta Block and the associated intense contemporary tectonism in the accompanying bedrock inliers, including the Barrier, Koonenberry and Grey Ranges.

The various styles of tectonism affect the Mesozoic succession in different ways. The regional structures in the east and central areas, as well as the range bounding structures in the west, control the main sediment distribution in the basal Mesozoic in the south of the area. These structures create the two main depocentres and intra-basinal highs that define extent of deposition of both the Cadna-owie Formation and the Bulldog Shale. In the far west and east of the area this structure is evident at surface, expressed within the ranges. In its contemporary form the structure generally presents as high-angle reverse faults, indicating a sense of inversion since the initial deposition of the Mesozoic. The Oodnadatta Formation equivalents are typically unaffected by these faults. Structure in the north of the embayment is dominated by smaller faults and slumps that dominantly affect the syn-depositional phase of the Winton Formation. These slumps create the general accommodations space for the Winton Formation and are interpreted to be the renewed basin subsidence after the retreat of the Eromanga Sea. The absence of the Winton Formation in the south of the area is attributed to the tectonics in this area not being reactivated during this period. The slump structures are generally subtle features without bounding structures, indicating that they are the product of extension not resulting in brittle deformation. This is concordant with many phases of basin formation in the north of the embayment where the structure is typically related to the gentle basinward structures defined previously. Other syn-depositional structures or structures affecting the distribution of structure include the Lake Blanche Lineament in which a thickening of the marine sediments occurs, along with the thicker sediment succession present on the north side of the fault.
Several generations of structure within the embayment have deformed the Mesozoic succession, indicating a post-deposition activation. These structures are dominated by the near E-W structures indicated to be the tear faults protruding from the ranges in the northeast and the west. The intra-basinal sub-N-S structures also deform the succession. Both these structures are normal faults with small offset and, in places, ramp-style ‘thrusting’.

Figure 4.59. Structural elements of the Frome Embayment.

4.6. Landscape Evolution

The Frome Embayment was formed by a series of morphotectonic events that have been active since the Proterozoic. Landscape exposures of sediments, accompanied with well data, seismic, potential field surveys and remotely-sensed imagery were used to create a regional reconstruction for the general Mesozoic.

The Contemporary Landscape

The contemporary landscape of the Frome Embayment is dominated by extensive longitudinal dunefields and the extensive gibber plains of the Strzelecki Desert encased by colluvial fans shedding off the surrounding ranges. The longitudinal dunes have a rotated pattern in the orientation of the dunes. In the south they are typically oriented ENE-WSW, while in the north they are close to a N-S orientation. This is representative of a rotation in the direction of the prevailing winds. Meanwhile, the formation of the dunes is representative of an increased aridity in the area during the Quaternary and Holocene. The lack of meteoric water in the area has resulted in a dry landscape in which sediments are loose and free to move around. This is accompanied by the strong winds that are very common in the area, which resulted in the formation of the aeolian ergs. The gibber plains that have formed in and around the dunes are a combination of colluvial distribution and aeolian processes. The plains are
dominated by colluvial clasts and gravel that are nestled amongst aeolian sands. The clasts are dominated by proximally-sourced lithologies which, in places, leads to the recognition of subcropping or discrete exposures of saprolite.

**Pre-Mesozoic**

The pre-Mesozoic landscape in the embayment is defined in the bounding ranges as well as in seismic and well profiles. Structure and general morphology is, in part, reflected within the potential field surveys. Delamerian and Thomson Orogens also control structural features such as the Flinders Ranges in the west and the Bancannia Trough in the east (respectively). Previous work highlighted basin terrain features (Williams et al. 2009); however, these studies did not touch on the state of the landscape before the Mesozoic-Cainozoic basin successions were deposited atop. Studies have speculated about the state of the landscape in the area since the Cambrian (for example Paul et al. 1999; Quigley et al. 2007 a & b); however, none of these studies address the evolution of the pre-Mesozoic landscape.

Basin terrains previously mentioned include the Yalkalpo Moorowie synclines in the east and west (respectively), the Bancannia Trough in the southeast, Koonenberry-Wonominta Block in the northeast, and Benagerie Ridge in the south-central embayment.

The presence of various troughs with thick wedges of Mesozoic and to a lesser extent Palaeocene sediments (and the on-lapping patterns of these sediments) indicates that the troughs were, at least in part, landscape features prior to the Mesozoic deposition. The structure that bounds the trough is largely associated with the basement structures associated with the Curnamona Province and the Delamerian and Thomson orogens. However, the basin reflectors within these troughs (particularly the Poontana Trough in the west) are inclined such that it is interpreted that they have been affected by post-sedimentation tilting. The overlying Lake Eyre Basin sediments form an angular unconformity over the sediments. This unconformity indicates that the post Eromanga tilting occurred before the deposition of the Eyre Basin sediments; that is, after the Cenomanian and before the Eocene.

In the west, distribution of the marine sequence and (in part) the Cadna-owie Formation are limited in extent by the Flinders Ranges. Sediments are shown in seismic profiles to be forming sedimentary growth patterns against a regional trend, coinciding with the range bounding structures along the eastern side of the Flinders Ranges (namely the Paralana Fault). The wedge-shaped profiles in the seismic indicates that there was at least some uplift along the ranges at the time of deposition, and a slump in the landscape in the approximate location of the Moorowie Syncline. A similar sediment profile forms in the east of the area, indicating that a pre-Mesozoic slump occurred in the east as well. These wedges are separated by an intra-basinal high corresponding to the Benagerie Ridge. In seismic profiles, this ridge is estimated to have approximately 200–300 m of relief.

In the southeast of the embayment, Willyama Supergroup sediments within the beach pebbles in the basal Marree Subgroup surrounding the northern Barrier Ranges around Fowlers Gap indicate that, during the Mesozoic, there had to be a clear mode of transport from Broken Hill to the basin. In the contemporary landscape there are channels that deposit clasts and sediments from the Broken Hill area into the Mundi Mundi Plains and Lake Eyre Basin; however, limited depositional routes into the pebble zones around Fowlers Gap. Furthermore, the attrition of the Willyama Supergroup clasts is similar to that of the other beach sediments in the area with the rounded and flattened shape typical of the beach environment. The clast morphology supports a beach environment, with the associated sandstones supporting a Mesozoic time frame, indicating that the morphology of the ranges was considerably different during the Mesozoic. Mesozoic sediments in the area were seen to be lapping up on to the ranges and over-turned against the ranges; however, there were no profiles of Mesozoic sediment on top of the ridges to conclusively indicate the extent or uplift and deposition in the area. The presence of the Mesozoic sediments in between the different ridges of the ranges suggest that there has either been extensive erosion or uplift since deposition. Sediment profiles in the area do not show considerable etching
profiles, and there is no evidence of erosional unconformities in the wells in the area surrounding the ranges. This does not conclusively rule out the possibility of large scale erosion; however, it does not typically support it. The over-turned sediments along the ranges support some tectonic activity along the ranges, indicating that uplift since deposition has occurred. The amount of uplift is unknown; however, the presence of locally derived, sub-angular clasts, particularly the Adelaidean Metasediments in the exposed sandstones in the region indicate that there was some exposure the ranges, particularly the ridges that are formed of the metasediments at the time of deposition. The presence of the Willyama Supergroup clasts in the beach deposits does indicate that there was some topography during the Mesozoic between Broken Hill and the Barrier Ranges to generate the potential energy to transport the clasts.

The presence of clasts from the re-working of the tillite unit in the Adelaidean metasediments in the beach pebbles of the Northern Flinders Ranges indicates that the tillite unit must have been exposed within the landscape pre-Mesozoic. Fan sediments shedding off the Flinders Ranges indicates a post-Mesozoic uplift of the ranges. The subsurface sediment morphology and growth previously mentioned show evidence of syn-deposition tectonics. This indicates that the uplift of the ranges has been a progressive growth over time. This is discussed further in chapter five. The far southern margin of the basin shows the sediments grading up onto a gentle rise. No prominent structure is present, suggesting that this area forms a natural and shallow grading rise that limits the formation of the basin simply by a natural degradation of accommodation space. In the far north the embayment is shown as a grading slope down into the main Basin depocentre. More detail about the marginal pre-Mesozoic terrains are discussed in chapters 5 and 6.

Late Jurassic to Early Cretaceous

The first phase of basin formation is represented by the deposition of the Algebuckina Sandstone. Deposition of this formation is limited to the north of the area, with the furthest south recognition around the north of the Flinders Ranges. The sediment profiles of the Algebuckina Sandstone are typically deep—a thick succession of sandstones with occasional clayey or conglomerate interbeds. The depositional environments typical to this sediment are interpreted to be fluvial, with some evidence of calmer environments interpreted as being lacustrine. Primary bedding structures include coarsening upward sequences stacked atop each other and the abundant cross-bedding and occasional ripple marks. The sandstones seen in core indicate that the sediments are typical channel sediments. The stacked nature of the sediments indicates that there were several generations of channel cycles, indicating several changes in the embayment’s base level. By contrast, the Cadna-owie Formation forms a thin veneer over much of the overlying in the south basal unit, and extends as far south as Lake Frome. Cadna-owie sediments crop out in the west around the margins of the northern Flinders Ranges and in the east around the Grey Ranges. Sediments vary laterally and vertically from interbedded sandstones and siltstones to claystones and occasional silty shales and conglomerates. The depositional environment for the Cadna-owie ranges from fluvial systems (including channels, bars and floodplains) to coastal plains with rhythmitic sequences with tidal (marine) influences. The formation thickness and depositional environments are attributed to different stages of basin morphology. The initial deposition phase, the Algebuckina Sandstone, is reflective of a poorly-developed, immature fluvial system. Channels and drainage systems charge energy in incision; that is, the river erodes down until it reaches base level. The subsequent landforms are, typically, simple floodplains and alluvial plains. The episodic base level changes evident in the sediments stacking and the sedimentary structures indicate that the fluvial system underwent several stages of the river system trying to reach base level. The Cadna-owie Formation represents the stage in the fluvial system in which the channel system has incised down to base level and, as such, fluvial energy is dissipated into the surrounding landscape, resulting in the formation of meandering and anatomising streams, channels and drainage systems. Because of this, sediments vary greatly laterally and vertically, as different components of the basin are under various depositional environments
that are, in part, controlled by the new dispersion of energy. The resulting basin profile at this stage of deposition is a laterally broader, vertically thinner basin profile. Cadna-owie sediments lap up the sides of the Benagerie Ridge, reaching about halfway up the structure. In no place do they cover it.

Figure 4.60. Schematic representation of the Cadna-owie depositional regime in the central embayment. Sediments lap up onto the edge of the Benagerie Ridge.

Syn-depositional tectonism was occurring during this time and was dominated by the normal fault active in the basin margins.

The Cadna-owie Formation also indicates the first presence of a marine signature within the embayment sediments. The intercalated clays and sandstones from core in the north of the embayment indicate a rhythmic sequence which had sporadic interaction from the marine environments as the marine incursion was accreting. This formation indicates the basin phase of the major marine transgressive systems tract (TST).

Marine Sedimentation

The Aptian-Albian period marks the major marine phase of the basin. Sediments from the Marree Formation cap the entire embayment, with the exception of small archipelago systems around the basin margins. The Marree sediments extend down past the Frome Lake Chain as far south as the mid-Flinders Ranges in the west and down to Lake Menindee in the Bancannia Trough in the east. The distribution of the shales and mudstones indicates the extent of the marine transgression inland. Seismic lines in the south of the area near Emu Dam show the sediments grading in the basin margin. Reflectors in the seismic show onlap patterns in both the Cadna-owie Formation and basal Marree units. The reflector trend indicates a retrogradational sediment trend in which sediments are successively deposited landward as a result of limited sediment supply. This retrogradation indicates the transgressive phase of the basin such that the onlapping sequence is indicative of the extent of that phase of transgression (Figure 5.61). The two marine sequences are separated by a sandy shale and, in places, by a silty sandstone. In the south of the area this unit is either absent or so thin that it is not picked up as a separate sequence in core. The seismic shows this segregation as far south as Lake Frome, as the coarser sequence in the seismic reflects are a very high amplitude band. The base of this unit marks the maximum flooding surface in the embayment; that is, the point at which the sequences changes from retrogradation to progradation in which sedimentation starts stepping back basinward as sediment supply exceeds accommodation space. Reflectors in the seismic also show the top Marree Formation caps (previously described in the retrograde sequence) such that the margin of the top Marree Subgroup is further south around the Anabana-Redan Fault Zone. The continuation of the top unit in the Marree over the basal unit indicates that there was a second phase of transgression in the basin in which sedimentation encroached on the landward phase of the basin. The double
transgression is what causes the segregation within the sediment profiles in the centre and northern parts of the embayment; that is, the segregation between the Bulldog Shale and the Oodnadatta Formation.

The sequence between the two marine units is the zone greatest affected by the intraformational faults. This unit, as previously described, is composed of sand, silt and shale in varying proportions deposited atop the Bulldog Shales, which in the contemporary landscape have yet to undergo complete lithification (Figure 4.62). Conformably atop the intra-marine sequence, the second phase of marine incursion occurred. There is no evidence of an unconformity at this time indicating that the second marine incursion caused continual deposition. The intra-marine unit sits atop the poorly-consolidated Bulldog Shale, and is capped by the wet Oodnadatta Formation and the second phase of the Eromanga Sea. The base of the intra-marine unit is unstable, because of the freedom of the clays and muds in the Bulldog Shale to move due to their poor consolidation. As such when the weight of the new sediment pile and sea were piled on the intra-marine unit, gravitational displacement occurred.

The Bulldog Shale sediments lap up the side of the Benagerie Ridge. These sediments do not cap it. The Oodnadatta Formation caps the ridge with approximately 100 m of sediments.
Sediments within the Winton Formation are limited in extent to the far north of the area. The sediments in the embayment fill slumps and gentle depressions that were created within the top Marree Subgroup. The slumps and depressions are not sedimentary difference; that is, they are not zones of non-deposition or intra-basinal bedrock highs or lows. The Marree Subgroup sediments in this area have relatively continuous reflectors in the seismic, with no obvious faults or folding. Furthermore, the slumps and irregularities in the top Marree are not represented in the underlying sediments. The Marree Subgroup, Cadna-owie and Algebuckina Sandstones maintain consistent thicknesses, such that the entire profile is subsiding. This indicates that the irregular surface is not a result of differential erosion but more so a result of gentle subsidence. This subsidence has occurred post Marree deposition. The irregularities in the subsidence can be up to 200 m over relatively small distances. The lack of ‘squeezing’ or bulging of the Marree sediments, which have been previously shown to be unstable, is due to water and the soft, unstable nature of the sediments. If the sediment package was as unstable as it was during the formation of the intraformational faults, the subsidence that occurred would have caused more gravitational stress. This indicates that the Marree sediments were at least, in part, lithified. The contemporary state of the sediments shows that they are poorly consolidated and only partially lithified. The lithification state indicated at the time of the Winton Formation is of general stability, with basic dewatering or partial diagenesis.

The Winton Formation sediments reflect the variations in subsidence. The areas that have undergone the most subsidence are dominated by thick channel deposit, while the areas with minimal subsidence typically have finer-grained sediments that are interpreted as fluvial plains.

The Winton Formation sediments are confined to the far north of the embayment. This reflects the limits of the subsidence in this final phase of deposition in the Eromanga Basin.
4.64. Schematic representation of the Winton Formation
Landscape and geological models for intracontinental Australia have tended to follow a cyclic trend as regards the geological driving mechanism behind their formation. Throughout the past 100 years, theories and hypotheses proposed for the formation of Australia’s landscape have been vacillating between tectonic (for example: Veevers 1984, 2000 & 2006; Betts et al. 2002; Sandiford 2003; Quigley et al. 2006), climate (for example: Frakes et al. 1987) and erosional (for example: Belton et al. 2004) models. Different theories transcend scientific method; that is, the segregation between theories is not limited to segregation between modern processes (such as dating and provenance analysis) and the more traditional geomorphological approaches. The northern Flinders Ranges in central South Australia is a landscape hosting extremely different evolution models and parameters, including Mesozoic landscape remnants representing landscape antiquity (Alley & Sheard unpublished; Twidale 1999 & 2000; Davey & Hill 2007 & 2009), in a highly tectonically active part of Australia (Greenhalgh et al. 1994; Quigley et al. 2006). The active tectonism of the area has been linked to high denudation rates, such as cosmogenic nuclide interpretations proposing summit erosion rates of 14 m/Ma, valley floor rates of up to 220 m/Ma and hill slope rates up to 20 m/Ma (Celerier et al. 2005; Quigley et al. 2006; Quigley et al. 2007 a & b).

Despite the extreme erosion rates and active tectonism, the area hosts the most abundant exposures of Eromanga Basin sediments from the South Australian portion of the Frome Embayment (refer to chapter 4). This abundance of Mesozoic remnants and landforms has resulted in the area being considered a tectonically-stable and geomorphologically-inactive environment (Twidale 1999 & 2000). This contradiction has previously been accounted for by suggesting that the intense tectonism is a very modern geomorphological process and that, until recently (maximum past 5 Ma), the area had been of low relief since the end of the Delamerian Orogeny (Celerier et al. 2005; Quigley et al. 2006).

Exposures of the basin sediments within the area, particularly the Eromanga Basin, are abundant and well-preserved. The sediments are hosted within a variety of landscape settings, some being a result of the contemporary tectonism and erosion and others a direct reflection of the original Mesozoic landforms. Exposures include a combination of the Eromanga Basin sediments senso stricto and their lateral marginal equivalents. In places, the contrast between the basinward and landward sediments are prevalent in exposures, such that lateral facies changes within the Mesozoic landscape are apparent.

The marginal basin setting of the exposures and their preservation not only provides the opportunity to study their preservation within the contemporary landscape, but also the opportunity to reconstruct the landscape and geological terrain in which they were deposited. This provides an area that allows for the integration of surficial geology into palaeogeological models, especially where the intense uplift in the area has exposed many relationships that can be used to confirm the results of the surficial study.

The Mesozoic rocks pertaining to the Eromanga Basin, hosted around and within the Mt Babbage and Mt Painter Inliers, are the subject of this study. Sedimentology, mineralogy, structure and geomorphology of these sediments are analysed, with the intention of creating a Mesozoic geological reconstruction.
5.1. Regional Geology

The northern Flinders Ranges, geologically referred to as the Mt Painter Province (Coates & Blissett 1971; Mitchell et al. 2002; Hore et al. 2005; McLaren et al. 2006), forms the northern extent of a discontinuous upland belt extending 600 km inland from coastal to central South Australia (Figure 4.1). The study area here is defined by being centred on the Mt Babbage and Mt Painter Inliers and extending into the surrounding basins, and corresponding to the approximate area of the South Australian 1 Mile map sheet of Moolawatana.

The basins surrounding the inliers include the Mesozoic Eromanga Basin and the Palaeogene to contemporary Lake Eyre Basin (Sheard 2001). Specifically, the area is host to the northwest margin of the Frome Embayment, the southernmost lobe of the Eromanga Basin (see chapter 4), and part of the approximate Palaeogene equivalent—the Tarkaroola Basin, also known as the Callabonna Sub-basin of the Lake Eyre Basin (Alley et al. 1998).

Figure 5.1. The northern Flinders Ranges relative to Australia, the GAB, and regional structural terrains. Quickbird imagery of the Mt Babbage and Mt Painter Inlier courtesy of Primary Resources and Industries South Australia.

5.1.1. Structure and Geomorphology

The northern Flinders Ranges has a complex deformation history that has been of great interest from both the structural (Paul et al. 1999; Gibson & Stuwe 2000; Sandiford 2003; Quigley et al. 2006; Quigley et al. 2007 a & b) and geomorphological perspectives (Twidale 1999).

Broadly, the contemporary landscape can be divided into three geomorphic zones: (1) the rugged mountains and hills that form the ranges, with average summit elevations being 300–500 m above sea-level (with local highs exceeding 600 m); (2) the undulating plains and rises of the Terrapinna Corridor; and (3) the low-lying plains that form the surrounding undulating basins, with elevations at or near sea-level.

The contemporary extent of these zones is largely structurally controlled by two, and in some places three, phases of morphotectonic deformation. The first phase includes regional structures emanating from the NE. This includes the Moolawatana Syncline and the inclined, nearly overturned, Mt Neil Anticline, within the Mt Painter Inlier. The less prominent Mudnawatana Syncline is a potential continuation of this folding in the Mt Babbage...
Inlier (Figure 5.2); however, the granitic sediments in the north are highly deformed and obscure the identification of field sections showing folding, such that extensions, and thus the strike of the fold, are largely inferred and based on remote sensing and topographic considerations. Brittle expressions of this deformation; however, include exposures of large thrust and reverse faults, such as the Birthday Well Fault and Paralana Fault (Figure 5.2). Folding from this deformation also controls the extent and morphology of the Terrapinna Corridor, which is a low-lying plateau between the inliers.

For the most part, the Mt Babbage Inlier is characterised by bevelled mountains and hills, whereas the Mt Painter Inlier is characterised by large, steep mountains and valleys and small plateau remnants interpreted as part of an incised peneplain (the Freeling Plateau) (Quigley et al. 2006). On average, summit elevations within the Mt Painter Inlier are 200–300 m higher than in the Mt Babbage Inlier. Regional folds and faults are typically tighter and of higher angle in the Mt Painter Inlier (Teale 1993 a & b), whereas regional structures are typically more subdued in the Mt Babbage Inlier. The extent and morphology of the Mt Babbage Inlier is also primarily controlled by localised folding and associated faulting, including the NS striking Mt Babbage Anticline and Syncline, and the similarly orientated Mt Babbage, Gunpowder and Moolawatana thrust faults (Figure 5.2). The trend of these structures extends throughout the north of the area, but is only very minor in the south. Throughout the Terrapinna Corridor, this structure is represented as parasitic folds and small cross-cutting faults that have minimal impact on the morphology of the corridor; however, they have facilitated erosion that has exhumed small exposures of the underlying geology.

The surrounding plains form the northwestern extension of the Frome Embayment, specifically the Poontana Sub-basin portion of the embayment (see chapter 4). The regional and localised faulting has also deformed the undulating basins. Expressions of this deformation in the basins are typically more subtle than within the inliers. Contemporary drainage within the basins in the north coincides with the basinward extension of many localised structures. Extensions of the regional deformation in the basins to the south coincide with slight changes in slope and the formation of alluvial fans (see section 5.3 of this chapter).

Recently, active tectonism within the area has been expressed by the steep drainage gradients within and flowing from the inliers, sequences of strath terraces within valleys (valley in valley erosion profiles), steep Quaternary colluvial fans (such as along the Paralana Fault and, to a lesser extent, the Birthday Well Fault), basement thrust up and over younger sediments (e.g. Paralana Fault and Lady Buxton Fault), and uplift of Mesozoic and Palaeogene sediments (e.g. Mt Babbage 323 m ASL). Recent studies have quantified this recent tectonism as having an uplift rate of 30–160 m/Ma (Sprigg 1984; Quigley et al. 2007a), which is a high rate for an intracontinental setting.

The inliers form an approximate drainage divide between the Lake Frome and Lake Eyre drainage basins, with streams and channels shedding basinward from Mt Babbage and flowing into the lower lakes of the Lake Eyre drainage basin, while basinward flow off the Mt Painter Inlier flows into Lake Frome. Initial uplift in the area is attributed to the Cambro-Ordovician Delamerian Orogeny (Gibson & Stuwe 2000). It has been suggested that relief production from this event produced ranges of up to 800 m high (Gibson & Stuwe 2000). The relief and major structures created by this orogeny were then destroyed during intense weathering and erosion in the early Palaeozoic, in which 300–500 m of erosion is interpreted to have occurred (Gibson & Stuwe 2000). This interpretation is supported by the abundance of Permian glacial clasts in central Australia that have a lithotype related to the rocks hosted within the northern Flinders Ranges (Flottman & Cockshell 1996), and the lack of morphological evidence of the fold belt in the contemporary landscape (Gibson & Stuwe 2000). In contrast to this, other studies support minimal uplift of the ranges until recent times (Quigley et al. 2006; Quigley et al. 2007 a & b). While the Delamerian Orogeny deformed the post Palaeozoic rocks, the area remained relatively flat-lying as a ‘peneplain’ until the Palaeogene (Celerier et al. 2005; Quigley et al. 2006). Mineralogical analysis of the volcanic and hydrothermal rocks from the Mt Painter Inlier, in particular the Mt Gee Sinter rocks, indicated that the sinter was expelled and precipitated during the Ordovician (McLaren et al. 2006). Near-surface
crystal growths, including vugular quartz, have been interpreted to have been at surface or near surface for their existence (Hore et al. 2005). Boulders, clasts and pebbles of sinter rock are scattered across the landsurface throughout the landscape, indicating that this has experienced some weathering and erosion; however, the main body of the sinter is still exposed. While there is evidence of neotectonism throughout the Mt Painter Inlier, the sinter is thought to be a minimum representation of a landscape feature of great antiquity (Hore et al. 2005). This is relevant for assessing the two end-member accounts of the landscape development and history within the northern Flinders Ranges.

5.1.2. Bedrock Geology
Crystalline basement within the northern Flinders Ranges is exposed within two structurally-controlled blocks that form the Mt Babbage Inlier in the north, and the Mt Painter Inlier in the south. These blocks consist of Palaeoproterozoic metasediments and metavolcanics of the Radium Creek Metamorphics (RCM); and, Mesoproterozoic silicic metasediments, intrusives and granites of the Mt Painter Suite (MPS) (Figure 5.2) (Teale 1993a & 1993b; Robertson et al. 1998; Sheard 2001; Mitchell et al. 2002).

The RCM are dominated by high-grade, arenaceous sequences and acid porphyries (Coats & Blissett 1971; Teale 1993a). More specifically, it includes poorly-preserved, sandy phyllites and psammites that grade into well-preserved, layered units of grey-pink quartzites, quartzose feldspathic gneisses, various grade gneisses (some containing assemblages with cordierite, phlogopite, hornblende, sillimanite or tourmaline), amphiboles and migmaites (Coats & Blissett 1971). These layered metasediments occur throughout the Mt Painter Inlier, and sporadically throughout the northeast of the Mt Babbage Inlier (Teale 1993a). Around Mt Neill, and sporadically around Mt Adams just south of the field area, this unit is conformably overlain by a dark-green, acid porphyry rich in albite, microcline and blue-quartz phenocrysts, hosted in a biotite-hornblende matrix locally known as the Pepegoona Porphyry (Coats & Blissett 1971). The top of the RCM is unconformably overlain by the layered gneisses and schists of the Brindana Schist (Coats & Blissett 1971). In the west and south of the field area, this unit is laterally and chronologically equivalent to the Freeing Heights Quartzite, which is a sequence of bedded quartzites, orthoquartzites and sporadic arenaceous schists (Coats & Blissett 1971). The mineralogy of these schists has resulted in differential weathering between the laterally equivalent units, such that the quartzite is more resistant and therefore more prominent in the landscape than the schist. Despite the intense metamorphism and deformation that these sediments have undergone, primary bedding structures are well-preserved. Where the metasediments have been intruded, the sediments have been granitised (Coats & Blissett 1971). Overall, the RCMs form the eastern portion of the Mt Babbage Inlier, and a central section of the Mt Painter Inlier, with sporadic quartzite exposures within both inliers (Teale 1993a).

The Mesoproterozoic MPS, previously referred to as the ‘Older Granites’ (Coats & Blissett 1971), consists of metasediments, metavolcanics and felsic intrusives (Teale 1993b) that intrude into the RCM. It is interpreted that the RCM was flat-lying and relatively undeformed prior to this, as the directional textures of the intrusions (such as laminar flow banding) match the orientation of the RCM bedding plains. The oldest granites in this suite are the massive, red porphyritic, U, Th and REE enriched Mt Neill Granites (1569 +/- 14 Ma) (Teale 1993b, McLaren et al. 2006) from Mt Neill and the eastern side of the Mt Painter Inlier (Figure 5.2). Following the intrusion of the Mt Neill Granite, in chronological order are the Yerila, Wattleowie, Box Bore and Terrapinn Granites. All four of these intrusive bodies are enriched in REE, U, Zr, W and F, with some units also being enriched in Zn, Nb, Fu, Th and Y (Teale 1993b). Non-granitic units from the MPS include the felsic porphyritic extrusives, volcanoclastics and epiclastics sandstones of the Petermorra Volcanic Suits (1560 +/- 2 Ma). These intrusives and metasediments form most of the Mt Babbage Inlier, and the western and eastern rangelfronts of the Mt Painter Inlier (Figure 5.2). Several deformation events throughout the late Proterozoic are inferred to have metamorphosed both the RCM and MPS throughout the area (Teale 1993b; McLaren et al. 2002; McLaren et al. 2006).
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Unconformably, and in places disconformably, overlying the crystalline basement is a thick (up to 15 km) sequence of sediments and metasediments of the Neoproterozoic Adelaidean Suite (Paul et al. 1999; Mitchell et al. 2002). Initial Adelaidean sedimentation in the area began around 830 Ma in a basinal system formed as a result of rift-related subsidence. This continued until the onset of the Delamarian Orogeny around 550 Ma (Preiss 1987, 2000). Sediment type is highly variable, including lithologies such as dolomites, psammites, quartzites and tillites, most of which support a shallow marine depositional environment. The Adelaidean metasediments are exposed in the area between the inliers through the structurally controlled Terrapinna Corridor, and over part of the western and central Mt Painter Inlier (Figure 5.2). The Proterozoic crystalline basement and the Adelaidean Suite were folded and deformed in the Cambro-Ordovician Delamarian Orogeny, which also heralded the end of deposition of the Adelaidean Suite. Throughout the area, structures concordant with this phase of deformation have a general NNE-SSW trend, similar to that of structures from elsewhere in the Flinders Ranges (Teale 1993 a & b). The crystalline basement and Adelaidean metasediments are both intruded by early Palaeozoic intrusives, previously referred to as the ‘Younger Granite’, and include the high U bearing, pegmatoidal-garnet-muscovite bearing, British Empire Granites; the medium-grained, Al-Na-Sr-Ca rich Paralana Granodiorite; and the I-type Mudnawatana Tonalite (McLaren et al. 2006). An exact age of these intrusions has yet to be established; however, field relationships suggest that they were emplaced syn-deformation during the Delamerian Orogeny (McLaren et al. 2006).

5.1.3. Mesozoic, Cainozoic and Quaternary Sediments

Late Jurassic to Early Cretaceous marginal sediments from the Eromanga Basin unconformably overlie the crystalline basement and, in places, the Adelaidean metasediments. The sediments are principally hosted within the low-lying plains, lapping onto the inlier margins. In places, recent tectonism has uplifted the sediments such that they are now elevated within the landscape. This is particularly evident within the Mt Babbage Inlier, where silicified Mesozoic sediments cap Mt Babbage (approximately 350 m ASL) and ridges and mesas of exhumed sandstones and conglomerates surround the Mt Babbage Inlet and Prospect Hill.

Mesozoic sediments are dominated by coarse-grained sandstones, weathered shales and clast-supported conglomerates, from both fluvial and marginal marine settings (Ludbrook 1966; Alexander & Kreig 1993; Sheard 2001). Mesozoic tillites have been identified in the northwest of the area (Alley & Frakes 2003). These sediments have been referred to by local nomenclature assigned during mapping in the 1960s (Ludbrook 1966). This includes the basal, fluvial Village Well Formation (Algebuckina Sandstone equivalent); the Neocomian, fluvial to shallow marine Pelican Well and Trinity Well formations and Parabarana Sandstone (Cadna-owie Formation equivalents); and the Aptian-Albian shallow marine Marree Subgroup (Bulldog Shale and Oodnadatta Formation equivalents).

The Village Well Formation is defined from a succession of sandstones from the northeast of the area, approximately 10 km west of Mt Gardner at Village Well.

The Cadna-owie Formation equivalent sediments in the area are highly variable, and therefore defined by three different type sections. The Pelican Well Formation from Pelican Creek, approximately 10 km southwest of Mt Freeling, contains sequences of pebbly conglomerates and silt sandstones of approximate Neocomian through to early Aptian age (Van Doan 1988). The Trinity Well Formation (from the Trinity Well area), approximately 5 km southwest of Emu Hill (Wopfner 1969), and the Parabarana Sandstone (from Parabarana near Mt Neill), define late Neocomian through to early Aptian interbedded fluvial and marginal marine cycles (Freytag 1966, Wopfner 1969). These sediments represent the last stages of fluvial deposition in the area, and the transition to the marine sediments (Ludbrook 1966; Van Doan 1988).

The Marree Subgroup sediments are the most extensively exposed Mesozoic sediments within the area. These sediments are typically grey-green mudstone, ‘mustard’-coloured claystones and various interbedded packages of fine-grained sandstones, siltstones and shales.
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- Mt Freeling Syncline
- Mt Fitton Anticline
- Billy Springs Syncline
- Birthday Well Fault
- Radium Ridge Anticline
- Mt Neill Anticline
- Mudnawatana Syncline
- Emu Hill Fault
- Paralana Fault
- Gunpowder Bore
- Terrapinna Corridor
- Mt Babbage Anticline
- Mt Babbage Syncline
- Mt Babbage Inlier
- Mt Painter Inlier
- Prospect Hill Fault
- Wilpena Group
- Yerelina Subgroup
- Callanna Beds

Sediments, sporadic Mesozoic and Palaeogene exposures

Mesozoic-Cenozoic

Quaternary

Alluvium

Palaeogene Sediments

Marree Subgroup

Undifferentiated Mesozoic Sediments

Adelaidean

Mesozoic Quaternary

Cainozoic

Mt Painter Suite

Radium Creek Metamorphics

Undifferentiated metasediments

Layered gneiss

Metavolcanics and gneisses

Metasediments

Fault

Anticline

Syncline

Mine (current and unworked)

Figure 5.2 Geological map of the Mt Painter & Mt Babbage Inliers, Flinders Ranges (after Teale 1993 a & b; Paul et al. 1999)

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To the west of the ranges is the Poontana Trough, a sub-basin of the Cainozoic Lake Eyre Basin (Callen 1975). Sediments from this sub-basin disconformably overlie the Mesozoic sediments and, in some places, the crystalline basement. The sub-basin succession is divided into three discontinuous units (1) the Palaeocene to Eocene Eyre Formation; (2) Late Oligocene to Pliocene Namba Formation; and (3) Pleistocene Willaworta Formation (Callen 1975, Callen et al 1995). These sediments are principally dominated by clast-supported conglomerates; coarse-grained sandstones; kaolin, smectite and illite clays; and carbonaceous silts and sands. Depositional environments for this succession are dominated by fluvial to lacustrine conditions, with the latter stages interpreted as being fan deposits initiated by the uplift of the Flinders Ranges (Callen 1975; Callen et al 1995). A common feature of the Namba and Eyre Formation sediments is secondary silicification, which has largely facilitated the preservation of these sediments within the contemporary landscape.

A prominent feature of the basins surrounding the ranges is extensive Quaternary regolith profiles. The regolith features include aeolian dunes and plains; colluvial fans, plains and rises; and alluvial channels and plains. Two types of colluvial fans dominate the landscape flanking the ranges. These include large, low-lying sheetflow fans that extend kilometres basinward; and small, high-angled talus cones that overlie recently activated faults. The low-lying fans shed off the inliers in the east toward Lake Frome, and in the north toward Lake Eyre. These fans include alternating bands (runoff zones) of proximally-sourced clasts (granites, sandstones, silicified pisoliths, vein quartz and volcanics), and barren bands (run-on zones) dominated by red-brown sands and silts. In the east, these fans extend across to the western margin of Lake Frome, some 100 km distant. In many areas up to three generations of fans can be recognised (see section 5.3 of chapter 5), such that there is a build-up of different types of colluvium throughout the basin. The small talus cones, such as along the rangefront, are localised landforms that are typically less that 4 m wide. They form as steep, gravity driven ‘flows’ over the top of high-angled hanging walls of recently activated faults. The sediments that occupy these cones are exclusively derived from the immediate surrounding area, typically shedding off the hanging wall of the fault that the fan overlies. Quaternary aeolian landforms are dominated by two types of dunes and extensive sand plains. This includes approximately east-west striking, longitudinal dunes, comprised of red-brown sands and silts, with densely vegetated swales; small, vegetated parabolic dunes, comprised of white-yellow sands; and elongated, undulating plains of red-brown sands and silts. The longitudinal dunes represent the approximate trend of the dunes on the west side of Lake Frome (see chapter 4). These dunes extend continuously for up to 12 km basinward, and over 30 km in discontinuous chains. The small parabolic dunes in the north are representative of local trends in aeolian sedimentation. These landforms represent the localised winds that swirl around the ranges and are often deflected in their intended paths by the steep rangefronts of the Mt Babbage Inlier. These dunes include white, quartzose and calcareous sands, and occasional accumulations of feldspathic sediments flanking bedrock exposures. The elongated sand plains occur sporadically throughout the area, the undulations of which indicate that the landform represents immature proximal dunes.
Table 5.1. Mesozoic and Cainozoic sediments: Basin nomenclature and local correlations with local sediment descriptions of Eromanga Basin Sediments (Holbrook 1966; Van Doan 1988) and the Lake Eyre Basin (Alley 1998; Holbrook 1966).

<table>
<thead>
<tr>
<th>AGE</th>
<th>STRATIGRAPHY</th>
<th>LOCAL NOMENCLATURE</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neogene</td>
<td>Pliocene</td>
<td>Trarri Formation</td>
<td>Sandy muds, silty clays, dolomites and occasional gravel beds</td>
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<td></td>
<td>Mioocene</td>
<td>Namba Formation</td>
<td>Smectite, thin yellow interbeds, transitioning to illic clays</td>
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<td></td>
<td>Oligocene</td>
<td>Eyre Formation</td>
<td>Basal, polished conglomerates, coarse-grained, quartzose sandstones</td>
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<td></td>
<td>Eocene</td>
<td></td>
<td>Not present within the field area</td>
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<td>Paleocene</td>
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<tr>
<td></td>
<td>Maastrichtian</td>
<td>Cadna-owie Formation</td>
<td>Grey-green shales, buff-white siltstones; carbonaceous, fine-grained sandstones; black carbonaceous banding common; basal conglomerate</td>
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<td>Campanian</td>
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<td>Albian</td>
<td>Bulldog Shale</td>
<td>Sporadic tillitic packages</td>
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5.1.4. Economic Geology

The northern Flinders Ranges hosts U, base metals (predominantly Cu and minor hydrothermal Au) and talc deposits. Two major mining projects are active within the area: the Beverley Uranium Mine in the south (365130mE / 6659250mN); and the Mt Fitton Talc mine in the northwest. The Beverley mine is hosted within sands of the Cainozoic Namba Formation. It includes the primary load, consisting of three lenticular bodies of coffinite and uraninite (McKay & Miezitis 2001). This portion of the basin is also host to the recently discovered Four Mile U deposit, a sedimentary-hosted coffinite lens. The Mt Painter Inlier also hosts considerable U anomalies and mineralisation in a zone called the ‘Mt Painter Deposits’ (Schindlmayer 1970; McKay & Miezitis 2001; Hore et al. 2005) or the ‘East Painter load’ (Dickinson et al. 1954). This includes the Radium Ridge, Mt Gee (2722 t U₃O₈ e) and Armchair prospects near Arkaroola, in which most of the mineralisation is hosted within hydrothermal haematitic breccias (McKay & Miezitis 2001). In the north of the inlier, known U mineralisation is limited to the Gunsight Prospect (371530mE / 6681130mN) (Whitehead 1966; Brewer & Marks 1980; McKay & Miezitis 2001; Hore et al. 2005), where there is abundant near-surface torbernite. However, this mineralisation is yet to be considered economic. Throughout both inliers there are small pods, boudins and dykes of Proterozoic metasediments and intrusives that contain U mineralisation, predominantly in the form of uraninite, carnitite and uranophane, while channels and small tributaries also host torbernite. These U-enriched zones are localised and currently recognised as uneconomic, yet further uranium exploration is currently active in this area.
Talc mineralisation is hosted within altered Neoproterozoic bedrock at the Mt Fitton Talc mine in the northwest of the area. Here, over 40 individual deposits are hosted within a zone spanning 60 km² (Dickinson 1961; McCallum 1990). These deposits are primarily associated with siliceous hydrothermal replacement along structures in the intensely-deformed dolomites of the Adelaidean Balcanoona Formation. Since 1945, over 400,000 t of talc has been mined from these metasediments, making this the largest talc workings in South Australia (McCallum 1990). Furthermore, talc mined from the Mt Fitton workings is considered to be the purest talc mined in Australia (Dickinson 1961). Talc mineralisation is common throughout the Adelaidean metasediments in the northwest of the Terrapinna Corridor. The mineralised zones are widespread, as the strata that typically hosts the zones is folded about three primary axes; however, the extent of the mineralisation is minimal.

Minor base metal mineralisation throughout the area includes Cu, Zn and Pb, all generally associated with zones of alteration within the granites around the north and eastern Mt Painter Inlier (Teale 1993a). Many of these deposits were mined in the late 1800s through to the early 1900s (Whitehead 1966; Sprigg 1984; Hore et al. 2005); however, none are currently active. Copper mineralisation is also abundant within the various metasediments in the area, in both native and secondary forms (Whitehead 1966; Sprigg 1984). Gold exploration has been active since the early 1900s; however, only minor mineralisation has been intersected (Hore et al. 2005). Detrital Au is also commonly observed around the ranges. This includes Lively’s Find (344141mE / 6643522mN) near Arkaroola, where considerable accumulations of surficial Au grains and nuggets have been reported and collected since the 1940s (Sprigg 1984). The source of the detrital Au deposits is speculative, with geochemical analysis indicating that the local bedrock is barren (Sprigg 1984). Minor W mineralisation in the form of scheelite occurs in the north of the Mt Painter Inlier (Teale 1993a). Non-gem quality grossula and corundum are within many highly-deformed Mesoproterozoic granites around Arkaroola and Mt Babbage (Teale 1993a).

As well as its mineral abundances, the area is also considered one of Australia’s hottest geothermal provinces. In the northern Flinders Ranges, there are over 500 square km of heat producing granites. The Proterozoic granites that form the majority of the contemporary expression of the inliers (see Figure 5.2) have an average heat production of 16 mW/m³, with local anomalies being in excess of 60 mW/m³ (McLaren et al. 2006). Average geothermal gradients in the basin flanking the inliers are in the range of 50 °C/km (data courtesy of Petratherm)—a gradient ideal for geothermal heating. Petroleum exploration within this area, although thus far unsuccessful, remains active.

5.1.5. Environmental Setting

The climate in the northern Flinders Ranges is semi-arid to arid, with extreme seasonal variations in temperature (BOM 2007-2008). Rainfall in the area is typically minimal, erratic and unpredictable, resulting in low-frequency and high-intensity ephemeral surface flow. Most of the perennial water supply comes from springs, such as the Paralana Hot Springs (349940mE / 6660810mN), and the small sandstone springs in the north including Petermorra Mound Spring (353023mE / 6706734mN) and Public House Springs (357854mE / 6707152mN). Occasionally sediments from the GAB from around Moolawatana pool water; however, this water is highly saline and evaporates very quickly. During the summer months, the low-lying areas typically experience strong winds and dust storms (Sprigg 1984). These are typically associated with easterly winds blowing off Lake Frome, and occasionally westerly winds blowing off Lake Torrens. For the most part, these winds are limited to the plains. Occasionally trains of wind are often tunnelled down the Terrapinna Corridor and through the small valleys of both inliers.

Vegetation within the area is dominated by arid species (particularly chenopod shrublands) dominated by bluebush (*Maireana* spp.), saltbush (*Atriplex* spp.) and emu bush (*Eremophila* spp.). Spinifex (*Triodia* spp.) occupies large areas within the Mt Painter Inlier; however, it is sparse in the Mt Babbage Inlier. Larger woodland species are abundant throughout the area, particularly gum-barked coolibah (*Eucalyptus intertexta*), mulga (*Acacia aneura*), and other wattles (*Acacia* spp.). River red gums (*Eucalyptus camaldulensis*) dominate active
ephemeral channels, with ground covers such as paddy melon (*Cucumis myriocarpus*). Sand dunes, alluvial fans and less active channels in the north are dominated by white tea tree (*Melaleuca glomerata*) and mulga (*Acacia aneura*). Seasonal vegetation typically associated with the wet season rains include Sturt’s desert pea (*Swainsonia formosa*). Aside from the active mining and exploration, land use in the area is limited due to the aridity. Sheep and some cattle are grazed in the low-lying areas, while goats are herded throughout the ranges. The area also hosts the Arkaroola Wilderness Sanctuary (Arkaroola Village: 340050mE / 6645520mN) and the Gammon national Park.
Figure 5.3. Surficial geomorphology map of the northern Flinders Ranges

5.2. Field site # 1: Parabarana
The Parabarana field site is confined to the small exposures of Mesozoic sediments between the Mt Painter rangefront east of Mt Neill (253810mE / 6531100mN) and the gibber plains approximately 1 km east of the rangefront (Figure 5.4). This area is hosted within the Poontana Sub-basin (Callen 1975), a shallow, structural sub-basin orientated parallel to the ranges that form the western extent of the Frome Embayment (see chapter 4). This area incorporates Parabarana Well (375343mE / 6680926mN) and is just to the east of the new Parabarana Bore (381550mE / 6680951mN) where anomalous geothermal gradients were obtained in test wells (http://www.petratherm.com.au).

Figure 5.4. 2006 Quickbird Imagery of Parabarana (Courtesy of PIRSA).

In the basin immediately flanking the Mt Painter Inlier, to the east of Mt Neill at Parabarana, is a near-complete succession of marginal Mesozoic sediments that have been folded, faulted and overturned within a local range bounding zone of deformation (Figure 5.5). The Mesozoic sediments at this location include exposures of the relationships between the different units within the sediments, the underlying bedrock and the overlying Lake Eyre Basin (LEB) sediments. The basal unconformity exposed here shows important aspects of the pre-basin landscape. While many exposures throughout the area expose this unconformity, few are this extensive or as well preserved. The exposures of the contact between the two basin sediments provides an important in situ comparison between the Eromanga Basin and LEB sediments that is essential for identifying the different basins sediments throughout the area. This site is also host to the Parabarana Sandstone type section (the local equivalent of the Cadna-owie Formation) and the only exposed segregation between the lower carboniferous shales from the Parabarana Sandstone and the carbonaceous shales from within the Marree Subgroup (Ludbrook 1966).

Parabarana is also known for its economic potential. The area hosts the Parabarana Mines (Ludbrook 1966), a group of abandoned base metal diggings and tunnels, as well as the Mt Neill Cu mines further west in the ranges. Uranium, Au and Cu exploration is currently active within this area. The area is also of considerable geothermal prospectivity. Surrounding the Paralana area is an anomalous heat-producing granite block 20 square km by 1 km thick. Paralana Well, a test geothermal well drilled approximately 4 km east of the ranges reached target geothermal gradients of 81.5°C/km at less than 2 km depth (data courtesy of Petratherm, 2005). This phenomenally high gradient at a relatively shallow setting is considered to be of economic interest, and is also one of the highest recorded shallow-setting gradients in Australia.
The nature and extent of the sediment exposures at Parabarana makes the area a prime site for a relative ‘reference section’ for the Mesozoic succession in the northern Flinders Ranges. Moreover, the deformation provides a key starting-point for landscape reconstructions. Exposures of the basal and upper unconformities confining the Mesozoic sediments also provide the starting and end points of palaeolandscape reconstructions in this study. Furthermore, this field site is ideally located to analyse the effects, if any, of the Poontana Sub-basin on the Mesozoic landscape.

5.2.1. Surficial Geology and Geomorphology
At Parabarana, regional tectonic deformation and local tectonic styles are expressed. The area is host to the northernmost exposure of the Paralana Fault, a structure responsible for much of the uplift in the ranges and thought to have been active in the past 60 ka (Quigley et al. 2006). This fault forms the rangefront at Parabarana; however, it also intersects the Mt Neill Anticline, at which point the fault exposures are masked by the basin sediments. The Mt Neill Anticline forms a large, open fold that is responsible for much of the morphology of the eastern side of the Mt Painter Inlier. For its part, the Paralana Fault mostly conforms to the general north-south trend of structures and deformation common throughout the ranges; however, here, at its northern end, just before its junction with the Mt Neill Anticline, it begins to bend to the east. This corresponds with where EW structures common to the northern ranges crosscut many of the NS trending structures, including the Paralana Fault, causing oblique, dextral, strike-slip displacement, and a ‘refraction’ of many of the larger structures (Figure 5.2). Localised deformation around Parabarana includes an anticline-syncline pair and the associated propagated faults and shears. These structures form a zone of deformation that spans from the Mt Painter Inlier rangefront 500 m basinward. Within this zone, the basin sediments have been uplifted, tilted and exhumed where they also form mesas.

Steep mountains and hills of the Mt Neill rangefront form the westernmost extent of the field area. These mountains and hills consist of the Mt Neill Granites and Petermorra Volcanics, both part of the Mesoproterozoic MPS (Figure 5.2 & 5.6). For the most part, the exposures that form the mountains and hills in this rangefront are slightly to moderately weathered. Areas of intensely altered or sheared sediments are typically highly weathered. Locally increased weathering grades are also common around mineralisation occurrences, such as in exposures on the drill pads and mine shafts associated with the Mt Neill Cu mines.

A series of uplifted mesas and low rises expose Mesozoic sediments in the basin surrounding the ranges (Figure 5.6). These landforms are exposed in a zone of intense local and regional structural deformation extending approximately 500 m from the Parabarana rangefront. They are characterised by steep slopes and bevelled tops,
and are surrounded by locally derived colluvium shedding of the mesas and rises, with prominent salt efflorescences at their footslopes. The slopes are unstable, often dominated by large, colluvial sheets and boulders forming a thin veneer over the basin sediments. The steeper slopes host minimal colluvium, and thus provide exposures of sediment profiles.

The area flanking the ranges is dominated by large colluvial plains (Figure 5.6), with undulating sand plains and sporadic small aeolian dunes (less than 1 m high). The plains are formed by two, and in some places three generations of shallow, low-lying, sheetflow fans that shed off the inlier and exhumed mesas. The basal fans are of very low angle, wide fans that extend for up to 4 km into the basin (possibly further). These fans sediments are characterised by populated bands (runoff zones) of vein quartz and granite clasts that become finer grained and more rounded in a basinward direction, and non-populated bands (run-on zones) of red-brown fine sands and silts. The sheetflow banding within these fans is prominent, with very thick runoff zones over 30 m wide and run-on zones typically <20 m wide, that can be mapped as discrete landform units (Figure 5.6: CHep1 & CHep2). These bands are slightly curved and have a general NW-SE strike. Dispersion vectors measured within the units indicate a general easterly (85°–100°) flow. This pattern, combined with the lithology of the clasts in these bands, indicates that the clasts populating the runoff zones are derived from the inliers within the ranges. However, in the contemporary landscape, the uplifted basin mesas inhibit this transportation. Thus for such vast quantities of these sediments to have been distributed across this part of the landscape, it is interpreted that these fans formed pre-uplift of the mesas. A series of smaller more elongated fans overlie the basal fans (Figure 5.6: CHFs1). These fans are characterised by sheetflow banding complied of rounded silcrete aggregates and sandstone clasts in the runoff zones and red-brown fine sands and silts in the run-on zones. Banding is more regular, with the run-on and off zones being 1–15 m. In many areas this banding is a result of the reworking of the runoff zones from the older fans. The strike of these contours is approximately N-S. In field exposures, the most obvious expressions of the two generations of fans are the variations in the contour banding strike and sediment type and accumulation. This contrast in banding sometimes presents as a cross-hatched pattern, well expressed on the remotely-sensed imagery (Figure 5.4). Throughout the plains, accumulations of maghemite and manganese oxide clasts form small (less than 1 m long and 30 cm wide) bowed bands defining contemporary dispersion.

Throughout the area, alluvial sediments are hosted within wide, shallow channels, squat fans and subtle depressions such as alluvial plains and depositional plains (Figure 5.6). The channels derived from the inlier initially conform to deep, incised, narrow streams that have profiles impeded and thus defined by exposures of sandstones and silicified sediments. The profiles of these channels decrease rapidly basinward, as the channel migrates through unconsolidated Quaternary sediments. Further into the basin, where the channels have tapered out and become broad shallow streams, they are typically surrounded by large alluvial and depositional plains (Figure 5.6). These landforms represent the overbank and flood plain deposits that have formed when the channel reached maximum capacity during major rainfall events. Such features are rare closer to the inlier, as the channel profiles there are deeper and steeper and therefore flow at a greater rate that rarely reaches maximum capacity. A few channels have maintained their intensity basinward, forming anastomosing streams. Regolith materials in these channels include red-brown, ‘mustard’-coloured sands and silts with minor components of small flattened lithic pebbles. Sparadically, exposures of silicified sandstone crop out in the base of the drainage, often forming small knickpoints. Alluvial fans have formed within the basins where subtle changes in slope occur. For the most part, the basin areas are flat-lying; however, sporadic undulations in the surface have resulted in streams filling and forming fans. This typically occurs around faults and fault zones that penetrate the basin sediments.

The arid climate of the area has resulted in extended dry periods in which the alluvial systems are reworked by colluvial and aeolian processes. Despite this reworking, and the occasional subtle nature of the landforms, drainage in the area is easily recognisable as it corresponds to the most densely vegetated parts of the landscape (Figure 5.4), and in some seasons indeed only the vegetated parts. Vegetation is dominated by low-
lying chenopods such as thorny saltbush (*Rhagodia spinescens*), bladder saltbush (*Atriplex vesicaria*) and velvet potato bush (*Solanum ellipticum*). Ground-cover plants such as paddy melons (*Cucumis myriocarpus*) are also common. Where sandstones are exposed or sub-crop in the drainage channel, larger woodland species grow, particularly whitewood (*Atalya hemiglauca*) and prickly wattle (*Acacia victoriae*). Preservation of aeolian contributions to the regolith profiles in the area are minimal; however, aeolian transport across the area is important. Yet, alluvial and sheetflow activity leads to the reworking and erosion of this material near the rangefront. Minor components of the fan units in the basins are attributed to aeolian processes. Small individual dunes have formed throughout the plains, where minor topographic undulations have provided a wind barrier and thus accommodation space for aeolian deposition. The vast gibber plains formed by the fans are littered with ventifacts; that is, wind polished clasts. These clasts define a dominant wind direction to the southeast (northwesterly wind). Small detrital wind ramps forming on ground cover and against trees and fence posts also support this dominate aeolian transport direction.

Figure 5.6. Landscape and surficial geology of Parabarana: (i) view SW of Parabarana including the Parabarana rangefront, an uplifted basin sediment rise, and the surrounding plains including a subtle channel; (ii) channel profile close to the rangefront (375193mE / 6682096mN); (iii) run-on zone from the older fans, minimal clasts, some small pebbles, and minor reworking from contemporary sheetflow (381495mE / 6681250mN); (iv) runoff zone from the older fans, populated with granite and lithic clasts, and minor reworking from modern colluvium (377184mE / 6692021mN); and (v) runoff zone from the younger fans, dominated by sandstone and silcrete clasts (375169mE / 6693507mN). Notebook used for scale is 15x8 cm.
Chapter Five: The Northern Flinders Ranges

CHep1 (Sheetflow sediments / erosional plain): red-brown fine sands and silts, rounded quartz, manganese oxide and lithic pebbles, minor incised drainage.

SSeh1 (Slightly weathered saprock / hill): slightly weathered, polished and rounded Mt Neil Granite.

SSel1 (Slightly weathered saprock / low hill): slightly weathered, polished and rounded Mt Neil Granite.

SSer1 (Slightly weathered saprock / erosional rise): slight to moderately weathered shales, highly silicified sandstones and conglomerates.

CHep3 (Sheetflow sediments / erosional plain): sub-angular to sub-rounded sandstone and conglomerate clasts, minor exposures of sandstones and shale.

CHpd1 (Sheetflow sediments / depositional plain): red-brown fine sands and silts, quartz and granite clasts, banded with red-brown sands and silts.

CHpd3 (Sheetflow sediments / depositional plain): sub-rounded to rounded silicified sandstone and conglomerates, quartz and granite clasts.

CHpd (Sheetflow sediments / erosional drainage): red-brown fine sands and silts, rounded quartz and lithic pebbles, incised drainages and flood plains.

CHpd1 (Sheetflow sediments / depositional plain): sub-rounded to sub-rounded sandstone and conglomerate clasts, minor exposures of shales, sandstones and conglomerates.

CHEp (Sheetflow sediments / erosional plain): sub-rounded to rounded silicified sandstone and conglomerates, quartz and granite clasts, banded with red-brown, sands and silts.

CHep (Sheetflow sediments / erosional plain): sub-rounded to rounded silicified sandstone and conglomerates, quartz and granite clasts, minor exposures of shales, sandstones and conglomerates.

SSEh1 (Slightly weathered saprock / hill): slightly weathered, polished and rounded Mt Neil Granite.

SSSeh (Slightly weathered saprock / low hill): slightly weathered, polished and rounded Mt Neil Granite.

Figure 5.7. Surficial geology map of Parabarana with an insert of surficial geomorphology surrogate map highlighting the multigeneration fan profile.
5.2.2. The Lake Eyre Basin

Throughout the northern Flinders Ranges, sediments of the Palaeogene Lake Eyre Basin (LEB) in part cover the Eromanga Basin sediments. These sediments have been described as coarse-grained and pebbly sandstones, highly-polished clast-supported conglomerates and siltstones with kaolin-rich beds (Alley 1998). This description generally matches those made during previous studies of Eromanga Basin sediments (Norton 1983; Van Doan 1988). Being able to discern LEB from Eromanga Basin sediments is, however, essential to ensuring the integrity and Mesozoic focus of this study. To account for this, a comprehensive description has been made of those sediments at Parabarana that are definitively from the LEB.

The most identifiable sediments within the LEB at Parabarana are the pebble beds and conglomerates from the base of the Eyre Formation (Figure 5.8), the oldest LEB sediments in the area (Table 5.1). These conglomerates are widespread throughout the basin and are widely used as a marker bed due to their distinctive characteristics and ease of recognition. The basal conglomerate typically consists of rounded, highly-polished, ‘jellybean’ like pebbles hosted within a silty matrix. At Parabarana, the base of the conglomerate is dominated by quartz pebbles; with the lithology varying greatly up the profile. Throughout the conglomerate, clast types include vein, volcanic, yellow (citrine) & black (smoky) quartz; black chert and jasper; tourmaline; red and purple granite; various siltstones and sandstones, including silcrete pisoliths; and, various slightly magnetic clasts (possibly magnetite and maghemite). Mixed within the highly-polished pebbles and clasts at Parabarana are minor accumulations of small, angular quartz and granite clasts. Their lithology and attrition differentiates them from the typical ‘jellybeans’ clast morphology in the conglomerates. The lithology of these clasts matches lithologies from within the ranges, particularly the Mt Neill Granites. Rather than being diagnostic of the Eyre Formation sediments, they represent a local variation.

Overlying the conglomerates are highly silicified, coarse to very coarse-grained, quartzose sandstones. Despite the silicification partially destroying some of the original features of the sandstones, these exposures provide the benchmark for the typical Eyre Formation sandstones. These sediments are characterised by siliceous, coarse-grained sands and gravels. These sands contain a notable absence of feldspar, plagioclase, mica and other relatively easily-weathered sediments. In essence, they are almost entirely comprised of quartz. The type of indurations that form within these sediments is often a grey-pink pisolithic silcrete. Whilst silicification is not a means to identify and correlate a unit, this type of induration is commonly associated with this unit, as these sediments appear to preferentially facilitate this type of induration to form (Figure 5.8). Where the landscape is littered with individual pisolith colluvium, it often indicates either an exposure or sub-crop of these sediments. Where these sediments have not undergone induration, the detritus is hosted in a kaolin-rich matrix, with kaolinite-rich bands up to 2 cm thick.

5.2.3. Mesozoic Sediments

The Mesozoic sediments at Parabarana are exposed within incised drainage, along the walls of fault-controlled mesas, and sporadically in small pods cropping out in the surrounding plains. Exposures within the mesas have
been typically overturned by recent deformation. These profiles expose near complete successions of the Mesozoic sequence. However, competency variations between the sediments have resulted in differential weathering and erosion in parts of these profiles. Two successions of Mesozoic sediments are analysed here: the Parabarana Sandstone Cadna-owie Formation equivalents (Table 5.1), and the Marree Subgroup Bulldog Shale and Oodnadatta Formation equivalents (Table 5.1).

**Parabarana Sandstone**

Parabarana hosts the exposures used to define the type section of the Parabarana Sandstone in the northern Flinders Ranges. This approximately 200 m long section was originally defined by Holbrook (1966) after collaboration with mapping teams for the Moolawatana and Paralana sheets in the 1960s, as the most extensive section of this transitional sandstone, preserving contacts with the overlying Marree Subgroup, and a comparison to the Tertiary sediments. The basal unconformity with the crystalline basement is obscured by colluvium. Holbrook’s (1966) analysis of this section was represented in a written section log (Figure 5.9); no stratigraphic log or profile was published.

1. At the base of the sandstone a poorly exposed sequence of grey carbonaceous sands and gravels: approximately 7 feet thick. Black carbonaceous sands and shale: 1 foot.
2. Light grey, with dark-grey patches, weathering to grey-brown, laminated medium to coarse-grained quartzite, finely micaceous, and weathering into hard blocks in a low cliff: 4 feet.
3. Interval partly obscured by talus: cream-white calcareous sandstone, micaceous, fairly soft but weathering hard and light to dark brown on the surface: 28 feet.
   Light grey, weathering to red-brown, calcareous medium-grained sandstone with plant stem impressions, forming a ledge and dipping east at about 12 degrees: 12 feet.
4. Above the ledge of unit 3, calcareous sandstone ferruginised and partly silicified, weathering in large blocks, with quartz and quartzite pebbles up to 3 inches in diameter: bedded on the eastern side, beds varying in thickness from 2 to 18 inches: 12 feet.
5. Coarse-grained quartzite with subvertical plant-stem impressions. The upper surface is silicified under the contact with the overlying shales: 6 feet; dip 45–70 degrees.

Figure 5.9. Composed written log of the Parabarana Sandstone type section from Holbrook (1966).

The sediments at the Parabarana type section represent both the basal Mesozoic and the transition to the marine sequence within the Parabarana area. To obtain a clear profile of these sediments, so that it could be used as a basis for defining these sediments in the area, these sediments were logged again, in more detail and analysed in terms of mineralogy (Figure 5.10) and depositional environments (Figure 5.10). Other sediment exposures around Parabarana were also incorporated into the analysis of the sandstone to create a better definition of the package.

The poorly lithified sand and gravel from the base of the Parabarana Sandstone represent the initiation of Mesozoic deposition in the area. These sediments (units 1–3 from the type section) are dominated by poorly-sorted quartz, feldspar, muscovite and an abundance of lithic detritus, with sporadic quartz and granite clasts at the base. In the type section log, surficial weathering patterns were used to mark the change of sequence; however, some weathering patterns transcend through different packages. Sequence boundaries are re-defined in the graphic log (Figure 5.10). For the most part, the basal sediments are highly to very highly weathered. Some sandstones display slight metamorphism and alteration, with small-scale crenulations visible in thin-section in the blocky sandstones (Figures 5.10 & 5.11). The top of this succession (approximate unit 3 from the original type section description) contains an abundance of poorly-preserved fossils, including leaf and twig imprints. The basal silty sandstones and shales resemble descriptions of Bulldog Shale sediments (Ludbrook 1966). Way-up indicators, such as truncated forests on cross-bedding and sporadic graded profiles, indicate that these sediments are at the base of the Parabarana Sandstone, rather than the top, and so do not correspond to the transition to the Marree Subgroup. Diagnostic features of these sediments include fine-grained, quartzose detrital fragments; large (sand-size) carbonaceous fragments; and a distinct red to red-grey weathering.
Figure 5.10. Basal Parabarana Sandstone (units 1-3) photo and stratigraphic log from the Parabarana Sandstone type section, Parabarana (375343mE / 6680926mN).

Figure 5.11 Basal Parabarana Sandstone: (i) and (ii) basal shales, highly cleaved, minor surficial goethitic staining on some surfaces (375225mE / 66822195mN); (iii) silty sandstones with large colluvial fan over the top; and (iv) deformed silty sandstone (photos courtesy of David McAvaney). Notebook used for scale is 15x8 cm.
The top of the Parabarana Sandstone (units 4–5) is lithologically indicative of typical Cadna-owie Formation sediments from elsewhere in the basin (see chapter 2). These sediments are dominated by medium-grained, clean, quartzose sandstones, with sporadic coarser-grained and pebbly beds. These sediments are typically homogenous, forming sedimentary sequences up to 3 m wide. The sediments are bedded, predominantly planar and occasionally convoluted. Mineralogy is dominated by quartz, with sporadic feldspars and muscovite (Figure 5.11). Beds that have not undergone induration are typically calcareous, with the calcareous portion of the rock being a silty matrix surrounding the quartz detritus. There is also a notable absence of lithic fragments within these sediments that are otherwise abundant in the lower units. There are also sporadic isometric pyrite grains. These sediments have formed distinct weathering patterns, including spheroidal blocks forming as a result of extensive jointing and exfoliation shrink-swelling (Figure 5.11); plumose structuring, also a product of the shrink-swell weathering; stained surface profiles (often haematitic and goethitic) (Figure 5.11); and, extensive mottling. Indurations are common within these sediments, being dominated by silcrete; however, minor ferruginisation has occurred throughout many beds. Hardpan regolith carbonate accumulations (typically dolocrete) infill (around some of the weathered sandstone spheroids) and powdered carbonates are common in the highly-weathered sediments. The extensive indurations have helped preserve what have been interpreted as being twig and plant imprints (Holbrook 1966), which in profile appear as elongated, vertical ‘pores’. Sandstones from the top of this unit are the most common exposed Mesozoic sediments throughout Parabarana. This is attributed to their resistance to weathering, which is most likely a result of the quartz dominance in the detritus, and most exposures of this sediment are silicified such that they are also relatively resistant. These exposures dominate the walls of channels in the area surrounding Parabarana Well. These sandstones also form small knickpoints within channels as they flow basinward.
Figure 5.12. Top Parabarana Sandstone (units 4–5) photo and stratigraphic log from the Parabarana Sandstone type section, Parabarana. Photomicrographs indicating >95% quartz detritus (almost entirely monocrystalline quartz), with minor plagioclase, pyrite and muscovite.

Figure 5.13. Top of the Parabarana Sandstone: (i) and (ii) tilted and cleaved Unit 5 sandstones (375361mE / 6681474mN), photos courtesy of David McAvaney; (iii) sheared sandstone (375193mE / 6682120mN); and (iv) ferruginised sandstone in a creek exposure (375193mE / 66820916mN).
In the incised channels abutting the western side of the mesas further north, exposures of the top of the Parabarana Sandstone are capped by a 3–5 m thick package of matrix-supported conglomerates (Figure 5.14. i-iii). This sequence consists of a fine-grained sandy and silty matrix with rounded to sub-rounded clasts and boulders (3–25 cm) of quartz, silicified sediments, volcanics and granites. The conglomerates are bedded, well sorted, with a greater abundance of clasts in the siltier matrix. Most exposures are overturned, sub-vertical profiles that highlight the gradational nature from the coarse-grained sandstones lithostratigraphically equivalent to the sandstones from the top of the type section (Figure 5.14).

The base of the Parabarana Sandstone consists of highly-variable depositional environments, which have a distinct cyclic pattern. The interbedded silty sandstones and shales are indicative of a periodic change in depositional environment, in which the variations represent a tidal phase. This is interpreted to be a representation of the erratic nature of the transgressive systems tract present at the time of deposition. The finer units are indicative of tidal environments, whereas the coarser-grained sediments are more indicative of the terrestrial environments with some marine influence. The red to grey and green weathering patterns on the sediments are a result of variable oxidation and reduction, with the variation in colour associated with different forms and mixtures of iron oxidation. Minor ferruginous components are common in the secondary cements from the overlying sediments, such that it is highly likely that there is some ferruginous component to these sandstones and siltstones.

The interbedded coarse-grained sandstones and homogenous fine to medium-grained sandstones from the top of the unit (approximate unit 4 equivalents) are indicative of a high-energy terrestrial environment that is dominantly fluvial with the plant fossils interpreted to be from a temperate, wet climatic setting (Ludbrook 1966). The coarser-grained interbedded nature of these sediments is indicative of an overbank type deposit. The coarse nature of the sediments indicates a higher energy environment typical of a flood plain; however, the environmental conditions would have provided higher energy flow due to the abundance of water, and thus the capacity to carry coarser sediment. These sediments are interpreted to be from an alluvial plain. The silty sandstones from the top of the Parabarana Sandstone are characteristic of lower energy terrestrial environments. The close to homogenous
nature of these sediments indicates a stable depositional environment, which experienced little change for the duration of the deposition of the unit. The fossil imprints and casts reflect a dominance of terrestrial environments, with the subtle tidal influence in the lower units area now absent. The conglomeratic layers at the top of the sequence, where the sandstone grades into the Marree Subgroup, is indicative of a transgressive lag deposit (as defined by Allen 2006), in which the onset of a major marine incursion initiates high energy flow, depositing larger clasts. The finer fraction of these sediments settled amongst the pebbles, as the transgressive system migrated into a high-stand systems tract when the marine-dominated environment prevailed.

Marree Subgroup

Shales and mudstones correlating with the Marree Subgroup are exposed throughout Parabarana, predominantly within the zone of deformation against the rangefront. These exposures are dominated by grey-green shales, and pallid mudstones (Figures 5.15). The base of the Marree Subgroup is difficult to define, as the shales grade upwards from the top of the Parabarana Sandstone with the transgressive lag deposits. This transgressive lag grades into a sandy shale (Figure 5.15. i), that is previously defined as the approximate base of the Marree Subgroup (see chapter 4).

Exposures of these sediments around Parabarana are typically limited to channel walls and incised valleys. These sediments are dominated by the grey-green, carbonaceous shales that are diagnostic of the Bulldog Shale. The highly-weathered nature of these sediments impedes the determination of original mineralogy. However, where the sediments are less weathered, the mineralogy includes smectite, illite and zeolite dominating the clay fractions and quartz dominating coarser fractions (Figure 5.14). Overall, these sediments are highly carbonaceous, with fragments of petrified wood and shell fragments preserved within some beds. Accumulations of glauconite (secondary iron phyllosilicate) and isometric pyrite are common within the highly carbonaceous units. Veins of calcite (Figure 5.14 iv & 5.15) and selenite are also common, along with authigenic disseminated gypsum and calcareous concretions. In some areas, the gypsum accumulations have formed a gypcrete duricrust in which the surface of the exposure is coated by a hard gypseous ‘skin’. The induration has formed as the result of a capillary transfer of dissolved gypsum toward the landsurface, which is typically a byproduct of sulphide weathering.

These shales also host a considerable amount of exotic boulders and clasts irregularly distributed throughout the unit. These clasts are mostly angular quartz (2–6 cm), sub-rounded to rounded sandstones, elongated and slightly rounded volcanics (up to 30 cm long) and some sub-angular to sub-rounded granitic boulders (Figure 5.14.iii). These sediments differ from the carbonaceous sandy silts from the base of the Parabarana Sandstone, primarily by the mineralogy and detrital components. The silty sandstones are predominantly coarser grained with an abundance of quartz detritus throughout, while the Marree Subgroup shales are finer-grained and have a distinct greenish tinge to fresh sediments. Mineralogical grain analysis of the shales indicates an abundance of glauconite, and clays including illite and smectite (Figure 5.15). For the most part these shales are poorly lithified and highly weathered; however, they contain an abundance of preserved dewatering structures, predominantly cone in cone structures (Figure 5.15), which indicate that the sediments had at least at some stage undergone partial digenesis.
Figure 5.15. Photomicrographs of Marree Subgroup sediments from Parabarana (x-polarised light): (i) shale—glaucnite, isometric pyrite and quartz clasts surrounded by zeolite and smectite (375259mE / 6682037mN); (ii) shale—clay coated quartz clasts, glauconite, pyrite and minor lithics, with microscopic dewatering cone-in-cone structures in the surrounding clays (375259mE / 6682037mN); (iii) shale—glaucnite pyrite and quartz clasts surrounded by clays, with dewatering cone-in-cone structures in the surrounding clays; (iv) silty shale—carbonate veining, glauconite, quartz, pyrite, zircon, muscovite and weathered clays; and (v) and (vi) fine-grained sandstone quartz, muscovite and plagioclase clasts in a slightly ferruginous, calcareous matrix (375981mE / 6682410mN).

The exposures of these sediments also contain pallid sandy siltstones. These exposures are typically isolated and rarely viewed in contact with other Marree Subgroup sediments; however, they may be overlain by Eyre Formation conglomerates. These sediments are also poorly consolidated, but not as highly weathered as the shales. There are also sediments from a distinct ‘glerpy’-type weathering profile (Figure 5.16 ii & ii). These sediments form a distinct surficial yellow-mustard, goethitic mottling and staining (Figure 5.16 iii).

The shales in the Parabarana area are indicative of a low-energy environment. The presence of glauconite defines the environments that these sediments were deposited in, as it is a secondary mica mineral that only forms diagenetically in sulphur-rich, reducing waters in marginal marine—coastal shelf environments conducive to slow rates of deposition. The source of sulphur in this system would most likely be sourced from the decaying organic matter, which is now represented by the abundant carbonaceous content in the shales. The fine-grained
nature and mineralogy of these sediments indicates a marginal marine depositional environment. The silty pallid units (Figure 5.16ii) within this package are also interpreted to have been deposited within a shallow marine environment; however, they have no specific characteristics other than grain size to imply this. The boulders within the shales are interpreted to be debris-type sediments and are otherwise not consistent with the general depositional environment responsible for the rest of the sediments. Similar features have been identified within the Marree Subgroup sediments throughout the southern margin of the basin (Van Doan 1988; Alexander & Kreig 1993). These boulders are more specifically interpreted to be ‘drop-stones’ transported into the basin via ice blocks that have melted and discharged sediment, including the larger boulders (Alexander & Kreig 1993). However, large dropstone boulders are typically surrounded by stress or impact clefts that form when a clast falls into the sediment. This is a diagnostic feature that the clasts have in fact dropped into the sediments as opposed to flowed, such as with debris flow or colluvial transportation. The clasts in the Marree Subgroup are surrounded by sediments that are so highly weathered that any evidence or potential evidence of such structures has been destroyed. Despite this, the random distribution, variation in lithotype, attrition, size and morphology (Figure 5.16. iv.) support the notion that these sediments are transported by ice.

Figure 5.16. Marree Sub-group sediments: (i) typical friable, grey-green, glauconitic shales (375259mE / 6682037mN); (ii) pallid, mottled siltstones; (iii) slightly ferruginised shales and claystones (375301mE / 6682149mN); and (iv) ice-rafted boulders hosted within grey-green shales (375259mE / 6682037mN).
### Table 5.2. Summary of the Mesozoic sediments from Parabarana Well.

<table>
<thead>
<tr>
<th>Features</th>
<th>Petrology</th>
<th>Field Relationships / Exposures</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large drop stones up to 40 cm in the basal sediments. Predominantly</td>
<td>Weathered feldspar, monocrystalline quartz and muscovite. Fragments of</td>
<td>Exposed in part within the type section, predominantly throughout channels, in the uplifted</td>
<td>Highly friable</td>
</tr>
<tr>
<td>rounded clasts (volcanics, granites and sandstones). Highly deformed</td>
<td>granite, mafics and pegmatite. Disseminated gypsum. Sphalerite and</td>
<td>mass within the zone of deformation. Channel exposures indicate an unconformable relationship</td>
<td></td>
</tr>
<tr>
<td>in places. Small milonitic zones. Some spheroidal weathering around</td>
<td>carbonate and selenite veins.</td>
<td>with the overlying Eyre Formation</td>
<td></td>
</tr>
<tr>
<td>jointed sandstones. Carbonate layers infilling joints. Partially</td>
<td>Highly weathered, often with a deep red-brown weathering pattern. Some</td>
<td>Exposed within incised channels and in creek beds, along small, localised faults and, in part,</td>
<td></td>
</tr>
<tr>
<td>indurated (silicified). Plant fossils.</td>
<td>in the base of small channels basinward, in small pods around the edge of the</td>
<td>in the type section, along channel and creek wells, sporadically in the base of small channels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>type section exposure</td>
<td>basinward, in small pods around the edge of the inlier and throughout the zone of</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>deformation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highly deformed in places. Small milonic zones.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some spheroidal weathering around jointed sandstones. Carbonite layers infilling joints.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partially indurated (silicified). Plant fossils.</td>
<td></td>
</tr>
</tbody>
</table>

#### 5.3. Field site # 2: The Pimples

The Pimples are an informal name given to a series of palaeovalley sediment remnants hosted within the Paralana Valley, previously referred to as the Brindana Gorge (Blight 1981), in the Mt Painter Inlier west of Mt Neill (Figure 5.17). This is an area approximately equivalent to the area mapped on the Brindana Schist geology map (Blight 1981; Teale 1993 a & b), which also host the Gunsight U-Cu-Co-REE and Parabarana Cu-U-Mo mineralisation (Brewer & Marks 1980; Hore et al. 2005).
Initial mapping of these sediments classified them as undifferentiated sandstones from the Jurassic-Cretaceous Pelican Well, Parabarana and Village Well formations (Coats et al. 1969). Until recently, this was not further investigated; however, the recent increase in U exploration within the area has renewed interest in the sediments that overlie the crystalline basement. These remnants were the focus of a regolith and landscape evolution study, analysing the potential for uranium in Mesozoic sediments in this area (Wilson 2007). The primary focus of this study was to bridge a gap in geochemical sampling throughout the area, ensuring that the sediments previously defined as Mesozoic (Coats et al. 1969) sediments were explored for their potential to host or footprint U mineralisation. Components of this study incorporated regolith-landform mapping, sedimentary logging, geochemistry and palaeocurrent analysis (Wilson 2007). However, landscape position, lithostratigraphy, palaeogeology and relationships to the basin sediments throughout the area were not fully assessed. These sediments were further analysed so as to establish the connection to the rest of the Mesozoic sediments throughout the region, and thereby extending Wilson's (2007) study.

5.3.1. Surficial Geology and Geomorphology
The portion of the Mt Painter Inlier hosting the Pimples is a broad, flat-based, structurally-controlled intermontane valley striking approximately NE-SW through the central part of the inlier. The contemporary margins of the valley are controlled by high-angle thrust faults that juxtapose schists and granitic rocks from the RCM and MPS to now overlie the Mesozoic sediments. This is controlled by the Paralana Fault and associated, similarly orientated, smaller fault sets that are mostly splays from the Paralana Fault system. Exposures of the fault planes are limited; however, sporadically throughout the valleys, granitic-bodies are juxtaposed atop the Mesozoic sediments. The area is crosscut by numerous generations of faults (Blight 1981), which are responsible for varying degrees of deformation on the sediments. Aside from the valley-side faulting, other structures and structural trends include a series of NW-SE trending faults that cause strike-slip displacement of the Paralana Fault and similarly orientated
structures. The displacement of the faults also indicates a rotational movement in the faulting, as the Paralana Fault has been reorientated in some areas. This faulting and rotation is consistent with the movement associated with some of the previously described localised deformation at Parabarana. Geobotanical associations trace out some faults in the valley, with woodland species preferentially colonising faults and fault zones (Wilson 2007). Surficial geology throughout the valley is analysed in detail and mapped in Wilson (2007) and in part in Blight (1981). A summary of this is presented in table 5.3.

Table 5.3. Summary of the regolith landform units for the Pimplies area. Table collaborated from Wilson (2007) regolith landform unit descriptions.

<table>
<thead>
<tr>
<th>Type</th>
<th>Class</th>
<th>Associated landforms</th>
<th>Description</th>
<th>Vegetation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ</td>
<td>Slight to moderately weathered bedrock</td>
<td>Erosional rises, hills and mountains</td>
<td>Micaceous schists, highly polished granites, quartzite and quartz veins</td>
<td>Eucalyptus intertexta, Eremophila spp. and Triodia spp.</td>
<td>Valley sides, sporadically throughout the valley</td>
</tr>
<tr>
<td></td>
<td>Slight to moderately weathered Mesozoic</td>
<td>Erosional plains and rises; depositional plains</td>
<td>Interbedded coarse-grained sandstones and conglomerates</td>
<td>Acacia spp. and Eremophila spp.</td>
<td>Remnants throughout the valley (the Pimplies), faulted against the valley walls</td>
</tr>
<tr>
<td>Alluvium</td>
<td>Ephemeral channels, alluvial plains, fans, depositional plains and erosional drainage</td>
<td>Fine-grained sand, rounded to sub-rounded clasts of granite, quartz, quartzite and schist.</td>
<td>Eremophila spp. Melaleuca glomerata and Eucalyptus camaldulensis</td>
<td></td>
<td>Within the valley plains</td>
</tr>
<tr>
<td>Aeolian sediments</td>
<td>Minor accumulations, small plains &amp; wind ramps</td>
<td>Fine-grained sand and silt</td>
<td>Not specified</td>
<td></td>
<td>Minor component of most landforms throughout the valley.</td>
</tr>
<tr>
<td>Colluvial</td>
<td>Erosional rises, low hills and sporadically as a transported overburden</td>
<td>Red-brown sand and gravel; surface lags of granite (1 cm up to 1 m)</td>
<td>Eremophila spp. and Triodia spp.</td>
<td>Throughout the valley plains, at breaks in slope and as thin veneers over the mountains and valley walls</td>
<td></td>
</tr>
<tr>
<td>Sheetflow</td>
<td>Erosional plains, rises and low hills; depositional plains and fans</td>
<td>Dominated by locally shedding saprock, minor pale-brown, red-brown &amp; buff coloured sand and silt.</td>
<td>Eremophila spp. and Triodia spp.</td>
<td>Throughout the valley plains</td>
<td></td>
</tr>
</tbody>
</table>

5.3.2. Mesozoic sediments

Remnants of Mesozoic sediments are preserved within the valley, in small mounds and in fault zones along the valley walls. Small pods of sediment are also exposed within fault-controlled drainage depressions within the valley floor. The most prominent of the exposures are two large mesas of sandstones and conglomerates, specifically referred to as the Pimplies (Figures 5.18 & 5.19). Previous mapping has also mistakenly included adjacent erosional rises with vein quartz within the same mapping units as these sediments (Blight 1981). Previous mapping has also mistakenly included adjacent erosional rises with vein quartz within the same mapping units as these sediments (Blight 1981). The mesas are composed of tectonically inclined, interbedded, coarse-grained sandstones, pebbly sandstones and conglomerates that have been recently correlated to Cadna-owie Formation sediments (Wilson 2007); that is, to approximately Parabarana Sandstone stratigraphic equivalents.
At the base of each pimple is a thick sequence of clast supported conglomerate. This sequence almost entirely consists of angular to sub-angular quartz clasts (up to 5 cm), hosted within a sandy matrix (Figure 5.18 ii). At Pimple #1 (the northern of the two main rises: 367894mE / 6679303mN), sediments above the basal conglomerate are poorly exposed, and are covered by colluvium. However, on the southern aspect of Pimple #2 (the southern of the two main rises, 366603mE / 6678000mN), a near complete succession of the Mesozoic sediments is exposed (Figure 5.19). From this, a basic lithostratigraphy for the Pimples can be established. Overlying the basal conglomerate is a sequence of interbedded pebbly and coarse-grained sandstones and pebbly beds with conglomeratic lenses. The pebbly sandstone sequence dominates the succession and includes angular, quartz pebbles, sub-angular to rounded spherical quartzose grains and abundant micas, predominated by muscovite. Furthermore, photomicrographs show minor zircon, abundant muscovite and several opaque grains and matrix (Figure 5.20). Cements surrounding the detritus, vary, but are dominated by microcrystalline quartz. The conglomerate lenses contain abundant quartz clasts of various attritions, with minor lithic fragments, including small plagioclase clasts and green, possibly fluorite-rich, metaigneous clasts. These sediments are hosted within a fine-grained, sandy matrix, which in places effervesces with dilute hydrochloric acid.

Within the Pimples, numerous primary sedimentary structures have been preserved. These include abundant tabular and trough cross-bedding, anti-dunes, burrow cast fossils and graded bedding (Figure 5.18 v). Tabular cross-bedding is more prevalent in the sandier sequences, while anti-dunes are more prominent in the coarser pebbly to conglomeratic sequences (Figure 5.19). The scale of these features varies from less than 5 cm to 30 cm forests; in bands that are continuous for over 2 m.

Figure 5.18 The Pimples: (i) Northern Aspect of Pimple #2, taken from a quartz mound in the centre of the valley; (ii) coarse-grained pebbly sandstones from the northern side of Pimple #1(367894mE / 6679303mN); (iii) pallid zone within Pimple #2 with minor yellow staining, red mottles and robins nests (366609mE / 6678004mN); (v) highly weathered siltstone with cross-bedding; and (iv) bioturbation (366624mE / 6678034mN)
Younging directions obtained from the tabular cross-bedding indicate that the sediments are right way up, although they have been tectonically tilted (up to 30°). Trough cross-bedding is on a relatively large scale, with the average trough over 1 m wide. These structures are representative of high-energy stream flow, which is also supported by the grain size, attrition and sorting of the grains and clasts in the hosting sediments. Graded bedding throughout the sediments supports the younging direction determined from the cross-bedding forests as being right way up. These structures also indicate a general dip of bedding of 16°–35° for the sediments. Burrow casts are preserved within the sequence at Pimple #2. While these may be within the other exposures in the area, they are prominent at #2, as the casts have been infilled with ferruginous cement. These features have been previously interpreted as being root casts (Wilson 2007). The general structure of the cast and the surrounding bioturbated sediments supports that they are burrows. Wilson (2007) collected palaeocurrent measurements from tabular cross-bedding from both Pimples, indicating a general NNE trend from #1, and a northerly trend from #2. However, no structural corrections were applied to these measurements. The NW-SE trending faults are noted to have caused dip-slip displacement within the area, but also have resulted in vertical displacement within the south of the area. This equates to an oblique displacement, which has been recognised to have caused ‘block rotation’ throughout the area (Blight 1981). By plotting these readings as rose diagrams, with associated dip and strike of corresponding top and bottom set beds incorporated, which resulted in #1 maintaining a general WNW direction, while #2 now has a NNW flow (Figure 5.19). This indicates that the sediments in the south are affected by the faulting more than those in the north, possibly attributing to the greater profile height of Pimple #2.

As well as the Pimple exposures, Mesozoic sediments are also exposed along the eastern rangefront of the valley (Figure 5.20). Here, basement is thrust above the Mesozoic sediments, such that the normally readily-eroded sandstones and conglomerates have been, in part, armoured from erosion by overlying granite. Drainage exposures of the Mesozoic is typically limited to the small gullies incised into the eastern rangefront, most of which are structurally controlled. For the most part, these sediments are characterised by a distinct thick (up to 2 m) bed of matrix supported conglomerate (Figure 5.20). This sequence is dominated by angular to sub-angular quartz clasts, hosted within a quartzose matrix, which has in part been replaced by a ferruginous (predominantly haematitic) induration (Figure 5.20). This bed can be lithologically correlated to the basal conglomerate at both pimples, despite looking different in profile. The equivalent bed at the base of the Pimples has undergone a lesser
degree of induration, which has been mostly of silica cement rather than the ferruginous cement typically at the valley sides. The purple colour of the sediments is a result of the ferruginous imprint. Mineralogically, the sediments are the same and support the quartz-dominated lithotype in the clast fraction.

Overlying the conglomerate beds are a sequence of interbedded, coarse-grained sandstones and conglomerates similar to those in the Pimples exposures. However, these sediments have not undergone intense induration and thus have preserved more of the integrity of the initial sediments than those found in the Pimple exposures. For the most part, these sediments are dominated by a coarse-grained, monocrystalline quartz detritus, with some polycrystalline quartz, mica, zircon and sporadic mafic minerals (Figures 5.21 & 5.23). The coarser fraction of the succession is dominated primarily by sub-angular to rounded quartz clasts (<5 cm). The finer fraction interchanges between a silicic silt and calcareous silt.
As for the exposures at the Pimples, the sediments against the valley side contain trough cross-bedding, partially preserved anti-dunes and small-scale, tabular cross-bedding (Figure 5.19). The lack of induration within these sediments has resulted in the partial destruction of the structures.

The various remnants within the area are eroded such that they are now isolated from each other. While the area is intensely faulted and structurally deformed, the extent of the Pimples is not primarily structurally controlled. Blight (1981) infers that #2 is bound by a fault on one side of the mesa, and slickenslides on the eastern exposure of Pimple 2 confirm this. Exposures along the ridge are, in part, structurally controlled, where the recent tectonism has thrust the Proterozoic basement over them. Slight fault drag has occurred within the Mesozoic sediments such that this faulting has tilted the sediments at a different angle to the general structural trend within the sediments in the valley.

For the isolation of the Pimples to have been preserved, either both substantial differential weathering and erosion has occurred within the area, or sedimentation was far more limited in extent than previously interpreted (for example Wilson 2007).

Figure 5.21. Channel remnants along the eastern valley rangefront: (i) partially silicified sandstones overlain by granitic boulders along the rangefront (367104mE / 6677892mN); (ii) ferruginised basal conglomerate (367111mE / 6677898mN; (iii) exposure of the northern aspect of a valley incision exposing sandstones that basement has been thrust upon view looking southwest; and (iv) coarse-grained to pebbly sandstones on a piedmont along the rangefront (367114mE / 6677881mN).
Table 5.4. Palaeocurrent measurements obtained from the palaeochannel remnants with structural corrections. All rose swaths are valued at 2. All data displayed has been corrected and reoriented for localised structure. Any data measured without structural data as well has been disregarded.

<table>
<thead>
<tr>
<th>Location</th>
<th>Structure</th>
<th>Flow Azimuth</th>
<th>Rose</th>
<th>Flow and MRD</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pimple #1</td>
<td>Tabular cross-bedding</td>
<td>241, 240, 105, 095, 245, 247, 252, 090, 241, 096, 249, 272, 075, 097, 098, 110, 261, 253, 261, 274, 275, 260, 095, 269, 246, 109, 245, 098, 260</td>
<td>Bi axial flow: a) 97° b) 255°</td>
<td>Swath: (a) 20°; (b) 35° CSD: (a) 0.2; (b) 0.2 CV: (a) 0.01; b) 0.02</td>
<td></td>
</tr>
<tr>
<td>Pimple #2</td>
<td>Tabular cross-bedding; anti-dunes</td>
<td>351, 340, 005, 359, 354, 351, 340, 333, 357, 359, 033, 027, 004, 008, 358, 005, 357</td>
<td>Uni axial flow: 359°</td>
<td>Swath: 60° CSD: 0.2 CV: 0.03</td>
<td></td>
</tr>
<tr>
<td>Fault #1</td>
<td>Tabular and planar cross-bedding</td>
<td>007, 014, 016, 008, 010, 021, 011, 010, 009, 011, 012, 015, 016, 029, 013, 012, 007, 010, 015, 010</td>
<td>Uni axial flow: 013°</td>
<td>Swath: 22° CSD: 0.1 CV: 0.00</td>
<td></td>
</tr>
<tr>
<td>Fault #2</td>
<td>Tabular cross-bedding; anti-dunes</td>
<td>344, 342, 341, 341, 339, 301, 338, 332, 345, 340, 342, 335, 338</td>
<td>Uni axial flow: 337°</td>
<td>Swath: 44° CSD: 0.2 CV: 0.02</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.22. Palaeocurrent flow vectors for the Paralana Valley
White-grey, coarse-grained sandstone, coarsening upward, with gravel ut.
White-grey, bedded, medium-grained, quartzose sandstone, with cross-bedding ut.
White, poorly sorted, medium-grained sandstone, fining upward, partially silicified.
Purple-maroon, clast supported conglomerate fining up to a matrix supported conglomerate. Clasts dominated by angular quartz (up to 4 cm). Ferruginous indurations.
Concealed: Sub-angular to angular sandstone colluvium (up to 30 cm)
Concealed: Sub-angular to angular sandstone colluvium (up to 30 cm)
White-pink, graded, medium-grained sandstone, cross-bedded, with gravel beds ut.
White-pink, graded, medium-grained sandstone, cross-bedded, with gravel beds ut.
White, bedded, medium-grained sandstone, with gravel beds throughout, partially silicified.
White-grey, coarse-grained sandstone, coarsening upward, with gravel ut.
Pale-brown-light-orange, medium-grained sandstone, with gravel t.
The distribution of the remnants within the valley indicates that the profile extent of the channel conforms approximately to the extent of the contemporary valley; albeit that approximately 100 m on the west side is void of exposures or sub-cropping sediments. This indicates, at least in part, that during the Mesozoic the approximate extent of the Paralana Valley held some of its contemporary profile. Recent, at least post-Mesozoic, tectonism within the area has caused much of the uplift; however, there was substantial valley formation during the Mesozoic to control the extent of this channel.

The sediment exposures within the valley are interpreted to be terrestrial sediments. The general grain size of the sediments is indicative of a high-energy environment. Grain and clast attrition varies within the profiles; however, it is dominated by sub-rounded grains with moderate sphericity (Figures 5.20, 5.21 & 5.23). This, accompanied by the cross-bedding and grading upward profiles, is indicative of a high-energy fluvial environment. The grading sequences are typical of braided meandering stream profiles in which the grading represents a filling and subsequent migration of the channel (Figure 5.24). The sediments within the Paralana Valley are interpreted to be lithologically equivalent to the Algebuckina Sandstone (as defined in chapter 2). This association is made because the Algebuckina Sandstone sediments are dominated by the coarser-grained sequences, as it was a period if high-energy deposition resulting from the initial change in base-level, i.e. the initial subsidence.

Figure 5.24 Schematic representation of the Paralana Valley Mesozoic braided channel system.

The features of the Mesozoic remnants in the valley are characteristic of possible glacial attributes. The vast variation in attrition between clasts within the same pebbly and conglomeratic sequences, the anti-dunes and lithic fragments from distal sources (such as the fluorite metaigneous clasts) may support some glacial input in the area. Furthermore, in correcting the landscape for the recent tectonism highlighted by Blight (1981), approximations on erosion, and incorporating the contemporary exposures of the sediments, the valley forms a broad-based, wide profile that is similar to typical dimensions of a glacial valley. The trough cross-bedding, anti-dune structures, sub-aqueous flow structures are potential glacial flows, which flowed intensely through the valley during ice melt. However, further sequence stratigraphic and sedimentological studies are needed to confirm this interpretation; specifically, a detailed morphological study of the area that looks for features such as striations, and typical glacial landforms such as roche moutonnee. A more detailed study of the valley morphology and the associated structure will also contribute to determining the likelihood of this valley having a glacial origin. Tectonic reconstructions associated with this may be able to provide detail on the morphology of the valley at the time of deposition of the Pimples.
5.4. Field site # 3: Mt Babbage Inlet
The Mt Babbage Inlet is a structurally controlled ‘embayment’ hosted within the northeast of the Mt Babbage Inlier (Figures 5.2 & 5.25). The area is defined by an embayment that forms in the north of the Mt Babbage Inlier. The south, east and western extent of the area are defined by the structural ridges and mountains that form the inlier. The north of the area defined for this study site extends basinward to Gunpowder Bore (368311mE / 6697851mN) in the north (Figure 5.25).

The landscape in the inlet is characterised by bevelled mountains and ridges forming a structurally-controlled ‘amphitheatre’ that encases undulating plains and shallow rises (Figures 5.26i & 5.29). The uplift and extent of the inlier is controlled by the Mt Babbage syncline and anticline, which are an approximately NNE-SSW striking, open-fold pair and a series of fold-propagated faults, namely the Mt Babbage and Gunpowder thrust faults. To a lesser extent, an approximate extension of the E-W striking Mudnawatana Syncline accompanied by the NW-SE striking oblique, strike-slip Pigeon Springs and Sandstone faults also contribute to the extent of the ‘amphitheatre’ structure, and thus the extent of the inlet (Figure 5.29).

The area has been incorporated into previous geomorphic (Twidale 1999) and sedimentological (Norton 1983, DeLurio 1995) studies conducted around Mt Babbage, as it hosts some of the most prominent exposures of the Mesozoic sediments and landforms in the area, including Mt Babbage (368898mE / 6692116mN) and the Mt Babbage Ridge. Granites in the east of the area host non-gem quality garnets, and pegmatite veins throughout the amphitheatre host acicular tourmaline. Both the tourmaline and garnet are sporadically reworked in the basin sediments.

Mesozoic landscape features preserved within the area include sediment sequences, shorelines, land surfaces and piedmonts. Furthermore, the inlet is of considerable importance as it hosts exposures of the basal fluvial sediments as well as the marine sediments. These sediments coexist with recent and potentially still active deformation. Despite this deformation being substantial, vast surficial exposures of the Mesozoic sediments have been preserved throughout the area. Extensive surficial evidence of the deformation (exposed fault planes,
identifiable fold hinges and large shear zones) allow for the landscape to be easily reconstructed, such that the Mesozoic sediments can be viewed in close to their original environments and landscape settings.

5.4.1. Surficial Geology
Surficial geology within the inlet is dominated by two primary regolith types: *in situ* regolith, including the mountains and hills of the inlier and structural ridges in the east; and, transported regolith, including the sheetflow plains and rises, and sand plains in the flanking basin (Figures 5.26, 5.27 & 5.29).

*In situ* regolith includes: Proterozoic granites, gneisses, pegmatite and mafic schists of RCM and MPS that form the bevelled rises and hills of the amphitheatre (Figures 5.26.i. & 5.29) and the Mesozoic sedimentary units that form the mesas and ridges in the east of the inlet, which both surround the base of many granitic exposures in the north, and sporadically crop out through the basin and alluvial systems (Figures 5.27 & 5.29).

For the most part, the amphitheatre is compiled of slightly- to moderately-weathered, highly-polished Wattleowie, Yerila and Terrapinna granites and metagranites (Figures 5.26 iii & 5.29). Exposures of the granites and metagranites are predominantly structurally controlled, forming large faulted ridges and folded hills. Some of the granites have been intensely jointed due to the brittle nature of the rocks. This has resulted in preferential weathering along the joint interface, together with the formation of core-stones such that they now form rounded exposures and in some places granitic tors (Figure 5.26 ii). This process is further explained in chapter 6.

Intrusions of quartz and pegmatite veins are abundant. These veins are very slightly weathered, and typically surrounded by accumulations of angular quartz clasts. The mafic schists that are sporadically exposed in the inlier are typically highly to very highly weathered, which is particularly enhanced by the abundance of biotite and amphiboles primary minerals. Because of the difference in the hardness of the schists and surrounding granites, differential erosion has occurred within the inlier. The ease of erosion of the mafic schists in comparison to that of the granites has caused the formation (and exposure) of shallow drainage depressions or small valleys.

Figure 5.26. *In situ* regolith exposures: (i) the view due west from the top of Mt Babbage (368898mE / 6692116mN) of bevelled MPS granite hills bounding the west of the inlet.; (ii) slightly-weathered Wattleowie Granite exposure; (iii) Pegmatite dyke, Rhiannon Brooke for scale (368855mE / 6692575mN)
Mesozoic sediments also compiled a considerable portion of the *in situ* regolith units within the inlet. These exposures are typically partially silicified, slightly- to moderately-weathered sandstones and highly-weathered shales. For the most part, exposures of the Mesozoic saprolite within the inlet are structurally controlled. NNE-SSW striking, faulted sandstone ridges and mesas occupy the east of the inlet (Figures 5.27.i & ii and 5.29). These exposures are controlled by the thrust faults that formed in response to the Mt Babbage folds. Within the inlet, exposures of small pods of sandstones up to 3 m wide are common.

Figure 5.27 *In situ* Mesozoic exposures: (i) Mesozoic sandstones surrounding the Mt Babbage Inlier (365000mE / 6697989mN); and (ii) mesa of slightly-ferruginised Mesozoic sediments (367857mE / 6694904mN).

Within the inlet, transported regolith is predominantly associated with the low-lying areas of the landscape. For the most part, this is the low to moderate rises and undulating plains that are surrounded by the amphitheatre. Regolith types dominating these units include colluvium, predominantly sheetflow sediments; and alluvium, predominantly active channel and flood plain sediments. Aeolian sediments form a minor component of most of these units; however, dunes and sand plains have formed in the far northeast of the area aeolian (Figure 5.19). Sheetflow sediments are the most abundant transported regolith type in the area. These units consist of runoff zones composed of angular to sub-rounded quartz, plagioclase and lithic clasts, with run-on zones of red-brown,
fine-grained sands and silts. In the south and east of the inlet, where the units are typically hosted on moderate rises, the runoff zones are characterised by an abundance of vein quartz clasts (up to 15 cm) (Figures 5.18 i & ii). The quartz dominated runoff zones in this area are slightly raised with comparison to the associated run-on zones. This is a result of the quartz clasts armouring the runoff bands that were once micro-topographic depressions. Differential erosion within these units has now created a micro-topographic inversion of the banding. Vegetation within these units is typically sparse, with many runoff zones being completely void of any growth. Some woodland species grow around sub-cropping sandstones in small gully incisions, and within shallow drainage depressions.

Further into the basin where the landscape is dominated by undulating plains, the banding is more subtle, with the runoff zones partially populated by accumulations of smaller quartz and plagioclase clasts (Figure 5.28 iii). Here, the banding is often so subtle that it is best highlighted by vegetation banding, with the run-on zones hosting grasses, small shrubs and occasional woodland species. Vegetation is almost void within the runoff zones. Exposures of sandstones and salt accumulations are common within these sediments, where the less ‘armoured’, fine-grained sediments have been eroded.

The colluvium within the sheetflow sediments is predominantly proximally sourced, for the most part shedding off the inlier. The ‘amphitheatre’ type structure of the surrounding mountains prevents the transportation and deposition of clasts sourced from distal environments, such that the colluvial sediments are a direct representation of local geology (Figure 5.28 i & 5.29). Quartz clasts shed off the pegmatite and quartz veins intruding through the crystalline basement. Clasts of the basement are rare; however, the abundant plagioclase clasts are weathered out of the MPS granites and augen gneisses. Where sandstones are exposed, the colluvium is dominated by silicified or ferruginised sediments, with a lack of plagioclase and angular quartz clasts. Run-on zones associated with the undulating plains within the basin tend to have an abundance of disseminated gypsum—a characteristic feature of some of the Mesozoic and Cainozoic sediments.

Alluvium within the inlet is dominated by active channel sediments. These sediments include rounded to sub-rounded quartz, plagioclase, granites, volcanics, sandstones and reworked tillite clasts hosted within wide, often shallow, ephemeral channels. The extent and distribution of these channels are governed by the saprock and localised structure. Many of the larger channels in the inlet are hosted along faults or within fault zones. Within the inlier, these channels are controlled by more resistant lithologies. These structurally-controlled channels define probable extensions in the basin where obvious structural exposure has been buried. Surrounding the major channels are extensive alluvial and depositional plains. These plains are characterised by red-brown sands and silts with shallow incised drainage.
Figure 5.28. Transported regolith: (i) Quartz clasts in the run-on zone in the inlet (365205mE / 6698126mN); (ii) View of the Mt Babbage Ridge top (369552mE / 6697688mN); (iii) Sheetflow banding in the east of the inlet (365131mE / 6697748mN). Dense populations of quartz clasts dominate the runoff zones, with the run-on zones almost void of any clasts; (iv) Sheetflow banding in the west of the inlet. Subtle banding highlighted by grass banding, with a small swamp forming in a run-on zone (364931mE / 6697053mN). (v) Yellow notebook used for scale is 15x8 cm.
5.4.2. Mesozoic Sediments

Mesozoic sediment exposures within the inlet are predominantly, but not exclusively, within the plains surrounding the inlier. Here, uplifted mesas and ridges along with small, low-lying ‘pods’ (up to 5 m wide) crop out among the colluvial and alluvial sheetflow plains and rises (Figure 5.29). Sediments are also exposed in arid river beds, forming the bed walls and knickpoints in the channels. Throughout the inlier, small pods of coarse-grained sandstone (typically <3 m wide) are exposed overlying the granitic hills and rises, indicating the original extent of sedimentation within the area. For the most part, these pods are too small to map; however, there are occasional larger exposures. This is evident at Mt Babbage where a 9 m high, 12 m wide exposure of silicified Mesozoic sediments is perched upon the granitic mountains almost 323m ASL. As well as the Mt Babbage exposure, a large mesa of Mesozoic sediments caps Proterozoic crystalline basement to the east of the Mt Babbage Ridge. This is the largest continuous exposure of Mesozoic sediments within the inlet, being over 1 km long and approximately 500 m wide.

The contemporary landscape expression of many of these exposures is structurally controlled. Along the Mt Babbage Thrust (Figure 5.2) is a ridge of Mesozoic sediments that has been uplifted and tilted as a result of post-Mesozoic activity along this fault. The vertical exposure of Mesozoic sediments along this ridge is as high as 30 m. Exposures along this fault are tilted and in part overturned by the folding, such that the vertical profiles do not represent true vertical sections of the Mesozoic. The altitude of the sediment cap at Mt Babbage is also a result of uplift along this fault. The Gunpowder Thrust has formed a similar, less continuous exposure of sediments parallel to the Mt Babbage Ridge sediments. Due to differential weathering and erosion, the exposures along the Gunpowder Thrust are preserved as a belt of mesas. These sediments are not as tilted as the ones along the Mt Babbage Thrust, such that the vertical expression of sediments is greater, but elevation is less. Exposures within the area are dominated by interbedded, coarse to medium-grained sandstones, fine-grained sandstones and conglomerates previously correlated to the mid to Late Jurassic Algebuckina Sandstone (Norton 1983; Van Doan 1988). This has primarily been a lithological correlation, as the sediments are similar to basal Village Well Formation from around Marree. However, recent palynology studies (Alley & Sheard unpublished), and fossil identification indicate that these are the oldest sediments within the area and are of early-Neocomian age. Although these sediments are chronologically equivalent to Cadna-owie Formation sediments, they are lithologically equivalent to Algebuckina Sandstone sediments from elsewhere within the basin (as defined in chapter 2). The marginal nature of these sediments (as demonstrated by the abundance of feldspar) accounts for the general increase in grain size and the erratic, variable nature of the sediments.

Lithostratigraphically, these sediments can be divided into two units:

- **Unit 1**: poorly-sorted conglomerates, coarse-grained quartz arenites, and feldspathic arenites interbedded with clast-supported conglomerates; and
- **Unit 2**: well-sorted, medium to fine-grained, fining upward quartz arenites with lenses of pebbly angular lithic sandstones, and clast supported conglomerates.

Large efflorescences of salt are associated with Unit 1 and, to a lesser extent, Unit 2. These accumulations occur as rising artesian water evaporates leaving behind a salt residue. The salt is typically more prominent in areas lower in the landscape; that is, where the surface is at lower altitudes, where water levels are closer to the surface, and where the sediments are not highly indurated. Besides the Neocomian sediments, there are both Aptian to Albian shales and mudstones of the Marree Subgroup. These sediments can loosely be further defined as being lithologically equivalent to the Bulldog Shale Formation as defined by Freytag (1966).
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Mesozoic Sediments: Slightly to moderately weathered, slightly indurated, coarse-grained and pebbly sandstones, clast-supported conglomerates, poorly lithified shales and sandy mudstones.

Alluvial Sediments: Fine to coarse-grained sand and silt, rounded pebbles and clasts, Minor angular clasts

Aeolian Sediments: Fine to medium-grained sand and silt, minor colluvium, winnowed pebbles and small clasts.

Cainozoic Sediments: Fine-grained sand and silt, rounded silcrete clasts, silicified arkosic sandstones and 'jellybean' conglomerates

Mesozoic Sediments: Slightly to moderately weathered, slightly indurated coarse-grained and pebbly sandstones, clast-supported conglomerates, poorly lithified shales and sandy mudstones.

Proterozoic Granites & Metasediments: Slightly weathered augen gneisses, rounded and highly polished granites and pegmatites; highly weathered mafic intrusives.

Neoproterozoic Adelaidean Metasediments: Slightly weathered quartzites, tillites and dolomites.

Alluvial Channel Sediments: fine-grained sand and silt, rounded pebbles, silcrete boulders and peds, sporadic sandstone and granitic exposures

Figure 5.30. Geomorphology and structural map of the Mt Babbage Inlet. Geomorphology units are a derivative of the surficial geology map.
Figure 5.29 Surficial Geology of the Mt Babbage Inlet. Detailed legend available in Appendix 5.
Unit 1: Basal Mesozoic

For the most part, Unit 1 overlies Proterozoic crystalline basement and occasionally Neoproterozoic bedrock. These sediments are lithologically dissimilar to the basal unit from Parabarana Well (chapter 5.4) or other basal sediments from other locations around the northern Flinders Ranges (chapter 2.5). However, like most other basal sediments around the area, they also cannot be definitively correlated to the type sections of the basal units from within the basin. Palynology data from around the inlet support a Cadna-owie Formation equivalent age (Alley & Sheard unpublished), but lithology and stratigraphy do not support this. This indicates that the Algebuckina Sandstone is more time transgressive than previously thought. Due to such irregularities and correlation difficulties, this unit will simply be referred to as the basal Mesozoic.

The basal unit is defined by irregularly-distributed, poorly-sorted beds of sandstones and conglomerates that have been preserved in the landscape mostly due to their authigenic cements and indurations. For the most part, the base of the unit is defined by a clast supported conglomerate, consisting of rounded to sub-rounded, milky quartz and sub-rounded plagioclase clasts (typically <4 cm), with sporadic rounded granitic, volcanic and gneissic lithic clasts. The matrix is a coarse- to medium-grained, buff-coloured, quartzose sand. In the north of the inlet the conglomeratic unit contains an abundance of angular milky quartz clasts (up to 4 cm), and small (<0.5 cm) muscovite, biotite, chlorite, tourmaline and garnet lithic fragments. The basal conglomerate gently grades into a matrix-supported conglomerate with a greater abundance of angular quartz fragments. The matrix-supported conglomerate also contains sporadic larger (up to 40 cm), sub-angular to sub-rounded boulders of granite, diorite and porphyritic rocks. Large-scale trough cross-bedding is abundant within this succession; however, it is more prevalent in the sandier units. The coarse-grained nature of these sediments, along with the abundance of trough cross-bedding and rounded clasts, is indicative of a braided river deposit. The lack of finer-grained sediments in the basal conglomerate is indicative of a higher energy deposit, progressing into a lower energy environment for the sandier conglomerates. The larger boulders consist of distinctive local basement lithologies; however, sporadic boulders are foreign, including some that resemble brecciated Gawler Range Volcanics. The foreign boulders are typically striated and similar to the clasts in the Umberturumerta Tillites from the Adelaidean Metasediments that form the structural and drainage divide between the inliers. It is interpreted that these foreign boulders have been reworked from the older tillite units. The origin of the larger boulders in the conglomerates is attributed to localised debris flows. The mineralogical variation within this succession can be attributed to the local variation in the crystalline basement, with the gneissic rock in the north contributing the unusual matrix detritus (garnet, biotite, tourmaline and chlorite), and pegmatite veins contributing the angular quartz.

The basal conglomerates grade into a thick succession of pebbly to coarse-grained, buff-grey-yellow sandstones. These sandstones are typically poorly-sorted, with sporadic pebbly lenses and beds (Figure 5.20).
Mineralogy is dominated by angular monocrystalline quartz, with minor muscovite, biotite, zircon, pyrite and polycrystalline quartz, classifying these sediments as quartz arenites. This package is sporadically intercalated with pink-grey sandstones (Figure 5.32). These sandstones contain an abundance of planar cross-bedding and occasional flute clasts. Mineralogy of the grey-pink sandstones is still dominated by monocrystalline quartz, but also contains 20–30% K-feldspar, abundant plagioclase and minor biotite and tourmaline. The mineralogy and grain size of these sediments indicate that they are still arenaceous sandstones of predominantly feldspathic arenites, occasionally verging on lith-arenites. Sporadic pebbly beds within this facies are dominated by sub-rounded quartz. Packages of the intercalated sediments are up to 8 m thick. In the southwest, and sporadically within the north of the inlet, the basal succession is absent such that this package unconformably overlies Proterozoic crystalline basement (Figures 5.32a & b). This is evident around Gunpowder Bore, where the interbedded quartz arenites and arkoses lap onto polished granite surfaces. Here, fold-related faulting has uplifted and tilted the sediments, exposing the unconformity and the underlying pre-Mesozoic surface (Figures 5.32a & b).

In the low-lying plains between the Mt Babbage Thrust and the Gunpowder Fault in the north is a zone of siliceous evaporitic sediments. This assemblage consists of waxy, banded sediments with a distinct fibrous appearance that is interbedded with petrified angiosperm fragments (Figures 5.33 i & ii). Sediment distribution and primary layering of this package is controlled by ‘pillow’-like structures that form a distinct bulbous shape. Mineralogy is sub-angular to sub-rounded monocrystalline quartz, plagioclase and K-feldspar clasts, with minor
diagenetic isometric pyrite (up to 0.5 cm of cubes and tetrahedrons) hosted within a cryptocrystalline chalcedonic matrix (Figures 5.22 iii & iv). Petrified angiosperm fragments are an accumulation of silica replacing the original organic structure, infilling cell and pore spaces. Radiating spherulitic crystals of chalcedony emanate from a layer of detritus at the base of the sediment, forming semi-hemispherical accumulations (Figures 5.22 iii & iv). These accumulations are limited to the zones in the rock above and, in part, within the petrified plant fragments. When viewed in thin-section under cross-polarised light, the chalcedony ‘fans’ exhibit periodic bands of extinction (Figure 5.22 iii). These extinction bands indicate a twisting of the crystal fibre around the c-axis of the crystal, an indicative property of length-slow (positive optical elongation) chalcedonic crystal habit (Heaney 1993). The layered nature of the different chalcedony indicates that it is a diagenetic feature within these sediments. The length-slow habit is further supported by the coexistence of the diagenetic chalcedony and pyrite, as the presence of sulphur in the mineral forming fluids only permits the growth of length-slow habit chalcedony (Bustillo 2003).

The diagenetic chalcedony and silica replacement within the petrified organics indicates that fluids charged with SiO₂ were percolating or pooling within the sediments after sedimentation and during lithification. Length-slow crystal habits are indicative of an evaporitic depositional environment. The abundance of preserved organic matter suggests that this was a ‘swampy’ environment. On a whole these sediments are very similar to tufa deposits, but are siliceous as opposed to calcareous. While uncommon, siliceous tufa deposits are associated with the rapid evaporation of waters charged with SiO₂ in ‘closed’ water systems such as lacustrine and spring environments. This is also supported by the presence of diagenetic isometric pyrite crystals, which typically form below the sediment-water interface in lacustrine and swampy environments (Wilkin & Arthur 2001). The ‘pillow’-like structures is indicative of a vertical percolation of fluid during deposition, favouring a spring environment (Figure 5.23).
The massive accumulation of salt in and around these sediments in the contemporary landscape indicates that the area is still partially active as a spring (Figure 5.24); however, not to the same degree as during the Mesozoic.

The top of the Basal Mesozoic is marked by a succession of buff-brown coloured, coarse-grained sandstones that grade into yellow-brown coloured, poorly-sorted, medium-grained sandstones. The thickest exposure of these sandstones is around the northwest of the inlet, where sediments lapping onto the base of granitic rises expose a 1 m profile of this succession. Mineralogy of the sediments is highly variable, with monocrystalline quartz and K-feldspar detritus dominating in the coarser-grained sandstones, and monocrystalline quartz sands (surrounded by siliceous and calcareous silts) in the medium-grained sandstones. This classifies these sediments as quartzose feldspathic arenites and silty, quartzose sandstones respectively. Sporadic calcareous layers at the top of the arenaceous sediments in the southeast are identifiable by a distinct yellow colouring. The lack of a finer fraction sediment within the very base of this succession indicates that this was a high-energy environment. The abundance of finer sediments in the sequence increases drastically upwards, indicating a calming of the energy of the depositional environment. The gradational change in these sediments are characteristic of a profile where the rate of sediment influx is greater than the rate of creation of accommodation space. While the sediments in the base of this package are generally coarse and thus high-energy, they are neither pebbly nor conglomeratic and thus not indicative of very high-energy environments. This package is therefore interpreted to be representative of a braided alluvial fan in which depositional environments vary from channels to flood plains and large sheetflow lobes.
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Unit 2: Transition Sediments

The quartzose feldspathic arenites and silty sandstones, from the top of the Basal Mesozoic, grade into a unit of medium to coarse-grained, well-sorted, arenites and siltstones. Given this unit represents the transition between major sedimentary packages and depositional environments within the inlet (from the fluvial to marine), it is not a distinctly unique unit. For this reason, these sediments will be referred to as the Transition Sediments. They are generally characterised by a well-sorted, fining upward succession of quartzofeldspathic arenites and silty sandstones.

An approximate base of this unit is assigned to the thin succession of massive, medium-grained, buff-coloured calcareous sandstones that typically marks the end of the intercalated arenites and silty sandstones. The detrital component of this succession is dominated by angular to sub-angular quartz sands, minor plagioclase, K-feldspar, muscovite and pyrite. The silty fraction is slightly calcareous. This succession also contains sporadic lenses (<30 cm wide) of micro-conglomerates, dominated by angular quartz clasts (<2 cm) with a silty matrix. This unit contains small (typically less than 5 cm) pieces of petrified wood. These wood fragments were analysed and compared to other wood fragments found throughout the basin. Larger fragments were identified as the gymnosperm *Nathorstianella babbagenis* (Figure 5.39 iii), first defined by Glaessner & Rao (1955). A thick package of intercalated fine-grained and medium-grained sandstones overlies the calcareous sandstones. The finer-grained layers are dominated by monocrystalline quartz with minor biotite, muscovite and plagioclase, indicating that the sandstones are fine-grained, quartz arenites. The medium-grained sandstones are also dominated by monocrystalline quartz, which show a distinct parallel fracturing pattern when viewed in thin-section. Infilling around the quartz grains is a calcareous matrix; however, this is often at least partially replaced by authigenic indurations, predominantly microcrystalline quartz, hematite and goethite. The indurations have altered and destroyed the original matrix and many primary sedimentary features within these rocks; however, they have preserved many fossilised leaf and wood impressions (Figure 5.39 iii). The wood impressions bear great similarity to the *Nathorstianella babbagenis* conifers.

Figure 5.36. Photomicrographs of Transition Sediments: (i) sub-angular to angular, poorly sorted quartz grains, partially ferruginised from a pebbly lens in the top of Unit 2 (367947mE / 6694086mN); (ii) quartz grains and lithic fragments, partially ferruginised; (iii) sub-angular quartz grains; and (iv) partially ‘melted’ quartz grains, with lithic fragments.
observed in older units. High degrees of induration have occurred in small pods within these sediments, thereby forming silcrete (hardpan siliceous indurations) and ferricrete (hardpan ferruginous induration) (Figures 5.35 ii & 5.39 i, ii & iii). Where ferruginous cements have indurated the sandstones, rock surfaces are characterised by lieusesegang weathering patterns.

The bulk of the Transition Sediments are characterised by sequences of graded gravelly sandstones fining up to sandy mudstones. These sequences are approximately 10 cm to 1 m thick and are stacked atop each other such that they form packages up to 9 m thick. Meso-scale anti-dune cross-bedding, asymmetrical ripple marks and graded bedding are common features throughout the sequences with trough cross-bedding evident on the package scale (Figures 5.37 & 5.38). Throughout the graded sequences are sporadic pebbly lenses up to 2 m wide. The Gunpowder and Mt Babbage Ridges host numerous exposures of these small lenses (Figure iii). They are dominated by sub-rounded to sub-angular quartz clasts (typically <1 cm), hosted within coarse-grained, quartzose sandstones (Figure 5.39 i & ii). Terrestrial wood and leaf casts are abundant within this package. The mineralogy of the sequences is almost entirely monocrystalline quartz, with sporadic biotite, muscovite and zircons in the coarser fractions, such that these sediments are characterised as orthoquartz-arenites. Thin beds of calcareous, fine- to medium-grained sediments are present in these cycles. Sedimentary structures within these sediments indicate a tidal influence during deposition; however, the sediments and associated fossils are still dominantly terrestrial.

Landscape exposures of these sediments are predominantly confined to the upper packages of the ridges around the fault zones in the inlier. Up to 7 m profiles of these sediments are exposed in the mesas in the south of the inlet (Figures 5.38 & 5.39 i). Here, highly indurated, fining upwards sequences stack onto each other, in many cases with sharp boundaries between successive packages. Throughout these sequences an abundance of angular quartz clasts (<2 cm) dominate the coarser fractions, while the finer fractions are dominated by sub-rounded quartz and K-feldspar grains. Herringbone cross-bedding is common where there is an abundance of fine to medium-grained sands, which overlie slump structures and, in some places, convoluted bedding. Other sediments within the plains may correlate with these successions; however, they do not have the extent of exposure to identify features that are indicative to this unit.

Vertical profiles along the banks of channels that incise through the plains in the northwest of the inlet expose the top of this unit. This succession consists of finer-grained sandstones and mudstones with interbedded carbonaceous shales. Mineralogy is dominated by monocrystalline quartz, with abundant pyrite, muscovite, tourmaline and weathered clays (Figure 5.36 iv). Petrified wood fragments are common to the more shaly units, and are occasionally opaline. In places this succession grades into the overlying Marree Subgroup with a clast-supported conglomerate (Figure 5.40 i & ii). This conglomerate contains rounded to sub-rounded quartz, quartzite, silicified sandstone (Unit 1), dolomite, ironstone, volcanics and granite clasts (typically <than 6 cm, with sporadic larger clasts up to 30 cm near the top of the conglomerate). A brown-grey, shaly matrix surrounds the clasts, which is in parts replaced by calcareous cement (Figure 5.40 i & ii). The interbedded fine-grained sandstones and carbonaceous shales are indicative of a low-energy, landward near-shore deposit. The interbedded nature of the sediments represents fluctuating environments, potentially a representation of the erratic incursion of the Eromanga Seaway. This conglomerate represents a transgressive lag. However, unlike the lag sediments from Parabarana, this sequence was deposited during the onset of a high-energy marine incursion in an environment as defined by the size and abundance of different clast lithologies.

In the east of the inlet, where the finer-grained sandstones are not overlain by the Marree Subgroup, a distinct lag of rounded and slightly-flattened quartz clasts armour the exposures (Figure 5.40 iii). The most common landscape position for these pebbles is atop the uplifted mesas that form the discontinuous ridges along the Mt Babbage Thrust and associated faults (Figure 5.40iii).
As the sediments are in an erosional landscape position (perched at least 10 m above the surrounding plains on free standing mesas) rather than not a contemporary depositional position, they are considered to be *in situ*. The rounded and flattened nature of these clasts is consistent with the morphology of beach pebbles (Figure 5.40 iii). The beach nature of these clasts is also supported by minor accumulations of shell hash. This package is a landward, lateral equivalent of the more basinward transgressive lag sediments.

![Figure 5.37. Graphic log of Mesozoic sediments from atop Mt Babbage (368898mE / 6692116mN). Photomicrographs indicating a predominantly monocrystalline quartz detritus, with minor lithics in the basal sediments (slide ii). Legend in appendix 4.](image-url)
Figure 5.38. Graphic log of Mesozoic exposure from an uplifted mesa along Gunpowder Ridge (367857mE / 6694904mN). The base of the log is obscured by extensive colluvium. Palaeocurrent measurements obtained from cross-bedding forests. Photomicrographs show abundant monocrystalline and polycrystalline quartz detritus, as well as an abundance of plagioclase, muscovite and sillimanite. Profile photo of the logged section is in figure 5.39 iii. For corresponding depositional environment interpretations and regional comparisons, see chapter 5.8. Legend in Appendix 4.
Figure 5.39. Exposures of Transition Sediments within the inlet: (i) silicified and slightly ferruginised coarse-grained to gravelly sandstones in a mesa, with salt accumulations around the base (367727mE / 6694764mN); (ii) folded silicified coarse-grained sandstone (0367878 / 6695026); and (iii) wood and leaf imprints in fossilised sandstone from Mt Babbage (368898mE / 6692116mN); Note book is 8x15 cm for scale.
Figure 5.40 Sediments from the transgressive lag and beach deposits: (i) and (ii) shaly conglomerate ‘transgressive lag’ sediments (363429mE / 669753mN); and (iii) beach pebbles (369308mE / 6696245mN).
Measurements of palaeocurrent flow indicators were obtained from two marker-beds from the Basal and Transition sediments units within the area. The marker-beds include the medium-grained sandstones from the grading between Units 1 and Unit 2 (bed #1); and the fine-grained sandstones from the top of the cyclic packages (bed #2). These packages were chosen due to their distribution, quality of exposure, consistent preservation of sedimentary structures and different depositional regimes. The angle of truncation of cross-bedding structures was measured in the graded sandstones, while cross-bedding truncation (and, where possible, a-symmetrical ripples) was also measured in the fine-grained sandstones.

Measurements taken from bed #1 are highly variable, with the skew between measurements in a cluster averaging 25°. This spread exceeds 50° in some locations. When averaged, the general flow direction for these sediments is to the WNW, with a slight rotation to the NW in sediments further north. The highly-varied, localised measurements within sediments are indicative of rapid, high-energy fluvial environments. The general flow direction obtained by the averages of the varied cluster measurements is more indicative of the fluvial system as a whole. Measurements from bed #2 are less varied, with average skews within clusters being mostly less than 8°. The general trend of these measurements is NNW, with a distinct rotation in directions to the north (Figure 5.41).

Figure 5.41 Palaeocurrent vectors projected onto the geomorphology surrogate map for the inlet. Bed #1 (the orange arrows) has a general NW to W flow direction, while bed #2 has a NNW direction.
The basal and transitional sediments in the Mt Babbage Inlet are not lithologically correlative to the Parabarana Sandstone. The characteristic shaly and silty base is absent and the general grain size of the different units are much coarser grained than the Parabarana Sandstone. The grain size, mineralogy and fossils from the Basal and Transition sediments in the inlet are indicative of terrestrial environments. The varying and vast array of packages further complicates the palaeoenvironmental and depositional interpretations. However, general trends in the sediments can be identified. The irregular, coarse-grained sands, pebbly sands and conglomeratic packages that disconformably overlie the bedrock throughout the area are characteristic of a fluvial river system in which flood plains, overbank deposits and alluvial plains surround high-energy river channels (Figure 5.42). This interpretation not only accounts for the varying sequences within the packages, but also the varying distribution of them.

![Figure 5.42 Schematic planar view of the interpreted depositional environment river system and associated sediments from the base of Unit 1.](image)

Similar packages are within these sediments, such as around the top of the transition sediments where there are cyclic sequences. Although the energy of the interpreted river system from the Transition Sediments is not as great as that of the basal unit, the sediment patterns are similar. The stacked fining sequences common in this package are indicative of a rhythmic succession, interpreted as being the result of a tidal influence. This indicates that these sediments were deposited in an environment dominated by a transgressive systems tract. These sediments are the first component of the marine incursion throughout the area.

Pebbly lenses within the sandstones in the Gunpowder and Mt Babbage ridges have both the typical sediment type and morphology of small channels. The typical size of these structures is 1–2 m.

In general, the sediment packages from the Transition Sediments are finer grained than those of the Basal Sediments. This also is indicative of the marine influence in the area.

Overall, the majority of the sediments in the area are characteristic of a braided fan in which fluvial channels and alluvial plains intertwine in a lobe that forms at a change of slope in the landscape. The higher-energy units are indicative of a system of anastomosing and anabranching channels incising through a broad fan lobe. This also accounts for the abundance of sediments that potentially represent overbank deposits and flood plains. Most notably, this environment accounts for the lateral variations in sediment types, and the maintenance of the general terrestrial/fluvial regime. The different components of the fan are represented predominantly through grain size, mineralogy and lithotype of the packages. Conglomerate beds in the area are indicative of the river systems incising through the fan, whereas the coarse sandstones form part of the fan lobe sediments.
The fan sediments within the inlet indicate that there was a substantial change in slope within the area at the time of deposition. Palaeocurrents indicate that the flow of the sediments within the fan is in a general NW direction (Figure 5.43), such that the apex of the fan must be to the south. No distinct features within the area indicate the presence of the fan apex such that the sediments are all part of the major fan lobe. This accounts for the broad, yet shallow nature of the channel sections within the sediments, as lobe profiles of channel have a shallow gradient and thus a broader shallower profile. The variation between the palaeocurrent measurements between the units within the area indicates that there are two different stages of the fan development; that is, the Basal Sediments from one lobe of the fan while the other set are from the overlying lobe (Figures 5.41 & 5.42).

The Unit 1 sediments are more indicative of a higher energy fan system, most likely a steeper-sourced fan. The calmer nature of the depositional environment from Unit 2 sediments represents a lower-energy system. This can be accounted for by the increase of the marine influence, by which the fan was transitioning from a continental shelf landform (lobe 1: Basal Sediments) to a pro-delta landform (lobe 2: Transition Sediments) during the transgressive systems tract.

Sporadic exposures of Marree Subgroup mudstones and shales occupy the inlet in the northeast, and occasionally Marree Subgroup sediments are exposed overlying the granites within the inlier. For the most part, these sediments grade from the Transition Sediments (Unit 2); however, in the far north east, they unconformably overlie Proterozoic crystalline basement.

In the inlet, the base of this unit is a succession of interbedded clast and matrix-supported conglomerates hosted in shaly sediments grading from the underlying Unit 2 transgressive lag sediments. These sediments are distinguished from the transgressive lag capping the Transition Sediments by a distinct variation in clast lithotype. The clasts that typically dominate the transgressive lag consist of lithologies sourced from both proximal and distal sources; they are highly rounded and, in some cases, polished. The clasts in the Marree Subgroup
conglomerate consist of sub-rounded quartz and sandstone, with some angular granite, all locally sourced. Not only is there a notable variation in attrition, lithotype and general provenance between these sediments, but also between the clast abundance and matrix type. For the most part, the Marree conglomerate is fine-grained, sandy and matrix-supported, and it often grades into a pebbly siltstone. Clasts are poorly-sorted, occasionally forming populated lenses within the typical conglomerate sediments. Shell hash is abundant, as are calcareous concretions and layers. These sediments are representative of the transition from the initial marine incursion into shallow marine environments. The lack of terrestrial fossils, such as the petrified wood fragments and leaf casts, common to the top of transition beds, accompanied with the shell hash, indicates the change from terrestrial- to marine-dominated environments. The abundance of clasts within the sediments indicates that the environment was still, in part, high-energy. For this sediment package, deposition occurred on a marine shelf, predominantly in the wave zone where the energy was high enough to transport these larger clasts.

Grading from the basal conglomeratic layers and occasionally overlying Proterozoic basement is the grey-green interbedded shales, silty-mudstones and fine-grained sandstones lithologically equivalent to the Marree Subgroup from Parabarana (chapter 2.5).

The shales infill small valleys around the northeast, unconformably overlie parts of the inlier, and overlie sandstones in a large mesa in the east of the inlier. These shales are also littered with large boulders interpreted as being ice-rafted dropstones. Within the shales are layers of fine-grained sandstones and siltstones. The siltstones form thin beds (typically <5 cm), interbedded with thicker beds of bioturbated shale (typically 10–15 cm), such that they form packages of intercalated sediments up to 1 m thick. The siltstones are greyish-pink, often containing an abundance of shell hash and shell casts. Mineralogy of these siltstones is dominated by feldspar and quartz with minor ferruginous inclusions, hosted within a calcareous matrix. The sandier layers are up to 30 cm thick and are most abundant within the sediments in the east of the inlier. Contacts at the top and base of the sandstones are sharp. These sediments contain abundant micro-scale cross-bedding, fine laminations and occasional convoluted bedding. On average, the dip of these beds is less than 10°—almost 20° below the average dip of the underlying Units 1 and 2. The abundant shell casts within these sediments are *Euspira reflecta*, a form of Aptian gastropod and groups of non-specific molluscs. The detrital component of the sandstones constitutes 70–80% of the rock and is typically dominated by polycrystalline quartz, muscovite and tourmaline with minor plagioclase grains. Surrounding the detritus is a very fine-grained, calcareous matrix that is widely replaced by slightly ferruginous cement. The ratio of detritus to matrix in this sandstone indicates that this is a silty-sandstone. Occasional conglomeratic lenses are also hosted within the shales, predominantly in the sediments in the east of the inlier. These lenses are up to 1 m thick, and contain angular to sub-angular quartz (3-4 cm), granite (2–6 cm) and metasediments. These lenses also contain an abundance of small grains of quartz, muscovite, biotite, chlorite, tourmaline, zircon and plagioclase in the conglomerate matrix.

Overlying the interbedded shales and sandstones in the inlet is a succession of yellow-brown mudstones and claystones (Figure 5.45). These sediments are best exposed within minor, incised drainage at the base of granitic rises in the northeast of the inlet. In the north, these sediments are also sub-cropping; typically covered by a thin transported overburden of sheetflow sediments (Figure 5.45). Profiles in the north expose these sediments conformably overlying the older Marree Subgroup, but sporadic rabbit Warren exposures in the northwest show that these sediments disconformably overlie the transgressive lag from the top of the Transition Sediments. The maximum thickness of this package is unknown; however, some of the rabbit Warrens could be traced down through this package to a depth of at least 3 m. Exposures of these sediments are traceable further into the basin immediately flanking the inlet. Mineralogy is dominated by zeolite, with sporadic thin beds (<3 cm) of kaolin. Disseminated gypsum and fragmented, hardpan regolith carbonate accumulations (predominantly dolocrete) are abundant within these sediments. Pods of these sediments have been indurated by goethite and haematite cements (Figure 5.45).
Figure 5.45. Exposures of Marree Subgroup sediments, with both images showing the landsurface hosting moderately to highly weathered shale (i: 368229mE / 6694247mN; ii: 370737mE / 6695664mN).

Fossils, grain size and sedimentary structures all indicate that marine environments dominate for the deposition of the interbedded shales, siltstones and sandstones. The carbonaceous grey-green shales are typically shallow marine deposits described from elsewhere in the area. The siltstone-shale intercalated packages are indicative of periodic progradation-retrogradation cycles. The silty units represent progradation, in which the shoreline migrated seaward as sediment supply exceeded the accommodation space in the basin. The seaward migration resulted in the depositional environment changing to slightly higher energy, i.e. to an environment most likely closer to the shoreline. The silty nature of these sediments still indicates that the environment remained relatively low-energy, while the shell hash and casts support it still being marine influenced but not necessarily marine dominated. The abundance of feldspar indicates that the sediments are also proximally sourced, as feldspar (particularly k-feldspar) would be expected to weather out of depositional systems very quickly. The marine influence and calm nature of the depositional environment for these sediments is most likely indicative of estuarine environments, where marine and terrestrial influences both contribute to sedimentation, and where energy is relatively calm. The shales in the intercalated packages represent the retrogradation, where sediment
supply did not exceed accommodation. The driving force behind this cyclic pattern might be an increase in sediment supply, eustatic fluctuations or changes in accommodation space. While the sea level throughout the Aptian varied (see chapter 2), these changes were not significant enough to be driving cyclic progradation retrogradation at the basin margin. Variations in rates of sediment supply would not typically produce such regular or sharp ‘cyclic’ sediment patterns, with such repetitive mineralogy. However, periodic changes in the relative base level of the basin at the margins could result in cyclic patterns. Such changes are most likely driven by syn-depositional tectonism causing uplift and down throw. This supports the sharp nature of the boundaries between the sequences in the package as tectonic changes are typically rapid, and also the repetitive nature of the mineralogy in successive sequences. There is evidence in the area for activation and reactivation along fault traces post-Mesozoic, such that it is likely that this was also occurring during the Mesozoic. The overall depositional environment interpretation for these sediments is shelf environments reverting to estuarine environments.

The sandstone layers within the shales represent a substantial, at least localised, seaward progradation. Whilst coarser than the other sediments within this unit, the sandstones are still very fine-grained, and exhibit marine signatures. This is notably a distinct tidal influence as represented by the cross-bedding and sporadic ripple marks. The cross-bedding is small and very shallow, indicating that the tide effect is present but not necessarily of high energy. The detrital gain size and relatively large component of silt in the sediments is characteristic of marine ‘wacke’ sediments often associated with calm, coastal plains where the marine environments influence rather than dominate sedimentation. The molluscs and gastropod fossils are both characteristic of species that live in both fresh and saline waters. For the most part, these fossils have been preserved intact, such that they have not been reworked by higher energy or destructive processes. These sediments are indicative of the seaward portion of a low-energy distributary channel where non-destructive tides dominate. The sandstone layers revert to the shales in a sharp contact, suggesting that the onset of the marine conditions was a result of a sudden change in base level.

The irregularly-distributed lenses of angular clasts and lithic fragments represent a terrestrial influence in the marine environments. The clasts and fragments are quite large and thus are indicative of a high-energy depositional environment. However, the clasts are very angular, and thus must be proximally sourced. The abundance of biotite and chlorite also supports this, as they are very unstable minerals that would normally have been otherwise weathered out of the sediments. These lenses are terrigenous debris flows shedding from the surrounding highlands. The mud and claystone sediments are indicative of a slightly deeper, lower-energy environment, such as a lower-shelf deposit where the tidal and terrestrial influences are almost negligible.

Overall, the interbedded shales through to the claystones are representative of a lateral equivalent of a basin-wide high-stand systems tract. The shale package atop the transgressive lag represents a flooding event in which sedimentation within the inlet was taken over by marine environments. The transition from the conglomeratic transgressive systems tract at the base of the Marree Subgroup to the shales is small, occurring over about 30 cm. This indicates that the onset of the marine environment was rapid—that there was a sudden change of base-level. The varying nature of the sediments and depositional environments within the Marree Subgroup sediments in the inlet is a product of subtle changes within the local base level. Exposures of the conglomerate beds and clasts within the unit were not continuous enough to determine palaeoflow directions.
<table>
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<th>Unit</th>
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<tr>
<td>Marree Subgroup</td>
<td>Yellow-brown mudstones and claystones; grey-green shales; brown, sandy mudstones; flattened quartz pebbles, shell fragments and loose, coarse-grained sand.</td>
<td>Weathered feldspar, monocrystalline quartz, muscovite. Fragments of granite, mafics and pegmatite. Disseminated gypsum. Sporadic selanite veins.</td>
<td>Exposed within incised drainage along the northeastern rangefront disconformably overlying granites; and within the inlier overlying sandstones, and disconformably overlying gneissic units. Flattened pebbles and shell fragments from shorelines around the base of small granitic rises and in some places around the edges of the granites in the inlier.</td>
<td>Cone in cone dewatering structures.</td>
</tr>
<tr>
<td>Transition Sediments</td>
<td>Coarse to medium-grained, buff-coloured, calcareous sandstones; medium-grained pale brown sandstones with minor pebbly layers, ferruginous, fine to medium-grained sandstones; clast-supported conglomerates.</td>
<td>Sandstones: Monocrystalline quartz 90%. Feldspar &lt;10% (can be up to 35% in some beds). Muscovite &lt;5%. Pyrite &lt;5%. Minor biotite, tourmaline, granitic clasts and quartz clasts.</td>
<td>Exposed along the edge of the ranges in uplifted mesas, in incised channels and lapping up onto the granitic margins of the inlier. Typically disconformably overlying granites. Some sporadic exposures within the plains. Pods of sediments up to 2 m wide and less than 30 cm high preserved within the inlier unconformably overlying granites. Exposures indicating succession thickness of at least 25 m.</td>
<td>Highly silicified for the most part. Some layers of ferruginisation. Herringbone and trough cross-bedding.</td>
</tr>
<tr>
<td>Basal Mesozoic</td>
<td>Pebbly conglomerates; coarse to very coarse-grained sandstones with pebbly beds throughout.</td>
<td>Conglomerates: predominantly re-worked Adelaidean clasts, quartz and quartzite pebbles. Minor large, rounded to sub-rounded volcanic and granitic clasts. Calcareous layers throughout.</td>
<td>Exposed along fault zone controlling major drainage channel, in small surface exposures.</td>
<td>Highly-rounded clasts up to 22 cm long. Matrix effervesces in HCl.</td>
</tr>
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5.5. Field site #4: Prospect Hill
Prospect Hill is in the far north of the Mt Babbage Inlier, straddling the dog fence at the Moolawatana and Mt Hopeless property boundary, due west of White Water Well and Bore. This field site is located <1 km south of the Marree Subgroup glendonite exposure type-section (De Lurio & Frakes 1999) in the ranges and immediately flanking basins. This area is host to the Prospect Hill Cu district, which incorporates the Prospect Hill Cu mine (Figure 5.46).

![Figure 5.46 Quickbird imagery (courtesy of Primary Industries and Resources South Australia) of Prospect Hill.](image)

5.5.1. Geomorphology and Surficial Geology
The morphology of the area is controlled primarily by the E-W striking Emu Hill and Prospect Hill Faults; and localised NW-SE faults, possibly splays associated with the larger faults (Figure 5.47). These faults control the extent of uplift in the area, exposing steep, elongated ridges of the basement and Adelaidean metasediments (Figure 5.47). Surrounding the ridges and valleys are relatively flat low-lying plains and undulating rises. Surficial geology within the Prospect Hill area is dominated by in situ regolith. This includes the slightly-weathered granites from the RCM; the slightly to moderately-weathered tillites and metasediments from the Adelaidean Metasediments; and the moderately-weathered, Mesozoic sandstones and conglomerates.
5.5.2. Mesozoic Sediments

Throughout the inlier, mesas and pods of Mesozoic sediments overlie the basement, and are exposed within the low-lying basins (Figure 5.47 & 5.48). These exposures are dominated by moderately to highly-weathered, coarse-grained to pebbly sandstones; small (less than 3 cm thick) beds of calcareous siltstones; and poorly-sorted coarse to medium-grained sandstones. Sedimentary structures are predominantly limited to large-scale trough cross-bedding and tabular cross-bedding which, in places, appear to be anti-dunes (but the high degree of weathering impedes distinguishing between the two). For the most part, the remnant exposures have been indurated by siliceous cements. Minor goethite and hematite accumulations form a slight yellow-pink staining in some layers (Figure 5.48 i & ii). Pods of ferruginous cementation also occur around the top of the profiles (Figure iv & v). Detritus in all of the sediments is dominated by sub-angular to sub-rounded quartz, with minor micaceous and mafic components. Photomicrographs indicate that quartz grains are both mono- and poly-crystalline aggregates, with monocry stalline grains dominating the younger sediments (Figure 5.49). Micaceous components are predominantly muscovite, with minor phengite and biotite. In the mesas in the Prospect Hill Valley, the ratio of detritus to matrix in the sediments varies greatly throughout profile. Typically, the sediments at the base of the unit are dominated by silty quartz arenites; however, upwards in the profile the abundance of the silt fraction decreases dramatically, such that the sediments are quartz arenites. This change also corresponds to a general increase in grain size as the silt fraction decreases. These coarse-grained and pebbly sequences are lithologically similar to the sediments from the Pimples within Paralana Valley (compare Figures 5.48 i & ii with 5.18 & 5.19). The morphology of the mesas from Prospect Hill also resembles the Pimple remnants from Paralana Valley.

Figure 5.48. Mesozoic sediments from Prospect Hill: coarse-grained and pebbly sandstones—(i) and (ii) 351468mE / 6703614mN; (iii) 354458mE / 6704006mN; (iv) ferruginised sandstone clasts and sub-crop (351518mE / 6703819mN); and (v) ferruginous quartzite and barite veinlets (354398mE / 6704209mN)
Small exposures of the Mesozoic sediments from within the basin to the NE of the inlier are dominated by highly ferruginised, coarse-grained quartzose sandstones, which in places have been metamorphosed to quartzites (Figure 5.49 i & ii).

Throughout these exposures, faults and fault zones have been indurated by authigenic barite cements such that little baritic veinlets have formed (Figure 5.49 iii & iv). Depth to basement throughout this area is relatively shallow, with channel profiles indicating in places that the Mesozoic sediments in this area are less than 1 m thick. Off the inlier to the north, where Marree Subgroup sediments are prevalent, the thickness of the Mesozoic sediments increases rapidly to tens of metres.

![Photomicrographs x-polar views: quartzite; barite veinlet](image)

Figure 5.49. Photomicrographs x-polar views: quartzite; barite veinlet (354458/6704006): (i) and (ii) interlocking and fused grain boundaries of recrystallised mono and polycrystalline quartz; (iii) and (iv) ‘veinlet’ of barite indurated quartzite. Barite cement (blue) infilling around the recrystallised quartz. Minor cryptocrystalline chalcedony throughout; and (v) and (vi) grain boundaries beginning to show signs of fusing, some recrystallised monocrystalline quartz, majority monocrystalline quartz grains. Goethitic cement with small quartz grains and recrystallised quartz.

In places around Prospect Hill the unconformity between the Mesozoic and the basement is exposed in profile. These exposures highlight the intense degree of weathering of the basement immediately underlying the Mesozoic (Figure 5.50). The weathered basement is similar in appearance to the fine-grained, grey silty and
Figure 5.47. Surface geology of the Prospect Hill area. Legend available in Appendix 5.
shaly units at the base of the Parabarana Sandstone-type section from Parabarana (compare Figures 5.50 & 5.10). However, the weathered basement lacks competency and the sedimentary structures common to the Parabarana Sandstone. Furthermore, the weathered basement is predominantly composed of highly-weathered smectite and illite, neither of which is typical of the Parabarana Sandstone. Profile exposures of the weathered basement highlight the gradational nature of the intense weathering from the relatively fresh basement below (Figure 5.50).

![Image of weathered basement and sedimentary structures](image)

Figure 5.50. Exposures of Mesozoic sediments and the Mesozoic-Basement unconformity at Prospect Hill (366492mE / 6703120mN). (Qtz = Quartz; Plag = Plagioclase)

### 5.6. Field site # 5: Moolawatana and Terrapinna

The Moolawatana field site encompasses the area surrounding the Moolawatana homestead and extends up the northeast margin of the Mt Babbage Inlier and to the opening of the Terrapinna Corridor (Figure 5.51). Terrapinna incorporates sporadic locations throughout the Terrapinna Corridor, none of which is big enough to be classified as individual field sites; yet they display important relationships with the Mesozoic sediments and the landscape. This area incorporates sections from both the Mt Babbage and Mt Painter Inlier, and a comparison between the sediment distribution on and around both inliers.
Chapter Five: The Northern Flinders Ranges

Figure 5.51. Quickbird Imagery (Courtesy of Primary Industries and Resources South Australia) of Moolawatana.

Exposures within the Moolawatana-Terrapinna field area incorporate several exposures of the contrast between the basinward and marginal sediments. Exposures around the northeast of Moolawatana are also not structurally controlled. While the sediments are perched on blocks that have been uplifted by the regional tectonism, on the scale of individual exposures they are unaffected by the tectonism. Although this provides an opportunity to view the exposures within their approximate original landscape context, as these exposures are not structurally controlled they are often subtle. These sediment exposures in many cases preserve their relationship with the pre-Mesozoic unconformity, making them very important exposures in terms of the Mesozoic landscape reconstruction.

By contrast, the majority of sediment exposures throughout Terrapinna are structurally controlled and are faulted, overturned and exhumed. These sediments are typically highly-weathered or have been altered either chemically or physically, providing not only a contrast to the sediments in the NE but also an insight into the pre-Mesozoic landscape history.

Previous studies in the area have identified at least two different packages of Mesozoic sediments, both of which have not been recognised elsewhere (Alley & Sheard unpublished). Lithological analysis and palynology of the sediments highlighted that the sediments are not concordant with the Parabarana Sandstone; however, they are of similar age. Relic Mesozoic landforms have also been recognised within the area.

5.6.1. Structure and Geomorphology

The Moolawatana field site encompasses the northeast extent of the Mt Painter Inlier and the eastern extent of the Mt Babbage Inlier. It also encompasses the opening of the Terrapinna Corridor and the plains that surround the Moolawatana homestead.

The area is morphologically defined by the structures that have formed the Terrapinna Corridor. This is primarily controlled by the Mt Fitton Anticline, an approximate E-W striking open to obtuse fold and associated thrust faults. The most significant of these thrust faults is the Birthday Well Fault, which controls the southern extent of the
Mt Babbage Inlier (Figure 5.52). The reverse and thrust faults along the Mt Babbage Inlier are interpreted to be a brittle expression of the folding. The Mt Fitton anticline deforms Adelaidean sediments, indicating that the structure is at least post Proterozoic. Exposures of the faults show that they deform Mesozoic sediments, but not the overlying Eyre Formation sediments. Furthermore, the Eyre Formation sediments are relatively flat-lying throughout the area, further supporting a negligible impact from this deformation. This constrains the most recent activation of this deformation to pre-Eocene rather than post-Mesozoic. The effects of this phase of deformation are evident throughout the Mt Babbage Inlier, in which small faults orientated similarly to the Birthday Well Fault incise the east of the Mt Babbage Inlier (Figure 5.52).

The area north of the Mt Painter Inlier is characterised by a stepped, fault-controlled, rangefront (Figure 5.52). The Mt Painter Fault, an approximate E-W striking high-angle reverse fault, displays at least three stages of reactivation preserved as range bounding palaeo-terraces (Figure 5.52). These terraces are in places bisected by gorges that incise into the rangefront. Knickpoints and strath terraces within the gorges preserve the episodic tectonism and their interaction with the geological substrate. These terraces represent the stream response to the tectonism, as the stream incises back into the rocks upon uplifting of the mountains. The presence of the strath terraces indicates that the rate of uplift exceeded the rate of stream incision in the uplift events. In the highest terrace, the gorge is narrow and has up to three strath terraces surrounding the channel. These channels are up to 1 m wide and up to 3 m deep. The most extensive gorge is the Terrapinna Gorge, which penetrates both the Mt Painter and Mt Babbage Inliers, along the N-S trending Birthday Well lineament.

Figure 5.52. Block diagram of a section from the northern side of the Mt Painter Inlier in the Terrapinna Corridor. Fault-controlled, stepped exposures of the RCM. Quaternary sediments cover the floor of the corridor, with sporadic mounds and low-lying exposures of Mesozoic sandstones and conglomerated.

The northern margin of the corridor is the steep rangefront that forms the southern margin of the Mt Babbage Inlier. This rangefront is also characterised by stepped expression; however, the steps are less prominent and the rangefront generally not as steep. The interior of the corridor is characterised by broad undulating rises that form the axis of the Mt Fitton Anticline and broad flat-lying plains in the north and southwest in the axis of the Billy Springs and Mt Freeling synclines respectively. Large broad alluvial channels flow through the base of the corridor.
Surrounding the Moolawatana homestead, around the northeast margins of the Mt Babbage Inlier, are rounded, granitic low hills and hills. These hills are composed of highly-polished granites similar to the exposures in the edges of the Terrapinna Corridor. These hills and rises are terminated by a relatively smooth boundary that is intermittently broken up by small embayments and inlets (Figure 5.53). These embayments are typically smaller versions of the Mt Babbage Inlet, characterised by small amphitheatres of granitic rises encasing the low-lying basin sediments. The small embayments typically bound the near E-W trending Birthday Well fault set traces.

The landscape surrounding the inliers near the Moolawata Homestead at the mouth of the Terrapinna Corridor is more subdued than the rest of the study area. Here, the flanking basins are juxtaposed against the inliers, in both sedimentary and tectonic unconformities. Landforms within this part of the basin include undulating rises and planes of Mesozoic, Palaeogene and Quaternary sediments, and tilted cuestas of Palaeogene sediments. The most prominent of these includes large alluvial plains and an alluvial fan that forms as the Terrapinna Creek spills out into the basin where the Mt Fitton anticline dissipates.

This area highlights the extremities of disharmonic deformation throughout the area. Unlike the faulted and folded mountains in the ranges from the inliers, deformation within the basins around this area is often subtle. Small mesas in the basin in the northeast mark out fault traces, alluvial fans form along shallow breaks in slope where faults have minimal surficial exposure, and larger channels form along the approximate extension of faults that cross-cut the inliers.

Figure 5.53. Terrapinna Corridor: (i) stepped expression along the Mt Painter Inlier northern rangefront, with the corridor base and southern rangefront of the Mt painter Inlier in the forefront of the photo; (ii) base of the corridor (photo courtesy S. M. Hill); and (iii) gorge exposure with knickpoint and strath formations.
5.6.2. Surficial Geology

As the surficial geology varies greatly throughout the area, for simplicity it has been represented in table 5.6.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Landforms</th>
<th>Vegetation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slightly-weathered RCM and MPS</td>
<td>Slightly-weathered, highly-polished granites, gneisses and schists. Exposed pegmatite and amphibolite veins.</td>
<td>Erosional rises, hills and mountains</td>
<td>Eremophila spp., Maireana spp.</td>
<td>Mt Babbage and Mt Painter Inliers</td>
</tr>
<tr>
<td>Slightly-weathered Adelaidean Metasediments</td>
<td>Slightly to moderately weathered quartzite, tills and psammitites</td>
<td>Erosional plains, hills and mountains</td>
<td>Maireana spp.</td>
<td>Terrapinna Corridor and southern margin of Mt Babbage Inlier</td>
</tr>
<tr>
<td>Moderately-weathered sandstones and conglomerates</td>
<td>Moderately weathered, interbedded, coarse-grained to pebbly, quartzose sandstones and sub-angular to rounded conglomerates with a shaly to silty matrix. Minor angular quartz and sandstone clast transported overburden</td>
<td>Erosional plains and rises, depositional plains, incised drainage and playa plains</td>
<td>Eremophila spp., Maireana spp., Atriplex spp., Melaleuca glomerata and Solanum ellipticum</td>
<td>Lapping up onto the N margin of Mt Babbage Inlier, in the plains and rises surrounding Mt Babbage HS</td>
</tr>
<tr>
<td>High-weathered shale and siltstones</td>
<td>Grey-green, carbonaceous shales and mudstone coloured clayey siltstones, with sporadic exotic clasts. Minor brown fine sand and silt</td>
<td>Depositional plains, erosional rises, drainage depressions &amp; valleys</td>
<td>Maireana spp. Solanum ellipticum &amp; Atriplex spp.</td>
<td>Infilling small valley of north Mt Babbage Inlier, exposed &amp; sub-cropping in the basin</td>
</tr>
<tr>
<td>Beach remnants</td>
<td>Rounded and flattened quartz clasts, shell hash, angular to sub-angular quartz and plagioclace clasts, overlying highly-polished, slightly-weathered granitic exposures</td>
<td>Erosional plains, rises, low hills and depositional plains</td>
<td>Eremophila spp., Maireana spp. Sporadac Acacia spp.</td>
<td>Along the NE margin of the Mt Babbage Inlier</td>
</tr>
<tr>
<td>Highly silicified sandstone (Eyre Fm.)</td>
<td>Highly silicified, high-weathered, pink-grey-buff, coarse-grained sandstone and pebbly sandstones, dark-purple and red ferruginous staining. Rounded pisolith nodules stacked together</td>
<td>Shallow rises and undulating plains</td>
<td>Small forbs and grasses</td>
<td>Basinward fault controlled mesas NE of Mt Babbage Inlier</td>
</tr>
<tr>
<td>Aeolian</td>
<td>Red-brown, fine-grained sands and silts, white-buff, quartzose, coarse to fine-grained sands. Winnowed pebbles throughout sand plains. Ventifacts clasts throughout basin profiles</td>
<td>Small, localised plains and wind rams.</td>
<td>Not specified</td>
<td>Minor component of most landforms, sporadic plains in the NW</td>
</tr>
<tr>
<td>Alluvium</td>
<td>Fine to coarse-grained, rounded quartzose sands, lithic pebbles (typically less than 2 cm), some sandstone exposures. Minor clasts of angular quartz and granite (typically &lt;4 cm)</td>
<td>Alluvial plains, fans, depositional plains and eolian drainage</td>
<td>Maireana spp. Atriplex spp. Minor Acacia spp.</td>
<td>Throughout the inlier, and in the surrounding basins</td>
</tr>
<tr>
<td>Channel Sediments</td>
<td>Grey-brown, sub-rounded to rounded, coarse-grained, quartzose sands, lithic pebbles, rounded quartz, granite, sandstone clasts. Minor exposures of granite, sandstone and conglomerates.</td>
<td>Active ephemeral channels</td>
<td>Eucalyptus camaldulensis, Acacia spp.</td>
<td>Narrow gorge-like channels through the inliers, and broad-based channels surrounding</td>
</tr>
<tr>
<td>Colluvium</td>
<td>Angular to sub-rounded granite, plagioclace and quartz clasts, minor red-brown sand &amp; silt</td>
<td>Rises, thin veneers on mountains &amp; hills</td>
<td>Eremophila spp.</td>
<td>Throughout the inliers, surrounding breaks of slope and at the base of basinward mesas</td>
</tr>
<tr>
<td>Sheetflow</td>
<td>Angular to sub-rounded quartz, granite fragments, sporadic exposures of sandstones</td>
<td>Erosional plains, rises, low hills and depositional plains</td>
<td>Eremophila spp., Maireana spp. Sporadac Acacia spp.</td>
<td>Basins surrounding the inliers; in part throughout the Terrapinna Corridor</td>
</tr>
</tbody>
</table>

Table 5.6. Summary of the surficial geology of the Moolawatana field site.

5.6.3. Mesozoic Sediments

Mesozoic sediments in the area are composed of a combination of fluvial sandstones, beach sediments, marine mudstones and shales.

Throughout the Terrapinna Corridor, exposures of the Mesozoic are sparse. The most prominent exposures are preserved around the mouth of the corridor where sandstones and conglomerates have been uplifted or exposed within the larger channels. These sediments are dominated by two different packages, including intercalated coarse- to medium-grained sandstones and sandy siltstones; and interbedded pebbly sandstones, pebbly conglomerates and clast-supported conglomerates. The sandstones and siltstone package are best exposed around the south of the homestead, in the rubbish tip and the adjacent tributary channel of Moolawatana Creek.
Here, a 10 m high exposure of the Mesozoic defines the channel margin. The profile of the sediments is characterised mostly by coarse-grained quartzose sandstones, with thin bands and beds of sandy siltstones. Some of the layers, particularly those of a finer grain, are calcareous (effervescing with dilute HCl), while many beds in the profile are partially silicified (Figure 5.54 i). Large-scale trough cross-bedding (up to 1 m wide) is abundant in the package, as are pebbly lenses and beds. Thin-section analysis of the sediments indicates that they are predominantly quartz-rich, poorly-sorted sandstones, with minor muscovite, zircon and sporadic biotite. Attrition of the grains and clasts is generally uniform, sub-rounded and spherical in shape. In the northwest of the corridor around Birthday Well, these sediments sporadically crop out at the base of the corridor and are overturned against the granites in the Birthday Well Fault.

These sediments are lithologically equivalent to the cyclic sequences from the Transition Sediments in the Mt Babbage Inlet further north. Anthropogenic features such as induration and weathering grade are slightly different to that of the typical surficial features of the sediments in the inlet; however, these sediments are in a different contemporary landscape position and thus have experienced a different exposure history.

The interbedded conglomerates and pebbly beds are best seen in exposure around the woolshed and along the Moolawatana-Mt Freeling track in small vertical profiles (Figure 5.55). These sediments consist of a pebbly conglomeratic sequence, dominated by rounded and sub-rounded quartz clasts (85%) and sub-rounded granitic and volcanic clasts hosted within a silty, occasionally calcareous matrix. The clasts are typically well sorted, and large-scale bedding (up to 20 cm sets) is well-preserved. The pebbly sandstones are quartz-dominated, consisting of angular, very coarse-grained quartz sand grains, and sub-rounded quartz clasts, typically <2 cm with sporadic petrified wood clasts (Figure 5.55). In the pebbly sandstones, herringbone cross-bedding is prevalent. These exposures are lithologically similar to the transitional lag sediments from around the Mt Babbage Inlet; however, the clasts are typically smaller and slightly more rounded.

Figure 5.54 Exposures of the pebbly sandstones and conglomerates and conglomerates (366131mE / 6687804mN): (i) pebbly sandstones off the Moolawatana-Mt Freeling track; and (ii) and (iii) exposure of conglomeratic saprock. Not book for scale is 8 x 15 cm.
Throughout the corridor, small mounds of Mesozoic sediments are exposed protruding through the Quaternary sediments in the low-lying parts of the landscape. These exposures are typically <3 m high, and up to 20 m wide. The sandstones and conglomerate exposures are typically highly indurated, with predominantly haematitic ferruginisation, and silicification in some beds, contributing to their preservation within the landscape. Sediments are predominantly very coarse-grained sandstones that are interbedded with pebbly sandstone beds and minor conglomerate beds. These mounds are typically surrounded by unconsolidated sands, with sub-cropping and poorly-exposed sandstones. A prominent feature of these exposures is abundant accumulations of petrified wood fragments and clasts (Figure 5.56). The wood clasts are predominantly trunks stems and branches, with no evidence of foliage preserved (Figure 5.57).
Figure 5.56. Pebby sandstone exposures, with clasts of petrified wood fragments throughout. Photomicrograph taken of a portion of the sandstone indicating a quartz dominance in the sediments, with minor lithic fragments throughout.

These sediments are typically exposed along the Birthday Well Thrust Fault in small valley and channel profiles that incise into the southern rangefront of the Mt Babbage Inlier. These exposures are dragged up into the fault, such that the sediments abutting the inlier are overturned with the bedrock overlying them. Fluids have percolated through these sediments, leaving them partially indurated and dominantly siliceous. In these profiles, flat-lying Eyre Formation ‘jelly-bean’ conglomerates overlie the Mesozoic.

Figure 5.57. Schematic representation of the overturned Mesozoic and the relationship between the basement and the overlying Eyre Formation, with photomicrograph of the Mesozoic sandstones. Mineralogy is dominated by quartz, with minor lithics. Attrition is highly variable and often hindered due to fluid percolation. (360880mE / 6683672mN)

Small mounds of the sediments surround the abandoned Mt Fitton Homestead (Figure 5.57). Here, three separate exposures, one to the east, west and one across the northwest, crop out through the alluvial plains and within the fan shedding of the southern margin of the Mt Babbage Inlier.
Chapter Five: The Northern Flinders Ranges

Figure 5.58. Low-lying exposure of coarse-grained and pebbly sandstones cropping out in the plains surrounding the abandoned Mt Fitton homestead (featured in the background) near Birthday Well (360628mE / 6683538mN).

In the exposures to the west of the homestead, the Mesozoic sediments are overlain by clasts and remnants of Eyre Formation ‘jelly-bean’ conglomerates. The plains surrounding these Mesozoic and the Eyre Formation exposures are littered with the ‘jelly-beans’.

Mesozoic exposures around the north of Moolawatana are subtle within the landscape. Despite this, these sediments preserve some of the most important exposures within the area.

Previous studies in the northern Flinders Ranges have focused on some of these packages, particularly small exposures of beach deposits interpreted to be shorelines (Frakes et al. 1987; Frakes & Bourne 2001; Alley & Sheard unpublished). These deposits feature prominently in shoreline interpretations and Cretaceous inland sea interpretations.

Remnants of shorelines lap onto the surrounding granitic rises and hills in a small embayment off the northeast side of the Mt Babbage Inlier. Exposures around the small inlets include clasts of rounded to sub-rounded quartz pebbles and shell hash that are mixed in with angular to sub-angular quartz, plagioclase and granitic clasts. The angular to sub-angular clasts are all locally sourced, with the quartz shedding from adjacent quartz veins, the plagioclase weathering out of the bedrock, and fragments of granitic bedrock. The rounded to sub-rounded clasts and the shell hash only partly extend up the rises.

Besides the shorelines, a basal sediment package of coarse-grained sandstones has been recognised throughout the area (Alley & Sheard unpublished). Palynology of these sediments identified them as not being concordant with the Parabarana Sandstone or any other previously classified sediments throughout the area. Yet, the recognition of these sediments did not include an assessment or analysis of the sediments or their significance in the landscape. For the most part, these sediments are typically characterised by sandstones lithologically equivalent to the sandstones from the previously-described rubbish tip exposure, and the packages from the Basal Sediments within the Mt Babbage Inlet. These sediments (both lithologically and in terms of interpreted palaeo-landscape setting) fit in with the fan interpretation.

Similar shorelines have been recognised in the area and were noted as a feature of the Aptian to Albian marine incursion. Importantly, these shorelines define a palaeolandscape, where Proterozoic granites formed small islands, within an embayment. Together, these small islands represented an archipelago system that stretched from at least the Moolawatana homestead to the Mt Babbage Inlet.
Table 5.7 Palaeocurrent analysis of the Moolawatana / Terrapinna Corridor.

<table>
<thead>
<tr>
<th>Location</th>
<th>Structure</th>
<th>Flow Azimuth (°)</th>
<th>Flow &amp; MRD</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubbish Dump (vertical profile / logged section)</td>
<td>Tabular cross-bedding</td>
<td>139, 175, 150, 088, 079, 089, 164, 172, 174, 175, 091, 080, 140, 083, 088, 094, 176, 157</td>
<td>Two layers</td>
<td>Uni-axial: (a) 87° (b) 162° Swath: (a) 15°; (b) 27° CSD: (a) 0.1; (b) 0.2 CV: (a) 0.00; (b) 0.03</td>
</tr>
<tr>
<td>Terrapinna #1 360663 / 6683465</td>
<td>Tabular cross-bedding</td>
<td>280, 274, 280, 261, 285, 286, 259, 290, 285</td>
<td>Uni-axial flow: 278°</td>
<td>Swath: 24° CSD: 0.2 CV: 0.02</td>
</tr>
<tr>
<td>Terrapinna #2 366300 / 6687822</td>
<td>Tabular cross-bedding</td>
<td>297, 035, 302, 299, 298, 291, 029, 043, 300, 297, 298, 028, 027, 296, 047, 039, 044, 029, 301, 289, 297</td>
<td>Bi-axial flow: (a) 297° (b) 34° Swath: (a) 13°; (b) 17° CSD: (a) 0.1; (b) 0.1 CV: (a) 0.00; (b) 0.01</td>
<td></td>
</tr>
<tr>
<td>Archipelago</td>
<td>Tabular cross-bedding</td>
<td>076, 079, 197, 300, 080, 315, 193, 192, 301, 314, 081, 084, 189, 080, 192, 301, 320, 188, 071, 078, 069, 165, 323, 081, 297, 285, 079, 189</td>
<td>Tri-axial flow: (a) 078 (b) 187 (c) 306 Swath: (a) 15°; (b) 32°; (c) 38° CSD: (a) 0.1; (b) 0.2; (c) 0.2 CV: (a) 0.00; (b) 0.01; (c) 0.02</td>
<td></td>
</tr>
<tr>
<td>Moolawatana #1 372292 / 6696452</td>
<td>Tabular cross-bedding</td>
<td>250, 245, 239, 267, 251, 254, 250, 231, 244, 250, 255, 251</td>
<td>Uni-axial flow: 249°</td>
<td>Swath: 38° CSD: 0.1 CV: 0.01</td>
</tr>
</tbody>
</table>

5.7. Discussion
The landscape of the northern Flinders Ranges is dominated by two basement inliers comprised of a series of mountains, hills and rises surrounded by low-lying plains covered by extensive colluvium, alluvium and aeolian dunes and plains that form the west of the Frome Embayment. Within this landscape are scattered remnants of Mesozoic sediments from the Eromanga Basin. These include elevated ridges of Mesozoic sandstone uplifted in large mesas and ridges; subtle exposures of highly-weathered, poorly-consolidated shales in the floors of the surrounding basin; and shorelines preserved around granite rises and in drainage profiles that have incised through regolith profiles to expose Mesozoic saprock. In some places these sediments have been exposed in the landscape since the Mesozoic, preserving evidence of the geological history since deposition. Elsewhere, these sediments have been uplifted, etched and eroded such that they are now exposed within the landscape. These sediments are used as the basis for the Mesozoic palaeolandscape reconstruction.

5.7.1. Marine Incursion
The youngest Eromanga Sediments in the northern Flinders Ranges are the shales, siltstones and beach sediments from the Marree Subgroup. These sediments are scattered (and, in places, elevated) throughout the landscape. The Marree Subgroup also forms much of the landsurface surrounding the Mt Babbage Inlier in the north, either exposed as moderately to highly-weathered saprock or subcropping below the fans and colluvium shedding of the ranges.
Remnants of beach pebbles and shells have been preserved lapping up onto and haloing small bedrock rises around the Moolawatana homestead. While these sediments have accumulations for modern regolith development, they still preserve the basic integrity of a shoreline lapping up onto the ranges. The haloing of some rises indicates that the shoreline formed around the rise, such that the bedrock was exposed as a small island at the time of marine incursion. The small archipelago in this area indicates that there was at least some relief in the landscape around the Mt Babbage Inlier area at the time of Marine sedimentation. The area to the north of the homestead, where these sediments have barely been affected by the contemporary tectonism, such that the remnants of the shoreline have been left relatively intact, is a landscape position similar to initial deposition. Other beach sediment exposures are found in the Mt Babbage Inlet overlie of uplifted mesas of Basal Eromanga sediments. These sediments have been preserved within the landscape as the uplift has limited accumulations of modern regolith attributes. Preservation of such delicate (attributed in the landscape for over 90 Ma) indicates that weathering and erosion has been minimal.

Other elevated deposits of the Marree Subgroup in the Mt Babbage Inlier overlie high mountains. These accumulations are dominated by the typical Bulldog Shale Equivalents, indicating that they are the grey-green shales and mudstones deposited in a shallow to mid-marine environment. These sediments, along with other similar exposures at Parabarana and in the Terrapinna Corridor, indicate that the marine incursion in the area exceeded a marginal marine / coastal plain deposit that would be expected around the margin of the basin. However, these sediments are the limits of the Marree Subgroup sediments in the area. While the exposures of the shales may be limited to the contemporary distribution, the presence of the delicate shorelines and abundant Marree Subgroup exposures within the area, despite poor lithification and general friable nature of the sediments, indicates no substantial erosion. From this, it is interpreted that the contemporary exposures demonstrate the approximate extent of marine sedimentation in the area, and that the nature of the sediment profiles is most likely a reflection of the syn-deposition landscape. The shales are indicative of a shallow marine environment. These sediments are found butting up against the ranges in the south and around the northern edge of the Mt Painter Inlier. These factors all account for there being elevation in the landscape syn-deposition. The sediments perched on the Mt Babbage Inlier indicate that the uplift was not present in that area syn-deposition. The contemporary elevation, particularly of the large pod of Shale atop the Mt Babbage Ridge, indicates significant uplift post Marree Deposition. This indicates that the major elevation within the landscape was confined to the Mt Painter Inlier, with some small rises and low hills within the Mt Babbage Inlier as indicated by the archipelago near Moolawatana.

The abundant glauconite in these sediments supports the marginal marine environment. Glauconite also indicates that the sediments are the result of slow deposition in sulphatic-charged waters. The sulphatic waters are attributed to the decaying of abundant carbonaceous materials, remnants of which are preserved in places within the sediments.

The bevelled surface that dominates the uplifted areas of the ranges in the Mt Babbage Inlier is interpreted as being the base level at this time as it has been planed off, is exposed within the landscape and forms the unconformity between the marine and basement. In places, where basal Mesozoic sediments have been deposited, the base level marine sediments conformably overlie the sandstones. This surface corresponds to a wave-cut platform preserved within the landscape located near the beach pebbles, while the shorelines are preserved around Gun Powder Bore. The platform sits at the edge of the bevelled terrace, in a zone interpreted as being a small extension of the archipelago.

Glendonites previously recognised within these sediments indicate that the general climate at the time of formation was cold, in the range of 4 to -7°C (DeLurio & Frakes 1999). The presence of the drop stones indicates that there was glacial activity, further supporting the cold climate.
5.7.2. *Basal Mesozoic*

The basal Mesozoic is exposed within drainage, atop the basement inliers, lapping up onto the inlier margins and sporadically within the plains that surround the inliers. These sediments are dominated by a series of sandstones and conglomerates with interbedded siltier units. Three major divisions can be found within the basal sediments, including:

- coarse-grained and pebbly sandstones interpreted to represent an alluvial fan system;
- coarse to fine-grained sandstones preserved within a valley in the Mt Painter Inlier and interpreted to be palaeochannel sediments; and
- chalcedony, quartzose pebble beds and angiosperm fossils, representing a lake/spring deposits.

The dominant unit within the basal sediments are the coarse-grained and pebbly sandstone, interpreted as representing a fan unit.

The general morphology, lateral distribution and sedimentology of the basal Mesozoic fans identified around the Mt Babbage Inlier in the north is similar to that of the fan currently seen spilling from the mouth of the Terrapinna Corridor (see chapter 4). This includes the multi-phase fan profile with several generations of fluvial discharge, and the grading of grain-size and attrition of the sediments in a halo around the landform. The rejuvenation and subsequent stacking of the fan system at Terrapinna has been attributed to the reactivation of the Paralana Fault causing a new spill point; that is, a new fan apex system (see chapter 4). A similar concept is proposed for the Mesozoic fan system at Mt Babbage, in which the Terrapinna Fault (that bounds the northern Mt Painter Inlier and forms the approximate apex point of the fan system) is interpreted as having been activated syn-deposition, thereby generating the onset of a new fan lobe. The recognition of tectonic terraces along the Terrapinna Fault supports multi-phase activation of the structure, such that the fan evolution is a likely event. The youngest of the Mesozoic fan apex, recognised by the gravely sandstones and conglomerates around the rubbish tip and abutting the Mt Painter Inlier, sits up as high as the middle tectonic terrace. There is no colluvial evidence perched on any of the higher terraces to determine if it sat higher; however, the lobe and toes of the fan, as well as the thickness of the sediment profile, do not support a high-angled fan.

The fan sediments are perched within all different landforms in the contemporary landscape. They have been identified atop the Mt Babbage ridge in an elongated cliff profile; atop Mt Babbage; in uplifted mesas to the immediate north of the inlier in the basin plains; onlapping shallow rises around Moolawatana and the inlet; within mesas, fault plains and incised valley profiles in the Terrapinna Corridor; and in discrete packages atop the bevelled terraces that dominated the uplifted ranges of the Mt Babbage Inlier itself. Despite the current extent of the sediments, at the time of deposition the fan would have been a relatively low-lying landform with the only form of elevation within the landform coming from the fan apex abutting the edge of the fault structure. The contemporary landscape position of the sediments indicates that much, if not all, of the uplift within the Mt Babbage Inlier has occurred post deposition of the fan sediments. The bevelled surface dominating the Mt Babbage Inlier, which has approximate equivalent elevation to the middle tectonic terrace along the northern Mt Painter Inlier rangefront (in some places second terrace others third terrace), is interpreted as being the base-level; that is, the base of the basin at that time. The bevelled nature of the range, the discrete pods of sediments and the association with the apex pointing further south support this concept. These sediments are caught up in the Birthday Well Fault along the southern margin of the Mt Babbage Inlier, such that in places they are overturned against the ranges. At this location, Eyre Formation sediments cap the Mesozoic. At the fault exposures, the Eyre Formation is relatively undeformed, such that the bedding is nearly horizontal. This indicates that faulting occurred post Mesozoic, but before deposition of the Eyre Formation.

These types of fans are typically associated with arid climates (McCarthy *et al.* 1995). Flora fossils preserved within the sandstones around Mt Babbage indicate a twig and wood dominance. This also supports a generally drier environment. This is in stark contrast to the glendonite assemblages found in the marine sequence that indicate a near-freezing environment.
The palaeochannel remnants in the Paralana Valley expose where a river system flowed through the area during the late Cretaceous. The distribution of the remnant sediments spans the entire valley width, indicating that the Mesozoic channel system flowed through a landform at least in part representing the current morphology of the valley. The valley is bound on both sides by large faults, and has been affected by the tear faulting that has reactivated the Paralana Fault and caused displacement within the basin. The unconformity between the Mesozoic and the basement is also exposed in areas such that the Mesozoic succession is sitting atop the Neoproterozoic granites, indicating that the granitic succession was exposed syn-deposition of the river. These factors all support that the morphology of the valley existed syn-deposition. The contemporary exposures of the palaeochannel in places are caught up in the bounding faults. This indicates that there has been activity along this structure post deposition, such that the contemporary morphology of the valley is a product of the pre- and post-deposition uplift.

The preservation of these ‘Pimples’ is a combination of the tectonism and slight induration. Similar sediments are present along the Mt Painter Inlier. Palaeocurrent measurements from the Pimples indicate a general flow direction to the N (with a 20° swath on either side). The remnants and their location define a large, braided, fluvial system flowing through the Paralana Valley. Remnants of the palaeochannel sediments are limited in distribution, making tracing the exact morphology of the channel difficult. However, the palaeoflow directions indicate that the channel is flowing out to the north. This coincides with the large fan previously described.

The third sediment profile in the basal succession is the chalcedony deposit around Gunpowder Bore in the northeast of the Mt Babbage Inlier. The crystallographic reflectance of the chalcedony indicated that the sediments were deposited and grew in silica-charged spring deposit, such that the sediments are equivalent to a siliceous tufa deposit. The deposit sits within a landscape situated between two large faults, one of which controls the uplift along the Mt Babbage Ridge. In the contemporary landscape, the spring deposit is situated within an area that has large salt pans forming a playa plain in the area between the two faults. The salt pans are indicative of a contemporary spring that evaporates in the arid environment. The spring deposit was interpreted as forming syn-deposition in the Mesozoic landscape at the same time the fan was being deposited. The angular unconformities between the basal sediments and the Marree Formation indicate that there was syn-depositional tectonism.

5.7.3. Pre-Mesozoic

The pre-Mesozoic landscape in the northern Flinders Ranges is a feature of great debate. The Mesozoic sediments help to clarify this. At the time of deposition, the north of the area was characterised as being relatively low, with small rises and low hills around the Moolawatana area. By contrast, the Mt Painter Inlier had some relief. Meanwhile, the Mt Babbage Inlier on average has a 200–350 m contemporary elevation, which occurred post marine deposition. The Mt Painter Inlier has a 500–600 m contemporary elevation, being a combination of pre and post uplift. Since the marine deposition, both inliers have been uplifted by faults trending in N-S and, more recently, by faults trending in approximately E-W. The bevelled surface that characterises much of the Mt Babbage Inlier, identified as being the base level at the time of at least Marree Subgroup deposition, approximately correlates to the middle tectonic surface along the edge of the Mt Painter Inlier. The 100–200 m of relief above the surface is estimated as being the amount of uplift in the Mt Painter Inlier pre-Eromanga deposition.
Chapter Six: Case study #2, The Tibooburra-Milparinka Inliers

The Tibooburra-Milparinka Inliers in far northwest New South Wales form the northeast boundary of the Frome Embayment. This area hosts the transition from the embayment to the main part of the basin, making the area critically located to help understanding the post Palaeozoic geological history of the Frome Embayment. Until recently, few geological studies have conducted within the area due to the abundance of regolith and the complex geology. A recent collaborative study in the Tibooburra-Milparinka Inliers has focused on overcoming these issues by mapping and reconstructing landscapes for individual inliers and focusing on specific features of the landscape in different areas (Hill et al. 2006). These studies included: in depth and detailed analysis of the modern landscape (Chamberlain 2001; Davey 2005; Davey & Hill 2005, 2008 & 2009; Davey et al. 2008); bedrock geological mapping (Brown & Vickery 2007; Greenfield et al. 2007; Greenfield & Reid 2007a, 2007b); post-Mesozoic weathering and induration patterns (Chamberlain 2001; Gibbons & Hill 2005; Hill 2005); sedimentation history and landscape remnants (Hill 2005; Hill et al. 2005; McAvaney 2006; Brown & Vickery 2007); economic geology and potential (Gibbons & Hill 2005; Greenfield & Reid 2006; Tucker & Hill 2006; McQueen 2008) and, even structural and tectonic history (Anderson et al. 2004; Davey 2005; Davey & Hill 2005; Davey & Hill 2009). Despite the effectiveness of these studies on a localised scale, as yet, a long-term regional evolution model has not been constructed, as the individual areas are all so different and all have what appear to be different driving forces behind their geological evolution. This has highlighted the need to find a component of the areas geology that can tie the complex post Palaeozoic landscape history into a coherent geological model. A feature recognised as a key component in all of the localised evolution models in the area included vast plains and remnants of Mesozoic sediments and saprock concurrent with the Jurassic to mid-Cretaceous Eromanga Basin. These exposures were often used as bench marks for the local models, as the remnants and surfaces preserved many different aspects of the areas geology. This includes: exposed unconformities between both the underlying bedrock and overlying successor basin sediments; evidence of modern endogenic geomorphic processes such as varying degrees of weathering and induration; and intense exposures of the areas tectonic and structural history (Anderson et al. 2004; Davey 2005; Davey & Hill 2005; McAvaney & Hill 2006). These sediments had been previously recognised and studied in areas where exposures are obvious, such as around the Tibooburra Inlier and along regional fault scarps (Morton 1982). However, analyses of these sediments have been limited to the stratigraphical and palaeontologic studies. As well as this, many of these studies have neglected to recognise the subtle remnants of these sediments, let alone the potential for these sediments to host evidence of the areas Phanerozoic geological and environmental evolution.

Recent Australian landscape studies have used regolith geology as the basis for geological evolution models (for example: DeRosea et al. 1991; Anand & Paine 2002; Hill 1999 & 2005; Davey & Hill 2009). By analysing different components of the regolith profile, these studies found key landforms and features that preserved evidence of the areas tectonic, denudation and preservation history (Hill 1999 & 2005). As well as this, these studies recognise the potential for remnants of ancient landscapes to be preserved within the modern regolith profiles and
contemporary landscapes (Hill 1999; Davey & Hill 2009). To combat the regional landscape evolution model, and the northeast evolution of the Frome Embayment, the Tibooburra and Milparinka Inliers were addressed using a combination of regolith, landscapes, structure and stratigraphy.

6.1. Regional Geology
The Tibooburra-Milparinka Inliers form the Tibooburra Ridge, the southernmost extent of the Grey Ranges (Rose & Brunker 1969; Cramsie & Hawke 1982a); a discontinuous ranges belt that extends into southwest Queensland into northwest New South Wales. The ridge is hosted within the controversial boundary between the Thomson, Lachlan and Delamerian orogens in the area to the northwest of the Wonominta Block, the bedrock block that forms much of northwest New South Wales (for example: Murray 1986; Thalhammer 1992; Thalhammer et al. 1998; Direen & Crawford 2003; Greenfield & Reid 2006). This area forms the northeast margin of the LFE (Figure 6.1) and the contemporary drainage divide between the Lake Eyre Basin to the west and the Bulloo-Bancannia Basin to the east (Hill 2005; Hill et al. 2008).

Figure 6.1. The Tibooburra-Milparinka Inliers, location relative to the Australia and the GAB, and relative to New South Wales. Brovey remotely sensed imagery from the Koonenberry Data Disk (courtesy of the NSW DPI).

6.1.1. Geomorphology and Structure
Broadly the Tibooburra-Milparinka area can be divided into three geomorphic zones. This includes: the mountains and rises that form the inliers, with average elevations between 200-350 m ASL; the low hills that form the extent of the Tibooburra Dome structure, with average elevations between 100-200 m ASL; and, the undulating plains and rises of the surrounding basins, with average elevations at or below 100 m ASL.
Figure 6.2. Simplified surficial geology of the Tibooburra-Milparinka Inliers from Hill (2005).

The mountains and rises include seven main, structurally controlled bedrock inliers (Tibooburra, Warratta, Mt Poole, Mt Browne, Gorge, New Bendigo and South Warratta), all of which protrude through the surrounding Mesozoic and Cainozoic Palaeogene basins (Figure 6.2). For the most part the inliers are fault controlled, with faulted range fronts a common feature.

The hills and rises that form the Tibooburra Dome are also structurally controlled landforms. These features, commonly referred to as the 'jump-ups', are uplifted mesas that form a discontinuous hemispherical ring around the inliers. In the west of the area this ring is disturbed by a smaller arcuate structure, the Warratta Dome, that forms a similar pattern of exposure and structure to the larger Tibooburra Dome. In the east, the Warratta Dome is bound by the Warratta Fault such that it forms an arc, unlike the near continuous ring that the Tibooburra Dome forms.
The surrounding basins are characterized by a combination of low-relief plains and undulating rises that onlap, and in some places have been juxtaposed against the bedrock inliers. These plains are dominated by sediments pertaining to the Mesozoic Eromanga Basin and the Palaeogene to near contemporary Lake Eyre and Bulloo-Bancannia basins. As well as this, these plains are capped by extensive Quaternary sediments. Throughout the basins are several small inliers and inlier fields (including: Gorge North, South Warratta Extensions and Mt Browne Plains), that protrude or sub-crop through the basin plains. These features are smaller versions of the bedrock inliers that form the mountains and rises.

The landscape in the area is largely controlled by several large scale faults and folds. The most prominent of these features is the Warratta Fault, a NW-SE trending structure thought to be concordant with the regional Olepoloko Fault (Stevens 1985; Anderson et al. 2004). This fault stretches through the centre of the field area controlling much of the uplift in the Warratta Inlier, and the formation of the Warratta Dome. To the immediate west of the Warratta Inlier is a similarly orientated structure, the New Bendigo Fault, in which controls up lift of the South Warratta and New Bendigo inliers and up lift within the Warratta Inlier. Displacement along the New Bendigo Fault is not as prominent as that associated with the Warratta Fault; however, is still notable. The trend of the Warratta and New Bendigo faults is concordant with many prominent structures in the area including the Mt Poole Fault and several range controlling faults within the Mt Browne Inlier (Davey 2005). For the most part, these faults control exposures of the bedrock in the south of the area. In the basin these structures are also expressed; however, expressions are typically subtle.

As well as the NW-SE trending structures several localised NE-SW to ENE-WSW trending structures affect the landscape. The most prominent of these structures is the Mt Browne Fault, the structure that forms the western range front of the Mt Browne Inlier (Davey 2005; Davey & Hill 2005, 2008). Exposures of bedrock in the Mt Poole and Tibooburra inliers express as a similar style of reverse faulting. However, in the basin sediments and inliers in the South Warratta and New Bendigo area these structures are expressed as open folds. The change in expression of these structures is a result of competency variations in the sediments resulting in an expression of disharmonic deformation. These fault sets control not only the uplift of the bedrock inliers, but also the morphology of many of the channels and streams in the area.

While weathering patterns and profiles are common, there is minimal evidence of large scarp erosion; however, fault scarps within the southern inliers show considerable slope retreat step back, indicating that some erosion has occurred.

6.1.2. Bedrock Geology

Bedrock exposures within the area are typically but not exclusively limited to the inliers that form the discontinuous Tibooburra Ridge (Figure 6.2). The oldest exposed bedrock units are the Cambrian metasediments from the Warratta, Teltawongee and Ponto groups (Table 6.1, Figures 6.3 & 6.6). These groups consist of interbedded sandstones, siltstones and tillites that have been regionally metamorphosed to greenschist facies (Greenfield & Reid 2007a). Until recently these groups were classified as being a sub-group of the Wonominta Formation, the general classification of all the bedrock to the west of the Koonenberry Fault in northwest New South Wales (Morton 1982; Webby 1984; Stevens 1985; Stevens & Etheridge 1989; Mills 1992; Chamberlain 2001; Pahl 2004). However, significant differences in geophysical properties and chronological analysis have resulted in these units being classified separate to the Wonominta Formation (Stevens & Fanning 1998; Greenfield & Reid 2007a). These metasediments are dominated by interbedded phyllites and psammites, with minor quartzite, slate and shale beds. For the most part, these metasediments are gently folded around the Tibooburra and Warratta inliers, and moderately to tight folds in the southern inliers. Degree of cleavage formation within these beds is defined by the lithology, with the finer-grained units expressing cleavage better than the coarser units.
Figure 6.3. Cambrian metasediment exposures: i) Cannela Beds, Mt Browne Inlier (577983/6707389); iii) Jefferies Flat Beds, Warratta Inlier.


<table>
<thead>
<tr>
<th>Location</th>
<th>Group</th>
<th>Unit</th>
<th>Age</th>
<th>Lithology</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibooburra Inlier</td>
<td>Warratta Group</td>
<td>Easter Monday Beds</td>
<td>Cambrian</td>
<td>Interbedded psammopelite, phyllites, psammite and slate with minor</td>
<td>Zones of chloritic alteration, breccias and</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>diamicite</td>
<td>calcite veins</td>
</tr>
<tr>
<td>Warratta Inlier</td>
<td>Warratta Group</td>
<td>Jefferies Flat Beds</td>
<td>Cambrian</td>
<td>Interbedded phyllites, slate and</td>
<td>Pyrite pits; highly cleaved with</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>psammite</td>
<td>zones of chloritic and sericitic alteration</td>
</tr>
<tr>
<td>South Warratta and New Bendigo Inliers</td>
<td>Warratta Group</td>
<td>Jefferies Flat Beds</td>
<td>Cambrian</td>
<td>Interbedded phyllites, slate and</td>
<td>Highly cleaved (in some places two distinct</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>psammite</td>
<td>cleavage profiles)</td>
</tr>
<tr>
<td>Mt Browne and Mt Poole Inliers</td>
<td>Teltawongee Group</td>
<td>Depot Glen Formation</td>
<td>Cambrian</td>
<td>Interbedded phyllites, psammite and slate with some minor grey-pink</td>
<td>Convoluted bedding, and some mylonitised beds;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>quartzites</td>
<td>pyrite pits; some sericitic alteration</td>
</tr>
<tr>
<td>Gorge Inlier</td>
<td>Ponto Group</td>
<td>Cannela Beds</td>
<td>Cambrian</td>
<td>Phylite with minor intercalated</td>
<td>Highly cleaved</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>psammites and grey-pink quartzites</td>
<td></td>
</tr>
</tbody>
</table>

Intruding through the bedrock is a series of Cambrian to Silurian dykes, sills and veins (Table 6.2). The most prominent of these is the Silurian Tibooburra Granodiorite, from the Tibooburra Suite (Thalhammer 1992; Browne & Vickery 2007; Greenfield & Reid 2007a). These intrusions form a large component of the Tibooburra Inlier,
exposed as massive rounded granitic tors and jointed blocks. Surrounding these intrusive bodies are large zones of chloritic and sericitic alteration. Sporadic exposures of these units intrude through the Warratta and Mt Poole Inlier (Greenfield & Reid 2007b). Intruding the southern inliers are a series of Cambrian to Ordovician mafic sills and dykes (Greenfield & Reid 2007b). The most prominent of these include a series of trachyte basalt subtrusives (Figure 6.4 iv), rich in plagioclase, exposed as low dykes and sills, and a large diorite body that occupies large areas along the hinge of a bedrock fold within the Mt Poole Inlier (Davey 2005).

Table 6.2. Summary of the intrusives, extrusives and subtrusives from the Tibooburra-Milparinka Inliers: Tibooburra, Warratta and South Warratta after Evernden & Richards, 1962; Thalhammer et al. (1998); Brown & Vickery (2007), Greenfield & Reid (2007a); Greenfield et al. (2007); Mt Browne, Mt Poole and Gorge after Thalhammer et al. (1998), Davey (2005), Greenfield & Reid (2007).

As well as the igneous suites, quartz veins and dykes intrude the bedrock exposed within the inliers. These intrusions are prominent features of the landscape, in some areas forming exposures up to 3 m high, and several meters wide, with continuous veins in the bedrock exposures within the Mt Poole Inlier being traced for up to 300 m. The Warratta Inlier hosts large quartz veins, including the White Lady Rock (579047mE / 6723653mN), and the exposures around Good Friday Diggings (Figure 6.4 i & ii). Exposures of these veins indicate that the veins are associated with the folding deformation of the bedrock, with some structures being bedding parallel, others being folded. This indicates that the quartz was intruding syn-deformation. Dating of some veins from the Mt Poole and Warratta inliers produced ages of 417-410 Ma for both inliers (Thalhammer 1992; Thalhammer et al. 1998), providing an approximate age for the deformation that caused the bedrock folding.
6.1.3. Mesozoic, Palaeocene and Quaternary Sediments

Unconformably overlying, onlapping and faulted against the metasediments are Mesozoic sandstones, conglomerates and siltstones from the southern margin of the Eromanga Basin; pebbly sandstones and conglomerates equivalent to the Lake Eyre Basin sediments; and, extensive Quaternary alluvium, colluvium, sheet wash and aeolian sediments.

Eromanga Basin sediments within the area are abundant in exposure, and also widespread (Pittman 1895; Kenny 1934; Morgan 1978; Cransie & Hawke 1982 a; Hawke & Cransie 1982; Morton 1982; Stevens 1988; Stevens & Fanning 1998; Hill 2005; Davey & Hill 2006; Greenfield & Reid 2007a). Equivalents of four out of the five main Eromanga Basin formations previously defined in chapter 2 have been identified in and around the inliers including the Algebuckina Sandstone; Cadna-owie Formation, Bulldog Shale and Oodnadatta Formation (Ludbrook 1962; Hawke & Cransie 1982). Local nomenclature for these units is defined in table 6.3. These sediments are exposed along uplifted fault scarps, in structurally controlled mesas, and cropping out through the undulating plains and channels that form the surrounding basins.

Unconformably overlying the Mesozoic sediments in some parts of the study area are sediments lithostratigraphically equivalent to the Palaeogene Eyre Formation of the Lake Eyre Basin (LEB). The contemporary margin of the LEB is estimated to be on the western side of the Tibooburra Dome (Figure 6.2 & Table 6.3), such that these sediments are technically not LEB sediments. Landscape studies in the area suggest that these are lateral equivalents of the Eyre Formation in the Bulloo-Bancannia Basin (Hill 2005). However, the Palaeogene sediments within the area contain distinct LEB marker beds such as the basal Eyre Formation ‘jellybean’ conglomerates (see Figure 6.47), and the overlying angular, quartzose pebble beds. These sediments also have an affinity to forming large silcrete pisoliths (Figure 6.51), which while not a unique or distinguishing
feature of LEB sediments, is a common type of induration to form in sediments that have the properties characteristic of that of the Eyre Formation sediments (Stevens 1988).

Quaternary sedimentation in the area has been dominated by colluvial and aeolian processes. This has resulted in the formation of extensive sheetwash and sand plains and in some areas the formation of linear and parabolic dune fields. In part, these sediments disconformably overly the Cambrian, Mesozoic and Palaeogene rocks. Until recently, it was thought that these sediments formed a blanket up to 400 m deep covering these rocks. However, regolith mapping in the south of the area highlighted that in the areas surrounding the Mt Browne, Mt Poole and Gorge inliers, this was on average less that 10 m (Davey 2005; Davey & Hill 2005; Hill et al. 2008). Sheet-flow sediments dominate the basin plains surrounding the inliers. These plains are characterised by run-on and run-off zones that form a distinct asymmetrical contour banding pattern. Bands are typically thin (<3 m wide) with clast populations directly associated with the underlying and sub-cropping geology. This acts as an indication of the sub-cropping or subtle exposures of bedrock. This association is extrapolated from abundant angular quartz clasts, indicating the presence of intruded metasediments. Creek exposures and shallow depressions in these areas have confirmed these associations. Linear dune fields in the northwest and marginal south east corners of the field areas indicate a general SW-NE axes of the dunes. This is concordant to the general trend of the dunes from within south central Australia, a result of the westerly to north-westerly winds common to that area. The parabolic dunes around the western inliers (namely Mt Poole and Warratta) are a local adaptation of the linear dunes, forming as a result of the winds ‘bending’ around the mountains. The abundance of aeolian sediments in the Quaternary sediments is a result of the increasing aridity within the area (Davey & Hill 2005; Hill 2005).

Table 6.3 Palæozoic stratigraphy and basic lithological descriptions. Table identifies the standard nomenclature defined in chapter 4 against the local nomenclature form the Tibooburra-Milparinka area. Eromanga Basin sedimentological descriptions after Hawke & Cramsie (1982) & Morton (1982), Cainozoic sediments described from field descriptions and after Hill 2005.

<table>
<thead>
<tr>
<th>AGE</th>
<th>STRATIGRAPHY</th>
<th>LOCAL NOMENCLATURE</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neogene</td>
<td>Pliocene</td>
<td>Tirari Formation</td>
<td>Not seen in area</td>
</tr>
<tr>
<td></td>
<td>Miocene</td>
<td>Namba Formation</td>
<td>Not seen in area</td>
</tr>
<tr>
<td></td>
<td>Oligocene</td>
<td>Eyer Formation</td>
<td>Eyer Formation Type</td>
</tr>
<tr>
<td></td>
<td>Eocene</td>
<td>Eyer Formation Type</td>
<td>Basal, polished conglomerates, coarse-grained, quartzose sandstones</td>
</tr>
<tr>
<td></td>
<td>Palaeocene</td>
<td></td>
<td>(Not seen in area)</td>
</tr>
<tr>
<td></td>
<td>Maastrichtian</td>
<td>Wintoon Formation</td>
<td>Green-yellow-brown claystones, grey-brown silty clays, grey-green shales; buff-white siltstones; carbonaceous, fine-grained sandstones;</td>
</tr>
<tr>
<td></td>
<td>Campanian</td>
<td>Oodnadatta Formation</td>
<td>Wintoon Formation</td>
</tr>
<tr>
<td></td>
<td>Santonian</td>
<td>Bulpdog Shale</td>
<td>Gunmau Formation</td>
</tr>
<tr>
<td></td>
<td>Coniacian</td>
<td>Cadna-owie Formation</td>
<td>Namur Sandstone</td>
</tr>
<tr>
<td></td>
<td>Turonian</td>
<td></td>
<td>Basal quartzose pebbly conglomerates; coarse-grained sandstones; pebbly sandstone; typically highly silicified</td>
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</table>
6.1.4. Economic Geology

The Tibooburra-Milparinka Inliers are renowned for their rich gold history. This was spurred by discoveries in the late 1800's of alluvial and detrital gold in the Mt Browne and Tibooburra goldfields (Brown 1881; Wilkinson 1889; Jackaman 1974; Marston 1984; Cramsie & Hawke 1982b; McQueen 2008). Quartz dominated lags that surrounding the southern inliers were renowned for hosting placer deposits of gold, from which nuggets and flakes were easily found (McQueen 2008). Initial exploration was limited to scrapings, in which prospectors could work through the lags and pick out gold. As these settings were stripped of gold, exploration was extended into shafts (Figure 6.5). These shafts were predominantly, but not exclusively, dug into Mesozoic sediments and highly weathered Metasediments throughout all of the inliers. Conglomerate formations from the base of the ‘Gumvale Formation’ are the most abundant host of the gold (Hill 2005; Hill et al. 2006). These sediments are interpreted to be a lithified form of the quartz rich lag where the initial gold was found. In the south of Mt Browne Inlier these sediments have been sourced and mined down to depths greater than 50 m, where the conglomerate bed is up to 1.5 m thick (Cramsie & Hawke 1982b). As well as the conglomerate beds and scrapings, quartz reefs and large veins intruding the Cambrian metasediments have also been worked (Wilkinson 1889). These features are thought to be the potential source of the placer deposits, as they are hosted in reworked lags shedding off these features. Since the late 1800s production from these goldfields has exceeded 1800 kg (Cramsie & Hawke 1982b).

Figure 6.5. remnants of the gold mining facilities: i) mine shaft from north Mt Browne; ii) ore separation equipment from the Battery, central Warratta (580317 mE / 6734897 mN).

In the 1970s gold exploration in the area resumed (Jackaman 1974). Mineral exploration leases have intermittently been held over the inliers since then (NSW DPI tenement records 2008). Exploration has focused on the Tibooburra, Warratta and Mt Browne inliers; however, to date; no specific mineralisation has been discovered. Prospectors still roam the inliers looking for nuggets and flakes that may have weathered out of the sediments or been washed downstream. Local reports indicate that this has been most productive around the quartz reefs to the north of the townsh ip of Tibooburra and at a place called Billy Goat Hill in the south of Mt Browne (573895mE / 6702594mN). In the Warratta Inlier, five main auriferous veins have been identified to date, these include: Phoenix; Elizabeth; Pioneer; Rosemount; and, Warratta (Jackaman & Koneck1974). The largest of these is the Pioneer Reef, which is up to 5 m thick (Hill et al. 2008).

Opal occurrences are common in the area, predominantly hosted in weathered Mesozoic sediments, or in stream beds. To the north of Tibooburra, exposures of highly weathered Rolling Downs Group sediments have been mined for opal, but the opal is scarce and of poor quality (Cramsie & Hawke 1982). These mines are no longer active. Fossickers have been known to find large gem quality opals in the area surrounding the shafts. In the south of the area petrified wood fragments common to the surface lags have been opalised; however, this is rarely gem quality opal.
No bedrock mineralisation is known in the area; however, there are extensive zones of alteration surrounding many of the intrusive packages that have mineralisation potential. These zones are dominated by chlorite-pyrite-sericite alteration with minor manganese ribboning, both commonly associated with hydrothermal gold, silver and copper mineralisation. Despite this, minimal evidence of actual mineralised zones has been found.

Sandstones from basin exposures, and slates from within the inliers have been quarried, and used for local pastoral buildings, and in some cases exported for use in commercial properties (including several historic buildings within the township). These quarries are typically small, and in most areas have been rehabilitated or have collapsed, such that they are not recognisable.

Petroleum exploration in the area has been limited; however, recent drilling to the north of Tibooburra has turned out three wells supporting a potential gas sink, and drilling to the west of the area has recovered trace oil in core. As well as the mineralisation economic values, the area is also renowned for its geo-tourism, with the spectacular landscapes around the township of Tibooburra, and the old township of Milparinka being particular drawcards (http://ozgeotours.110mb.com/index.html).

![Figure 6.6. Gold workings, scrapings and shafts throughout the inliers projected on a simplified geology map (Hill et al. 2008)](image)
6.1.5. Physical Geography

The Tibooburra-Milparinka field area is hosted with in an arid to semi-arid climate. Average summer temperatures are typically in excess of 30°C while winter temperatures are typically at or below 20°C (BOM 2006-2008). Rainfall within the area is low (<228 mm/yr at Tibooburra), with a slight trend towards a summer fall (BOM 2006-2008) (Figure 6.7).

Figure 6.7. Rainfall for the Tibooburra Region for the year 2008 (www.bom.gov.au)

Vegetation within the area is dominated by arid land chenopod shrubs and woodland species. Chenopod species include: bluebush (*Maireana spp.*); emu bush (*Eremophila spp.*); and, sporadic saltbush (*Atriplex spp.*) (Figure 6.8 i). Woodlands are dominated by whitewood (*Atalaya hemiglua*); cabbage tree wattle (); gidgee (*Acacia cambagei*); dead finish (*Acacia tetragonophylla*); and, sporadic beefwood (*Grevillea striata*). Sand plains and dune fields are typically populated by mulga (*Acacia aneura*) and bastard mulga (*Acacia clivicola*); with some Christmas tree mulga (*Acacia aneura var. conifera*) in the plains in the south of the area. River red gums (*Eucalyptus camaldulensis*) populate active ephemeral channels (Figure 6.8 ii). Some tributaries in the west and the south of the area are populated by dense western rosewood (*Alectryon oleifolius*) colonies.

Figure 6.8. Vegetation communities around the Tibooburra-Milparinka inliers: i) banded chenopod shrublands surrounding the Mt Browne Inlier (573904mE / 6705120mN). Species pictured include black bluebush (*Maireana pyrimidata*) and pearl bluebush (*Maireana sedifolia*); ii) river red gums in Depot Glen gorge, Mt Poole Inlier (574237mE / 6708206mN).

The formation of the townships in the area was principally a result of gold discoveries within and surrounding Milparinka during the 1880s. This was a short lived settlement as conditions were harsh, and the resources to
fully explore the goldfields were limited. Current land use in the area is dominated by pastoral grazing of cattle and sheep.

6.2. Field site #1: Tibooburra

The Tibooburra field site includes the Tibooburra Inlier and surrounding basins (Figure 6.9), the approximate area incorporated on the Tibooburra 1:25,000 Geological Map Sheet (Brown & Vickery 2007) and the Tibooburra 1:25,000 Regolith Landform Map (Chamberlain & Hill 2002). This area includes part of the Sturt National Park, which encompasses over 340,000 ha of land including the old Wittabrenna, Mt. King, Olive Downs, Fort Grey, Binerah Downs and Mt. Wood Stations, and the small township of Tibooburra.

Figure 6.9. Landsat Brovey (2005 issue) remotely sensed imagery of Tibooburra with a green-red band interchange to enhance detail within the ranges (data courtesy of the NSW DPI)

Mesozoic sediments in the Tibooburra area have been the focus of and incorporated into many studies (for example: Morton 1982; Stevens 1988; Chamberlain 2001; Hill et al. 2005). A comprehensive study of the Mesozoic sediments surrounding Tibooburra was conducted by Morton (1982). This study included fossil identification and sediment classification with the intention to segregate the Mesozoic sediments from the Cainozoic sediments. This study also worked on identifying depositional regimes, environmental conditions with some palaeogeographical reconstructions. This study has provided the basis for other studies in the area. The area featured prominently in the analysis of the Eromanga Basin in New South Wales (Hawke & Cramsie 1982a). Sediment profiles defined by Kenny (1934), Rose et al. (1967), Rose & Brunker (1969) and Morton (1982) were used as type sections and as a basis for understanding other exposures of the Mesozoic in New South Wales. Stevens (1988) refined classification of sediments that were contentious, or unaddressed in Morton (1982), incorporating evidence from past studies to aid with the clarification (for example: Kenny 1934; Rose et al. 1967). More recent studies have focused on regolith features of the area (for example: Chamberlain 2001; Hill 2005; Hill
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et al. 2005; Hill et al. 2006). These studies have been refining distribution of the sediments, and incorporating exposures that area weathered, indurated or deformed previously not recognised as Mesozoic.

6.2.1. Surficial geology and geomorphology

The regolith geology of the Tibooburra Inlier was compiled by Chamberlain (2001). A major component of this study was the 1:25,000 Regolith Geology map of the Tibooburra Inlier (Chamberlain 2001; Chamberlain & Hill 2002). This work was followed by more comprehensive studies within and surrounding the inlier (Hill et al. 2005; Hill et al. 2008) (Figure 6.10). These studies provide the basis for this field site.

Figure 6.10. Surficial geology of the Tibooburra Inlier from Hill et al. (2005)

As with many landscapes within central Australia, Tibooburra is dominated by arid zone regolith and landforms. This includes vast plains and low rises of transported sediments distributed by wind and ephemeral water that have built up or spread over the landscape.

The area is characterised by an elongated bedrock inlier comprised of metasedimenst, granite and granodiorite. Landforms forming the inlier include rounded hills, low-hills and rises. The majority of the inlier is slight to moderately weathered metasediments from the Easter Monday Formation (Scheibner & Basden 1998; Thalhammer et al. 1998; Brown & Vickery 2007). The metasediments are a series of interbedded phyllite, psammite, slate and shale with occasional quartzite beds. These sediments are all highly cleaved, slightly metamorphised and in some places altered, typically to a chloritic or sericitic rock.

In the east of the inlier the landscape is dominated by rounded highly polished granite tors (Figure 6.12). The tors formed as a result of preferential weathering along jointed granite blocks. Simple factors such as temperature variations between day and night, micro-earthquakes and excessive heat cause granites to fracture (Twidale 1982; Campbell 1997). The abundance of felsic minerals (particularly quartz) in the rock induces brittle response...
to variations in stress on the rock. This develops orthogonal joint sets (Figure 6.11). Preferential weathering occurs along the joints and fractures within the granites where the fracturing provides a conduit for fluid movement, as well as zones of weakness from the brittle stress (Twidale 1982; Campbell 1997). The fluid flow through the joints and cracks eventually strips down the rock to a corestone (Figure 6.11).

![Figure 6.11. Stages of tor formation: (1) fluid flow through jointing; (2) joint formation and physical weathering; (3) corestone tors after Twidale (1982).](image)

The tors have also had minor ‘onion skin’ weathering or exfoliation in which layers of the granite are shed as a result of temperature fluctuations and the brittle nature of the granite.

![Figure 6.12. Granodiorite exposure from the Tibooburra Inlier (photo taken from 594549mE / 6746633mN). Rounded tors form remnants of the granite insleberg that once protruded from the landscape.](image)
Other exposures of *in situ* regolith includes sandstones, siltstones, claystones and conglomerates from the Eromanga Basin and Lake Eyre Basin. These sediments are typically hosted within the lowlying parts of the landscape; however, are occasionally exposed mesas and in vertical exposure along fault zones.

The plains surrounding the inlier are dominated by colluvial plains, sandsheets and small dunes (Figure 6.10). Colluvial sediments flank the inlier and dominate regolith units in the distal basin. Surrounding the inlier, the colluvium is dominated by sheetflow sediments. These sediments are characterised by rounded to angular quartz, sub-angular to sub-rounded metasediments, sub-angular to rounded granite and sub-rounded to sub-angular sandstone and conglomerate clasts. The banding of the sheetflow is characterised by run-on zones of red-brown fine sands and silts and run-off zones with quartz, metasediment and granite clasts. These plains and rises often have subtle exposures of the basin sediments, typically slightly weathered sandstones.

The aeolian units surrounds the inlier and the flanking colluvial profiles. Extensive sandsheets and small dunes dominate the landforms. The aeolian sands are red-brown stained quartzose grains that are typically rounded. Minor attributes of colluvial sediments are mixed in with these sediments as a result of proximal derivation (Figure 6.13). The sandsheets have abundant exposures of sandstones and hardpan regolith carbonate accumulations. Aeolian units are typically densely vegitated, particularly by mulga (*Acacia aneura*), with minor bastard mulga (*Acacia clivicola*), dead finish (*Acacia tetragonaphylla*). Assorted chenopods colonise the sand sheets as well.

Three major and three minor channels control the primary drainage in the area. the major channels include: Thomsons, Wittabrenna and Cutting Creek. the minor channels include: Dee Dee Creek, Kings Creek and Racecourse Creek. The alluvial channels are broad low relief landforms often surrounded by extensive alluvial plains, ephemeral swamps and sandbars. The alluvial sediments vary locally; however, are dominated by red-brown-grey sands and assorted gravels (including quartz, quartzite, metasediments and granite clasts).

Structurally, the area is controlled by a series of tight to acute east verging folds and associated thrust faults with an axial trend of NW-SE. These structures have been recognised as the deformation event that formed cleavage in the metasediments (Greenfield & Reid 2006), and possibly the jointing within the granites. In the east of the Inlier, the sand sheets near Kings Creek are bound by a large NW-SE trending reverse fault.
6.2.2. Mesozoic Sediments

Mesozoic sediments within and surrounding the Tibooburra Inlier have been previously interpreted to include the full suite of Eromanga sediments (Table 6.4).

Table 6.4. Mesozoic sediments from the Tibooburra Inlier. Table shows the basin nomenclature and the nomenclature defined by localised studies around Tibooburra. Local Nomenclature after Rose & Brunker (1969), descriptions of sediments from Kenny (1934); Morton (1982) & Chamberlain (2001).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Local Nomenclature</th>
<th>Age</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winton Formation</td>
<td>Yulpunga Beds</td>
<td>Late Cretaceous</td>
<td>Pallid claystones and interbedded sandstones, occasional conglomerate layers</td>
</tr>
<tr>
<td>Oodnadatta Formation</td>
<td>Oornoo Beds, Allaru Mudstone, Tambo Sandstone</td>
<td>Albian</td>
<td>Glaucolithic and calcareous sandstone and claystones. Some pallid mudstones and claystones</td>
</tr>
<tr>
<td>Bulldog Shale</td>
<td>Wittabrenna Shale</td>
<td>Aptian</td>
<td>Fine- to medium, grey, muddy sandstones and siltstones, grey-green-yellow claystones, grey-black shales and claystones often with large drop stones.</td>
</tr>
<tr>
<td>Cadna-owie Formation</td>
<td>Wallumbilla Formation, Gumvale Formation</td>
<td>Neocomian</td>
<td>Fine- to coarse-grained sandstones with interbedded claystones, siltstones and occasional conglomerates and gravel lenses. Often highly ferruginised</td>
</tr>
<tr>
<td>Algebuckina Sandstone</td>
<td>Injune Creek Group, Mooga Formation, Hooray Sandstone</td>
<td>Mid to late Jurassic</td>
<td>Interbedded conglomerates, claystones, coarse-grained sandstones and occasional siltstones</td>
</tr>
</tbody>
</table>

Mesozoic sediments surround the inlier as lithified sediment packages, indurated bodies, gravels and lags. Previous studies have identified these sediments using typical sedimentological markers such as fossils (Kenny 1934; Morgan 1978; Morton 1982) and lithology (Kenny 1934; Rose et al. 1967; Rose & Brunker 1969; Morton 1982; Chamberlain 2001). Some of the major studies and geological maps have used features such as topographic associations and indurations to determine the age and classification of the Mesozoic sediments (for example Stevens 1988). Many of these studies inadvertently contradict each other, and confuse the classification of Mesozoic sediments in the area. An example of this is the classification of the sediments in uplifted profiles to the north and west of the inlier. These sediments were initially classified as Late Jurassic to Early Cretaceous Cadna-owie Formation equivalents (Kenny 1934; Rose et al. 1967; Rose & Brunker 1969). However, these sediments were reclassified as Eocene Eyre Formation sediments (Morton 1982; Stevens 1989). Since this classification, regolith and landform studies using lithostratigraphic associations for relative ages of sediments have disputed this reclassification, suggesting that many of the sediments may in fact be of Mesozoic age (Chamberlain 2001; Hill et al. 2005). The issues discussed here have been attributed to the difficulties in associating discontinuous exposures that have been modified by weathering, erosion, alterations, deformation and induration (Hill et al. 2005). The distinction between the basins is further complicated by the classifications of sediments by regolith characteristics. Factors such as silicification and weathering grade have been used to categorize sediments (for example Stevens 1988). While particular lithologies and mineralogies pre-dispose a rock to specific reactions, factors such as fluid flow and stress are not typically uniform processes in a landscape. The affects of dynamic landscape processes are not typically unique to one formation and often not homogeneous across large areas. Identification of sediments in the Tibooburra area is further complicated because of the marginal nature of the basin. Here, formations are characterised by numerous sequences many of which are not unique to specific formations. This highlights the issue of non-uniqueness between the formations. Because of this, the relationships between sequences are just as important as the sequence itself.

Two prominent basin exposures in the area are the uplifted mesas at Tunnel Hill and Quarry Hill (Figure 6.14). At both locations, extensive profiles have been exposed as a result of uplift and exhumation. Both sections are lithologically and stratigraphically equivalent, with interbedded sandstones and conglomerates overlying weathered bedrock.
These exposures are two of the most referenced sections in the area. The first recognition of the exposures was by Kenny (1934), where plant fossils preserved within the sandstone units were used to classify the succession as late Jurassic (for example Figure 6.15). These sandstones were as such identified to be equivalent to the basal Mesozoic from the South Australian and Queensland portions of the basin (Kenny 1934). However, the sediments at Quarry Hill were later reclassified as belonging to the Eocene Eyre Formation equivalents (Morton 1982). This reclassification was based upon an apparent lithostratigraphic correlation of the Quarry Hill sediments to the Eyre Formation sediments around the margins of the Tibooburra Dome (Morton 1982). This association has since been discounted, and the sediments classification has reverted to the initial Late Jurassic classification (Hawke & Cramsie1982; Stevens 1989; Chamberlain 2001). The change to the initial classification was made by further assessment of plant fossils and the correlation to the sediments at Tunnel Hill (Hawke & Cramsie 1982; Stevens 1989; Chamberlain 2001). The extensive and detailed logging of these sediments from these studies provided a basis for classification of the Late Jurassic sediments across the inlier (for example Chamberlain 2001).
The base of the unit at Tunnel Hill and Quarry Hill is characterised by an unconformity in which a clast supported conglomerate sequence overlies moderately- to highly-weathered bedrock (Figure 6.16). The basal conglomerate sequence contains abundant rounded to angular quartz and quartzite clasts with minor highly weathered granite and metasediment clasts hosted in a calcareous mud matrix. Clast size is highly variable, ranging from 3 mm to 8 cm. Most clasts are 2-4 cm long. The conglomerate is thickest at the base of the Tunnel Hill exposure, where over one meter of the conglomerate is exposed overlying the weathered bedrock, forming part of a 7 m succession of thick conglomerate beds (1-2 m thick) intercalated with thin (<30 cm) fine grained sandstone sequences. The matrix of the conglomerates finesse upward in the different conglomerate units ranging from a approximate 30 % sand, 70% mud ratio to a 5 % sand, 95% mud ration in the top conglomerate. At Quarry hill, the conglomerate – sandstone succession occurs over a two meter profile; however, parts of this profile are obscured by colluvium.
The interbedded fine-grained sandstones from both exposures are characterised by angular to sub-rounded grains of monocrystalline quartz. The sandstones also have minor micas (predominantly muscovite, and some biotite), zircons and plagioclase (Figure 6.17 i). Further away from the bedrock unconformity, the sandstones have less micas and plagioclase and contain almost only monocrystalline quartz (Figure 6.17 ii).

Figure 6.17. Plain polarise light photomicrographs from Tunnel Hill: (i) sandstone unit overlying basal conglomerate (589457mE / 6744711mN). Sandstone is dominated by angular to sub-rounded, poorly sorted quartz with minor plagioclase, muscovite and some very small zircons; (ii) quartz arenite sandstone overlying the basal conglomerate succession, 7 meters above the bedrock unconformity (589437mE / 6744767mN). (plag = plagioclase; qtz = quartz, musc = muscovite).

Conformably overlying the conglomerate-sandstone interbeds is a succession of fine- to very coarse-grained sandstones with occasional conglomerate and silt lenses and thin beds. The sandstone sequences in this unit are characterised by fining upward profiles of well sorted, coarse-grained grading to fine-grained, quartzose sandstones, with abundant muscovite and minor biotite fragments. These sandstones are in part ferruginised with yellow staining indicating goethite cement. Lenticular gravel and conglomerate beds break up the sandstone sequence. The gravel lenses are characterised by gravel-sized grains of angular to sub-rounded quartz grains, that vary in size from 2 mm up to 1 cm, hosted within a red-orange matrix (Figure 6.18). The gravel-sized-quartz beds are rarely more than 10 cm thick; however, the conglomeratic lenses can be up to 30 cm thick. The lenticular nature of the sediments is indicative of channel. The gravel lenses represent a calmer depositional environment, while the conglomerates are indicative of higher energy environments – possibly crevasse channels or splays. This unit has abundant cross-bedding structures with large foresets (up to 30 cm), and occasional sole markings in the finer-grained units.

Large (up to 3 m), homogeneous, fine-grained sandstone sequences cap the exposures at both locations. These sandstones are quartzose sandstones with abundant muscovite. Occasional planar cross-bedding is seen at the base of the unit, with foresets typically being less that 2 cm.
The sediments at Tunnel Hill and Quarry Hill have been previously classified as part basal Jurassic (Injune Creek Formation) and part Gumvale Formation (Chamberlain 2001). The basal unit is well defined by the plant fossils to be Late Jurassic (Kenny 1934; Stevens 1989; Chamberlain 2001). The overlying sandstone sequences have been interpreted to be Cadna-owie Formation equivalents, locally referred to as the Gumvale Formation. However, the lenses and thick homogenous sandstone units are characteristic of Hooray Sandstone, Namur Sandstone and Mooga Formation (approximate Algebuckina Sandstone equivalents) sandstones that are exposed further north in the Queensland portion of the basin (Hawke & Cramsie 1982). While the interbedded nature of the sediments is characteristic of Cadna-owie Formation type sediments, the sands and conglomerate are much coarser-grained that typical Cadna-owie Formation equivalents. While marginal exposures of the Cadna-owie Formation can be coarse grained, they tend not to be this coarse-grained (for example Freytag 1966). The lithological correlation with the Algebuckina Sandstone equivalents is thus used to define these sediments as basal Mesozoic.

Other exposures of Mesozoic sediments in and around the inlier include the large cliff exposures to the east of Dead Horse Gully (Figure 6.19), small and subtle exposures in channels and the plains surrounding the inlier, exposures protruding from the sand sheets and profiles in excavated dams and rubbish tips.

The cliff exposures to the north of the Tibooburra Inlier (Figure 6.19) are characterised by interbedded fine- to medium-grained sandstones, clays stones, siltstones and occasional conglomerates. The sandstones sequences are typically up to 1 m thick. Mineralogy is dominated by monocrystalline quartz with micas, pyrite and some lithic fragments (Figure 6.20). The sandstones in the base of the unit are slightly silicified, and occasionally have pink-purple staining on exposed surfaces. Purple-green mottles with reddish-brown halos are also common. Siderite (iron carbonate) concretions have formed within the sandstones in the base of the sandstones. These concretions are characterised by red-brown stained, dense, amoebic blobs encasing greenish-yellow, highly weathered pyrite crystals. These concretions are often associated with the beds containing abundant manganese nodules. The association with the abundance of manganese and siderite concretions can be attributed to the isomorphic nature of the minerals. Both form as carbonate complexes in which cations are free to interchange such that the iron and manganese complex form concurrently.
The sediments at the top of the succession have been indurated, typically by ferruginous cements. The indurations are red indicating haematite (Figure 6.21). These sediments are characterised by very fine-grained sands and possibly mudstones and claystones; however, the extensive induration inhibits recognition of the different components. Photomicrograph of a ferruginised sandstone bed within the succession identifies the main mineralogy of the unit as monocrystalline quartz with minor lithic fragments (granite clasts). Ferruginous matrix is opaque to the reflected light.

Figure 6.20. Hand samples and associated plain polarised light photomicrograph of the sandstone from the cliff exposure along the Silver City Highway north of Tibooburra (591407mE / 6747498mN). The sandstone is partially ferruginised, as indicated by the pale pink-purple staining on the top half of the rock. The shiny lustre of the rock indicates an abundance of muscovite. Very small siderite concretions are present (typically less than 1 cm). Photo micrograph shows a monocrystalline quartz dominance with minor pyrite and lithic fragments.

Figure 6.21. Plain polarised light photomicrograph of the ferruginised sandstone layer from the top of the cliff exposures (sample collected from 591412mE / 6747516mN). Image shows monocrystalline quartz dominance with lithic fragments. Ferruginous induration is opaque to the reflective light.
The sediments exposed along this cliff face are lithologically equivalent to the Cadna-owie Formation from South Australia and Queensland (Forbes 1966; Ludbrook 1962 & 1966; Hawke & Cramsie 1982; Hawke & Bourke 1982; Truelove 1984; Moore & Pitt 1985; Forbes 1986) indicating that they are Gumvale Formation sediments. The Gumvale Formation type section is further south along the Warratta Fault. These sediments have been logged and described in the Milparinka section of this chapter. The sediments along the cliff face are lithologically equivalent to the type section sediment profiles as well.

More subtle exposures of the Mesozoic sediments are scattered across the plains and rises that surround the inlier. These exposures are dominated by fine-grained sandstones with occasional claystone interbeds. Photomicrographs indicate that the sandstone units are dominated by monocrystalline quartz, with muscovite, biotite and some lithic fragments (Figure 6.22). These sandstones are often indurated or associated with indurations (Figure 6.22 & 6.23). Exposures of the sandstones are typically slightly indurated. Ferruginous and siliceous cements are most common, with the ferruginous indurations indicated by a slight purple-red staining on the sediments. The silcretes are dominantly glabeular or massive. Hardpan, fragmented hardpan and powdered regolith carbonate accumulations are also a commonly associated with the sandstones.

Sandstones on the northern and eastern sides of the inlier have small (up to 15 cm wide) veins and veinlets that have grown within cracks, fractures and large runnel crevices in the fine-grained sandstone sequence (Figure 6.24). These growths are characterised by elongated, rhombohedral, translucent to white-yellow crystals that are radiating inward from the edges of the fracture that they are filling. Surrounding the veins in the edges of the fracture are very thin (<4 mm) coatings of hardpan regolith carbonate accumulation. The regolith carbonate
coatings effervesce with dilute HCl indicating they are most likely calcrete. The veins and veinlets have been previously identified as being intraformational quartz veins (Chamberlain 2001). However, the crystals within the veins can be scratched with a knife and effervesce in dilute HCl indicating that they are not quartz, and are in fact calcite veins (Figure 6.24). The calcite identification is supported by the crystal habit of the growths, as quartz typically has a trigonal to hexagonal crystal habit.

![Figure 6.24. Calcite vein in a fine-grained sandstone sequence in the east of the Tibooburra Inlier (602081mE / 6745587mN).](image)

As well as the sandstone exposures, exposures of claystones and mudstones are scattered around the edges of the sand sheets. These sediments are also exposed in recently excavated dams. An example of this is in the south of Thomsons Creek in the south of the area. Here claystones line the base of the dams. These claystones are characterised by brow-grey clays, occasional calcrete veins and abundant plant fossils (Figure 6.25). The plant fossils have been previously identified as being Early Cretaceous in ages (Chamberlain 2001).

Photomicrographs of the claystones show minor accumulations of small quartz grains nestled in amongst the clays. These sections also show the dewatering structures, and shrink swell clay fracture. Very small micas inclusions are also present.

These clays have been previously identified as being deposited in marine environments, and as being Cadna-owie Formation equivalents (Brown & Vickery 2007). The clays are typical of a marine environment; however, where excavation is deep around the dam walls near the Tibooburra Landing Strip to the east of Thomson Creek the profile is shown to be over 1 m thick of the homogeneous clay unit (6.26). In the area, variations in sediment type in the Cadna-owie Formation equivalents (Gumvale Formation) are typically in the magnitudes of centimetres rather than meters. The profile is limited in extent by the landsurface, and as such the 1 m profile could extend deeper. Because of this, the sediments are interpreted to be either final stage transition sediments...
(very late Gumvale Formation Sediments or part of the Rolling Downs Group), specifically the Wittabrenna Shale. Other locations where these sediments are exposed include around the northeast of the inlier at the edge of the sand sheet, to the southwest around Dynamite tank and throughout the south of the area (Figure 6.26 ii).

Figure 6.26. Plain polarised light photomicrograph of the claystones surrounding the Tibooburra Inlier: (i) dewatering structures in a pallid claystone; (ii) quartz grains imbedded into a pale-brown – grey colourer sandstone from the south of the area (599024 mE / 6737941 mN).

6.3. Field Site #2: Warratta

The Warratta field site incorporates the Warratta Inlier, the largest of all seven bedrock inliers, and the surrounding basins (Figures 6.6 & 6.27). This field site forms the northern part of the Warratta 1:25,000 Geological Map Sheet (Greenfield et al. 2007), and the eastern part is incorporated on the Warratta 1:75,000 Regolith Landform Map (Anderson 2004). Historically, the Warratta Inlier has been one of the focuses for gold exploration, with several surficial and shallow gold reefs in the central and south of the inlier, as well as some ancient diggings and alluvial scourings scattered around the inlier margins. The inlier is also host to several ruins of old gold mining towns and plants that were active during the early 1900’s (Pittman 1901; McQueen 2008).

6.3.1. Geomorphology and Structure

The area is dominated by large rounded mountains and hills that protrude through the relatively flat lying, surrounding basins. The landscape, particularly the uplift of the Warratta inlier is largely controlled by the Warratta and New Bendigo faults. Both of these structures are NW-SE trending regional faults that have stepped fault terraces, indicating several stages of activation. The Warratta Fault is thought to be a northern Extension of the Olepoloko Fault (Stevens 1991).

Geophysical modelling and interpretation of the area suggested that the Warratta fault was originally a pre-Mesozoic thrust fault that was reactivated during the Mesozoic. This reactivation is interpreted such that the fault was active as a normal structure during this time creating almost 1300 m of accommodation space (Anderson et al. 2004). This interpretation was derived from throw on the inlier its self, as well as the sediments thicknesses of the Eromanga Basin sediments that surround the inlier (Anderson et al. 2004). Contemporary expressions of the fault plane and fault zone in the north and south of the inlier indicate that the structure, at least in its most recent reactivation, is a reverse fault. In the north of the Warratta Inlier Mesozoic sediments are over turned along the fault plane in a zone of drag, such that the inlier itself is the hanging wall, juxtaposed atop the Mesozoic sediments. Similar exposures are common in the south; however, the exposures are more subtle, and the sediments are not dragged into the fault zone as they are in the north. However, fault plane exposures in the
centre of the inlier are very high angle, in some places >90°. These exposures suggest that the fault in these areas is a normal fault. The inconsistencies along the exposures could indicate that the fault is either a ‘scissor’ fault in which wrench style faulting has resulted in hinging deformation with both normal and reverse style faulting. Another possibility is that there has been incomplete reactivation of the fault, such that part of the structure has preserved the interpreted Mesozoic normal morphology of the fault plane. However, stepped expressions of the fault plane along the range front indicate that the reactivation along the fault has been consistent at this point (Anderson 2004); that is there is consistent terrace development between the normal and reverse faulted areas. This indicated that the most probable account of the faults mixed expression is due to scissoring. Wrench faulting is common, causing ‘scissoring on several smaller structures in the north.

Throughout the inlier small expressions of faults in a similar orientation to the Warratta and New Bendigo Faults are common.

Cross cut by the NW-SE trending structures are a series of small, localised, NE-SW trending, reverse faults. These structures are sinistrally displaced by the movement along the Warratta and New Bendigo faults, indicating that the NW-SE structures have at least a small component of sinistral strike-slip movement on them. Expressions of NE-SW faults that are not intersected by the regional faulting indicate that the southern expressions of the displaced NE-SW structures have been slightly rotated (approximately 10° to north). This further supports that the movement along the regional structures is a wrench style fault, as these types of structure are concordant with strike-slip drag movement and reorientation.
6.3.2. Surficial Geology

The Warratta Inlier is dominated by low hills and rises comprising of slight to moderately weathered, highly cleaved, interbedded psammite, slate and phyllite commonly referred to as the Jefferies Flat Beds (Anderson 2004; Anderson et al. 2004; Davey & Hill 2005; McAvaney & Hill 2006; Greenfield et al. 2007). The distribution and uplift of the inlier is controlled by the near N-S trending Warratta and New Bendigo faults.

Surrounding the inlier are undulating plains and rises of contemporary through to Mesozoic sediments. This area is dominated by the vast gibber plains of silcrete, quartz and sandstone clasts with occasional exposures of slight to moderately weathered sandstones and conglomerates. The major drainage network in the area is controlled by the Evelyn Creek system in the west and by the Warratta Creek in the east and up through the inlier. Evelyn creek is dominated by a broad channel system with anastomosing and anabranching patterns. The base of the channel is limited by the presence of partially silicified sandstones that are exposed or sub-cropping beneath the alluvial sediments. These sediments are also occasionally exposed within the banks of the channel indicating that the sandstone in part control the limits of the breadth of the channel. The channel sediments contain a combination of proximally and distally sourced clasts including abundant metasediment, quartz, silcrete and occasional granite pebbles and clasts. The creek runs through the basin from the northwest of the area such that it never runs through a prominent exposure of the metasediments. The abundant clasts and pebbles are interpreted to have been sourced from the many tributary streams that shed off the west of the inlier into the main channel. This is also interpreted to be the source of the quartz. Silcrete clasts are a local feature of the plains surrounding the channel, and thus are most likely locally sourced. The Warratta Creek flows through the inlier and then into the basin in the south west of the area. The creek flows through the low-lying part of the inlier between the Warratta and New Bendigo faults. At the end of the inlier the creek diverted along the base of the inlier and feeds into the channel that flows along the Warratta Fault. The profile of the Warratta Creek within the inlier is controlled by the exposures of the metasediments and the abundant structure present within the area. The ephemeral channel profile is reflected by the dry nature of the channel with stick and litter dams indicating previous flow (Figure 6.28).
**Acch1** (active channel sediments / active channel): grey-brown, fine-to-coarse grained sands, sub-rounded to rounded gravels, rounded, lithic clasts hosted within broad ephemeral channels. Vegetation is dominated by Eucalyptus camaldulensis.

**Acch2** (active channel sediments / active channel): red-brown, fine sands to coarse pebbles, overlying slightly to moderately weathered bed rock, hosted within steep ephemeral channels. Vegetation is dominated by Eremophila spp.

**Aed1** (alluvial sediments / erosional drainage): grey-brown, fine-to-coarse-grained sands, sub-rounded to rounded gravels with minor exposures of slight to moderately weathered sandstones and shales in shallow incised channels. Vegetation is dominated by chenopod shrubs.

**Aed2** (alluvial sediments / erosional drainage): slight to moderately weathered sandstones, with minor sands and silts hosted within shallow incised channels. Vegetation is dominated by chenopod shrubs.

**Aap1** (alluvial sediments / alluvial plain): orange brown, fine sands and silts with minor sandstones, shale and silcrete exposures, hosted on a low to moderate angle fan. Moderate shallow drainage throughout. Minor sandstone exposures. Vegetation is woodlands species.

**Afa1** (alluvial sediments / alluvial fan): orange brown, fine sands and silts with sub-rounded lithic gravels hosted in low angled elongated fans. Vegetation is woodland species with minor chenopod shrubs.

**Afa2** (alluvial sediments / alluvial fan): orange brown, fine sands and silts with sub-rounded lithic gravels hosted within low-lying plain. Vegetation is dominated by Acacia aneura.

**ISps1** (aeolian sediments / sand plain): red-brown, fine sands and silts, minor quartz pebbles and lithic fragments hosted on a low-lying plain. Minor sandstone exposures. Vegetation is dominated by Acacia aneura.

**ISps2** (aeolian sediments / sand plain): red-brown, fine sands and silts, ferruginised clasts, quartz pebbles and lithic fragments hosted on a low-lying plain. Minor sandstone exposures and dune formation. Vegetation is dominated by Acacia aneura.

**CHfs1** (sheetflow sediments / sheetflow fan): angular to sub-angular quartz, metasediment and sandstone clasts banded with red-brown fine sands and silts hosted on a low to moderate angle fan. Minor sandstone exposures. Vegetation is dominated by Maireana spp.

**CHfs2** (sheetflow sediments / sheetflow fan): angular to sub-angular quartz and metasediment clasts with minor, red-brown fine sands and silts hosted on steep to moderate, elongated fans within undulating depositional plain. Minor channel incision. Vegetation is sparse, typically Maireana spp.

**CHep1** (sheetflow sediments / erosional plain): angular to sub-angular sandstone and ferruginised sandstone clasts, exposures of shales, sandstone and albite hosted within an undulating depositional plain. Minor channel incision. Vegetation is dominated by chenopod shrubs.

**CHep2** (sheetflow sediments / erosional plain): angular to sub-angular quartz, metasediment and sandstone clasts banded with red-brown fine sands and silts hosted on a low to moderate angle fan. Minor sandstone exposures. Vegetation is dominated by chenopod shrubs.

**SSel3** (Slightly weathered bedrock / low hill): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. High relief (90-300 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts).

**SSel4** (Slightly weathered bedrock / low hill): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. High relief (30-90 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts).

**SSe** (Slightly weathered bedrock / erosional rise): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. High relief (9-30 m).

**SMet1** (Moderately weathered bedrock / low hill): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Moderate relief (0-9 m).

**SMet2** (Moderately weathered bedrock / low hill): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Low relief (0-3 m).

**SMet3** (Moderately weathered bedrock / erosional rise): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Moderate relief (0-9 m).

**SMet4** (Moderately weathered bedrock / erosional rise): slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Low relief (0-3 m).

**Appendix**

Figure 6.30. Regolith-landform map of the Warnatta Inlier. Detailed legend is available in appendix 5.
Figure 6.29 simplified geology and geomorphology map of Warratta Inlier.
6.3.3. Mesozoic Sediments

Mesozoic sediments capping and surrounding the Warratta Inlier are dominated by exposures of sandstones, conglomerates and claystones equivalent to the Algebuckina Sandstone and Cadna-owie Formation. Surrounding the northwest margin of the inlier, and capping the inlier around Jefferies Flat, the basal Mesozoic is exposed. Exposures are dominated by low-lying sandstones and conglomerates in the plains surrounding the inlier, occasionally in streams and channels and lapping up on to the Jefferies Flat Beds in the inlier margins. A large exposure of sediments is located within the inlier itself at Jefferies Flat (580159mE / 6734524mN), in an extension of Gumvale Creek in the low-lying area between the Warratta and New Bendigo faults. This area is host to the Phoenix Reef and Claries Prospect gold deposits.

Exposures of the base of the Mesozoic is characterised by a thick (typically up to 1 m) conglomerate unit. In one place in the north of the inlier the profile is over 2 m thick (576714mE / 674237mN). The basal conglomerate is distinctive from other conglomerates in the Mesozoic as it is the only clast-supported conglomerate sequence, with up to 80% of the conglomerate estimated to be clasts. Sub-angular and rounded quartz, sub-rounded to angular metasediments and sub-rounded granite clasts constitute 95% of the lithologies hosted in the sequence. Occasional mafic clasts with abundant hornblende, chloritised and serisitic slates, rhyolite and micaceous schist make up the remaining 5%. The matrix of the conglomerate effervesces in cold dilute HCl, indicating that it has a calcareous basis. The matrix is very fine-grained, almost mud texture, with occasional small quartz grains in the lower part of the sequence. As the conglomerate sequences fill in the sediment pile and progress further away from bedrock, the abundance of the exotic fragments decrease drastically, such that the clasts almost entirely consist of metasediments and quartz with the occasional granite boulder. The matrix is still dominantly calcareous; however, in places is replaced by a kaolanic clay.

Exposures in creek beds and channels shedding of the northwest of the inlier show the conglomerate grading into a sandstone unit (Figures 6.31 & 6.33). The sandstone units are dominated by fine-grained, quartzose sediments (Figure 6.31). The grains are typically sub-angular, monocrystalline quartz. Minor attributes include muscovite, isometric pyrite and few lithic fragments (Figure 6.32). Some exposures have abundant feldspar, in places constituting more than 25% of the detrital component. Exposures of this unit are often slightly indurated by ferruginous (dominantly haematitic indurations) and minor siliceous indurations. Primary sedimentary structures are often preserved within these units. These are dominated by herringbone and planar cross-bedding, with minor exposures of ripple marks. The sandstone commonly have graded grain size profiles, with the sequence grading upwards, with the grading cycles up to 20 cm in profile.

Intermitantly intercalated with the sandstone, and occasionally throughout the conglomerates is a clay-mud unit dominated by pale-brown almost white coloured sequence. Characteristic features of the claystone unit include red-purple mottles corresponding to possible burrows indicating a degree of bioturbation in the sediments profile. Occasional yellow mottles haloed by a black rim and abundant ferruginised zones are other features associated with this unit. This claystone marks the onset of an inter-bedded claystone, sandstone, conglomerate sequence. The claystone sequences higher up in the succession are typically homogenous light-brown with yellow mottles similar to the ones in the lower claystone, with the only major variation in the abundance of motting. The yellow mottles are characteristic of weathered pyrite.
Figure 6.32. Photomicrograph of a thin-section from the basal sandstone exposed at Jefferies Flat (580159mE / 6734524mN). The sequence is dominated by monocrystalline quartz grains, with granite clasts and muscovite. The sediments have been indurated by ferruginous cement.

Figure 6.33. Interbedded sandstones and conglomerates from the west of the Warratta Inlier (575294mE / 673502mN). Fine-grained sandstone facies interbedded with the calcareous conglomeratic lenses. Hardpan regolith carbonate accumulations formed in between the different facies.

Both the sandstone and the conglomerate are associated with regolith carbonate accumulations (Figure 6.33). The most common of these indurations are hardpan calcrite and dolocrete. The calcrite samples collected from around the Warratta Inlier off the sandstones have fragments of the sandstone caught up in the induration (Figure...
This calcrete is interpreted to have formed from an accumulation of calcium that has been leached out of the calcareous sandstones from the Gumvale Formation. In many profiles around the Warratta Inlier, the calcrete is found intra-facies, that is, in between different sedimentary layers in the Gumvale Formation. This potentially indicates that at least some of the calcrete formed syn-deposition. Hardpan calcrete and dolocrete also formed on exposed sandstone surfaces in fault planes and fault zones in the south of the area.

Figure 6.34. Cross-polarized light (1/4 wavelength) photomicrograph of a thin-section through a hardpan regolith carbonate accumulate that has formed in between the main basal sandstone facies and a conglomerate lens. Micrograph shows the layering of the carbonate, and the ‘sand’ grains accumulated within. Sample from collected from the west of the Warratta Inlier in the basins surrounding the ranges (575923mE / 6735126mN).

Exposures of the basal Mesozoic in incised channels and drainage depression also have powdered regolith carbonate accumulations associated with them. These accumulations are also assumed to be calcrete, possibly dolocrete; however, the disseminated nature deflects the ability to determine between the two. These powdered accumulations are a modern formation, resulting from the absolute accumulation of carbonate deposited or evaporated out of the fluids most likely associated with the drainage. Occasionally calcrete is also found in the transported regolith profiles surrounding the sandstone exposures as small (up to 5 cm wide) clumps. These clumps are interpreted to be fragmented off the in situ hardpan accumulations. Because of this association, when these accumulations were found out in the basin areas away from the ranges, they acted as conduits to fining sub-crop or exposed sandstones.

In places these sediments have also been affected by ferruginous indurations, dominantly goethitic in the sandstone and haematitic in the conglomerates. Many exposures are also slightly silicified with some exposures being highly silicified.

The contrast, in the interbedded sediments in the basal Mesozoic succession indicate rapidly varying depositional environments. The abundant cross-bedding, fining up sequences and occasional pebbles within the sandstone units indicates that they are most likely a channel, possibly channel bar sediment. The conglomerate sequences are representative of higher energy depositional environment interpreted to also be channel sediments. The finer-
grained sediments are interpreted to have been deposited in fluvial environments in the plains, bars and flood-outs surrounding the channels. The abundant changes in the sediments is indicative of the frequent change in depositional environments. Frequent changes in depositional environments indicates regular changes in the bases level of the basin at that point.

The successions of the basal Mesozoic around the Warratta Inlier are equivalent to the Namur Sandstone exposures identified around Tibooburra. Typically, the Namur Sandstone is dominated by quartzose sandstone with minor siltstone occasional shale interbeds. The sediments around the Warratta Inlier are the furthers south these sediments are distributed in this part of the basin. They are interpreted to be a marginal equivalent of the typical Namur Sandstone succession.

Mesozoic exposures in the low-lying plains further into the basins in this area are dominated by Gumvale Formation sediments with some small exposures of Wittabrenna Shale. The sediments are typically hosted in escarpments along fault traces and in incised channels (Figure 6.35).

Figure 6.35. Exposures of Gumvale Formation sandstones in the basins in the south of the Warratta Inlier along the Warratta Fault (587989mE / 6722146mN). Sediments at this exposure are folded and exhibit a broad cleavage displayed in the blocky nature of the sandstones.

Subtle exposures of the sediments are also scattered around the plains. These exposures are subtle because they have been planed off such that they sit almost flat with the landsurface (Figure 6.36). These exposures are often identified by a change in the vegetation or a change in the colluvium. In the west of the area, exposures of the Gumvale Formation are prominent by abundant pearl bluebush (Maireana sedifolia) and occasionally cabbage tree wattle (Acacia cana). Both of these species have a geobotanical association with calcite (Cunningham et al. 1992; Chamberlain 2001). Other associations with the subtle exposures include an abrupt change in dominant colluvium. Abundant quartz and sandstone fragments were the dominant colluvium up to 10 m surrounding the exposure. Occasionally, these areas are marked by abundant petrified wood fragments.
The Gumvale Formation grades from the interbedded conglomerate sequences from the underlying Namur Sandstone into a succession of coarse-grained sandstones and siltstones. There is no distinct boundary between the two formations as the transition is gradational. Exposures in the south show the gradation occurring over as little as 1 m of sediment. This exposure shows the conglomerate beds becoming smaller and phased out vertically (Figure 6.37). The succession changes from a thick conglomerate sequence into the sandy units of the Gumvale Formation over approximately 6 m. The sequences start off being interbedded with only thin layers of the sandstone, and progress to sandstone with few conglomerate lenses.
Figure 6.37. Graphic log of the Mesozoic sediments exposed along a fault plane in the south of the Warrata Inlier (580747mE / 6724128mN).
The Gumvale Formation sandstones are dominated by fine- to coarse-grained poorly sorted calcareous sandstone with gravelly interbeds. Grains are dominated by sub-angular, monocrystalline quartz, with minor isometric pyrite, zircon and mica (Figure 6.38). The matrix is calcareous, occasionally partially silicified. On average the sandstones are dominated by 60-70% quartz, 30% lithics, authigenic indurations and isometric crystals. The sandstones are classified as litharenites, despite the abundant isometric crystals and indurations. This classification is assigned to the unit despite this because most samples have at least 25% lithic fragments (Figure 6.38 ii).

Figure 6.38. Plain polarised light photomicrographs of basal sandstones from the basin surrounding the Warratta Inlier: i) quartz sandstone with isometric pyrite and monocrystalline quartz; ii) monocrystalline quartz with minor pyrite, mica and lithic fragments with a calcareous matrix surrounding the grains (581027mE / 6724325mN).

Lenses of matrix-supported conglomerates are common amongst the sandstone units. Exposures of the conglomerate lenses range from 20 cm to several meters long. Clasts include sub-rounded metasediment, sub-angular granite, rounded to angular quartz and rare mafic igneous clasts. Many lenses have abundant gravel beds, dominated by angular quartz. The matrix is dominantly calcareous; however, in places has been ferruginised by authigenic ferruginous indurations. In the south of the area, the basal facies are dominated by gravelly sandstones. This sandstone is dominated by angular grains of quartz that are typically 2-4 mm wide. The gravel clasts are held together by a white chalky matrix that does not effervesce when exposed to HCl. When the matrix is scraped out of the sandstones, it effervesces slightly in HCl.
Gumvale Formation exposures in the south of the area are dominated by interbedded fine-grained sandstones and gravel beds. The sandstones typically have a higher lithic abundance, and are often highly ferruginised (Figure 6.39).

The top of the Gumvale Formation in the area is characterised by a series of interbedded claystones, siltstones and sandstones. These sediments are exposed haloing the inlier in the low-lying plains. Poorly consolidated claystones dominate the succession. These sediments are characterised by grey-brown claystones with yellow mottles. Occasional pallid zones typically < 2 cm are present. These pallid zones stick to a wet tongue when licked indicating the presence of kaolinite. Cone-in-cone structures are common, indicating that the sequence has undergone at least some dewatering. Minor marine fossils have been identified in this unit in the far north (Morton 1982). The inter-bedded siltstones are characterised by a pale brown-buff coloured mudstone with abundant micaceous grains, dominantly muscovite (Figure 6.39). The siltstones often have red, yellow and purple surface staining, and occasional white mottles. In places the siltstones have small round carbonate concretions < 5 mm. The sandstones are lithologically similar to the sequences in the basal Gumvale Formation with similar mineralogies, grain distribution and attrition.

The interbedded claystone, siltstone and sandstone relationship represents a continual change in base-level. The presence of marine fossils in the north indicates that at least part of this succession has a marine input. As with the sandstones from the basal Gumvale Formation, they indicate a distinct high-energy, possibly fluvial environment.

Caught up in the Gumvale Formation conglomerates and within the pebble units around the south are abundant fragments of petrified wood (Figure 6.40). The wood samples are fibrous, with the actual grain of the wood being preserved during induration. Thin-sections indicate that the wood cells and tree rings have also been preserved (Figure 6.40). Some samples have been opalised. The opal is dominantly a brown opal with some uncommon white-blue specimens in the clasts in the pebble beds in the far south. The clasts and thin-sections we compared to images and samples from databases of Mesozoic flora (Dettmann & Playford 1969; Retallack & Dilcher 1981; Burger 1986 & 1990; Dettmann et al. 1992; Batten & Dutta 1997; Philippe et al. 2004; Kunzmanna et al. 2009; South Australian Museum Fossil Collection Catalogue – viewed in 2008). From this analysis, it was established that the wood fragments belonged to the genus Araucarian of the family Araucariaceae. These trees are a species of gymnosperms, specifically an evergreen conifer. This genus has been identified in Australia in the Surat and Clarence-Moreton basins to the east, and globally in Chile, Argentina and Brazil (Retallack & Dilcher 1981; Burger 1986 & 1990).
Chapter Six: Tibooburra-Milparinka Inliers

Figure 6.40. Petrified wood: (i and ii) samples of petrified wood with opal veining; (iii) Plain polarised light photomicrograph of petrified wood sample from the south of the Warratta Inlier (576002mE / 6724521mN). Cell structure and tree rings have been preserved in the wood. Some opalisation and crystallisation over-printing the wood structure.

Globally, the oldest known gymnosperm palaeoenvironments colonised coastal regions, typically in the coastal plains, tributary river banks and in the flood-banks of the tributary rivers (Retallack & Dilcher 1981). While this criteria is not absolute, it further emphasises the depositional environment interpreted from the exposures of the sediments in the basin surrounding the inlier.

A prominent feature of the colluvial profiles surrounding the inlier are rounded and flattened quartz clasts. These clasts are characteristic of the beach pebbles seen haloing the Tibooburra Inlier and other landforms around the north of the area. The beach pebbles have been previously recognised within in the area as part of a major study.
focusing on the Warratta Fault (Anderson 2004; Anderson et al. 2004). This study identified these pebbles perched atop of a range bounding tectonic terrace along the Warratta Fault (Anderson 2004). Small exposures of Wittabrenna Shale are located in the basins far from the inlier. The most prominent exposure is located southwest of Sandstone Tank in the northwest of the area. Here the sediments are characterised by brown-grey claystones with abundant small (up to 6 mm long) grains of muscovite and minor accumulations of disseminated gypsum. The claystones are highly friable, often highly weathered, and in places associated with large rabbit warrens. The clays have preserved cone-in-cone dewatering structures and occasional shatter cone striations. Thin-sections of the claystones have isometric pyrite and the abundance of muscovite in the unit (Figure 6.41).

For the most part, these exposures are very subtle, and often hard to find. The most prominent exposures are in small incised drainage in the west of the inlier in the occasionally in small exposures in the sand plains and occasionally in the south capping the uplifted profiles of Gumvale Formation.

6.4. Field Site #3: The Milparinka Inliers

The Milparinka Inliers incorporates the Mt Poole, Mt Browne, Gorge, South Warratta and New Bendigo inliers and the plains and basins that surround them (Figure 6.42). This area is a merger of the southern portion of the Warratta 1:25,000 Geological Map Sheet (Greenfield et al. 2007) and the Mt Browne, Mt Poole and Gorge 1:25,000 Geological Map Sheet (Greenfield & Reid 2007b). The area is also an approximate merger of the Mt Browne and Mt Poole 1:10,000 Regolith Map (Davey 2005; Davey & Hill 2008) and the Southern Warratta Inliers 1:25,000 Regolith Landform Map (McAvaney 2006). These five bedrock inliers form the southernmost exposures from the Grey Ranges, and the south portion of the Tibooburra Ridge. The area host historic land marks, including: the ruins from the gold mining villages from the Albert Gold fields; the Milparinka ghost town; and the cairn that was erected at Mt Poole while the Sturt's Expedition camped at Depot Glen for six months.
Previous geological expeditions in the area were hampered by access limitations to areas in the west, and what was initially described as a ‘bland array’ of geology (Stevens 1988) in the main inliers. Until recently because of this, the area has been comparatively poorly understood. However, as part of the Tibooburra collaborative studies (Hill et al. 2007), the inliers have been the focus of landscape, regolith, structural and geological studies (for example Davey 2005; Davey & Hill 2005; Gibbons & Hill 2005; McAvaney 2006; McAvaney & Hill 2006; Greenfield & Reid 2007a). In particular these studies have revealed that the area preserves a contrast of how geological events and features are expressed actively and passively in landscapes (Davey 2005; McAvaney 2006). This is evident with the intense tectonism and its variations in expressions between the contrasting features of the landscape, namely the contrast between expressions within the defined fault planes in the bedrock inliers and subtle expressions causing Changes in the regolith in the surrounding plains (Davey 2005; McAvaney 2006).

As well as this, the Milparinka Inliers host some of the most extensive and well preserved exposures of the Mesozoic sediments in the Grey Range. Here, Mesozoic exposures range from subtle plains of sediments and saprock, to extensive vertical profiles exposed along fault zones. Unlike the other areas in the region, only two packages of Mesozoic sediments have been recognised, the basal transitional units fluvial units and some expressions of the shallow marine sediments.

6.4.1. Geomorphology and Structure
The area is characterised by vast, undulating plains that surround bedrock inliers and small bevelled mesas of Mesozoic and Cainozoic sediments.

Structure within the area is complicated, with at least three generations of recent faulting and folding evident in both the inliers and basins (Davey 2005; Davey & Hill 2005; McAvaney 2006). The main uplift and general
distribution and extent of all the inliers is controlled by a series of NW-SE trending, high-angle, reverse faults including the Mt Poole Fault and continuations of the Warratta and New Bendigo faults. The Mt Poole and Mt Browne inliers are the largest of the five bedrock exposures in the area (Davey 2005; Davey & Hill 2008). These inliers are characterised by a series of elongated, fold controlled valleys and rises and hills (Figure 6.43). The exposure of the folded ridges and valleys is primarily fault controlled.

Figure 6.43. Fold style, morphology and primary stress orientation for the structures that from the bedrock hills and ridges within the Mt Browne Inlier.

The Mt Browne Inlier is bound by three faults: to the west by the Mt Browne Fault, a high angle reverse fault, with a steep, stepped range front (Figure 6.44); and, to the east by a set of conjugate faults; on northeast by a NW-SE trending, and the south eastern one with a NE-SW trend. The Mt Poole Inlier is also fault bound, including: the NE-SW trending Mt Poole Fault.

The Gorge Inlier forms a series of shallow rises and low hills bound by a series of small, often localised faults. This includes the approximately N-S striking Mt Shannon Fault (Figure 6.44). The metasediments within the inlier have been folded about the approximate same axis as that of the Mt Browne and Mt Poole inliers; however, the expression of the folds is not as obvious as the exposures are not as prominent. The inlier is surrounded by shallow rises and undulating plains.

The South Warratta and New Bendigo inliers in the east of the area have been uplifted by the Warratta fault, and exposed by a series of NE-SW open folds. These inliers are considerably smaller than the Mt Browne and Mt Poole inliers, and even the Gorge Inlier. Despite this their morphology is rather similar to that of the larger inliers, particularly the Gorge Inlier. The east range of both inliers is bound by the Warratta Fault (Figure 6.44), the fault responsible for much of the uplift of the Warratta Inlier. Fault scarp retreat has occurred along the Warratta fault in the area, such that there is up to 10 m between the range front of the inliers and the interpreted location of the fault.

The hills and ranges within each inlier is controlled by a series of anticlines and synclines that are concordant with the NE-SW faulting from around the Mt Browne and Mt Poole inliers. The change in expression of the structure is interpreted to be a result of a thickening of the basin sediments in east, which behave in a ductile manner, as opposed to the metasediments which behave in a brittle manner. The exposures of the inliers are hosted within the anticlines, with the topography of the rises that form them bent around this axes (that is the highest part of the inliers are hosted within the axis).

In the south east of the area and the west of the area are small uplifted mesas, that form large table tops and in the west uplifted dome structures that have eroded away to form concentric stepped pinnacles. Mt Poole forms a
similar structure in the north. These mesas and pinnacles have been uplifted by the different generations of deformation that has uplifted the inliers.

Two parallel, NW-SW trending alluvial systems dominate the area, the Evelyn Creek and the Warratta Creek catchments (Figure 6.44 & 6.54). Both of these systems form anabranching streams fed by small channels and streams that shed off the inliers. These drainage systems follow a similar trend to the Warratta and New Bendigo faults. The feeding streams that shed off the inliers are also concordant with the NE-SW fault systems and the uplifted and down thrown blocks. Where the creek is penetrating through an uplifted block the stream profile is relatively straight, and where in a down thrown block, the stream profile meanders (Figure 6.44). Alluvial systems within the inliers are typically dominated by steep sided gorges with small ephemeral channels migrating through.

Figure 6.44. Structure and geomorphology map of the Milparinka Inliers.

6.4.2. Surficial Geology

The Milparinka area is characterised by five major bedrock inliers and several smaller inliers surrounded by low-lying plains of sediments from the Cainozoic through to the Mesozoic.
Several ‘pop-up’ structures, or mesas of Mesozoic or Eocene sediments also protrude from the low-lying plains. Bedrock is typically but not exclusively exposed within the bedrock inliers. Exposures are characterised by highly cleaved metasediments from the Cannala Beds (Figure 6.45). Exposures are typically slightly weathered with some expressions of moderate to highly weathered in areas of abundant tectonism and alteration. The metasediments are typically hosted in the rises, low hills, hills and mountains in the inliers. Small exposures are also scattered around the landscape in incised drainage, along fault plains and occasionally as subtle exposures in the undulating plains that surround the inliers.

Figure 6.45. exposures of metasediments from the Milparinka Inliers: (i) crosscutting quartz vein in the South Warratta Inlier (585989mE / 6721027mN); (ii) highly cleaved metasediments and associated colluvial accumulations at the break in slope in the Mt Poole Inlier (575042mE / 6717869mN); (iii) metasediment exposure atop of the Mt Browne Inlier (577225mE / 6706165mN).

Minor features of the bedrock exposures are large bedding parallel and cross cutting quartz veins and basalt and diorite dikes sills and pipes as well as some rhyolite exposures. These features are predominantly exposed within the inliers; however, some are exposed within the undulating plains.

Other exposures of saprock within the Milparinka area include the sandstones, conglomerates, siltstones, shales and mudstones from the Mesozoic and Cainozoic basins. These exposures are preserved within the undulating plains, uplifted along fault zones and in the mesas and ‘jump-ups’ in the south of the Tibooburra Dome. These sediments range from slightly weathered to highly weathered. Degree of weathering of these units is dependent upon lithology but also degree of silicification, any transported lags that maybe acting as barrier or armour, and associations with structure.
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Figure 6.46. Exposures of intrusives in the Milparinka area: (i) quartz vein in the north of the Mt Browne Inlier (579248mE / 6709809mN); (ii) Basalt exposure in the plains surrounding the Mt Poole Inlier (574598mE / 6709998mN).

Distinguishing between the two basins sediments can be difficulty; however, the Eyre Basin equivalents are characterised by a basal conglomerate (Figure 6.47), which can be identified in almost all exposures around the Milparinka area. Exposures of the Mesozoic are also relatively easy to identify as the type sections defined in the Warratta and Tibooburra inliers provide examples of the sediments for comparison.

Figure 6.47. Exposure of basal ‘jelly-bean’ conglomerate from south of the New Bendigo Inlier (6705005mE / 592361mN). Like most exposures of the conglomerate in the area, the sequence has been silicified.

Throughout the inliers, abundant colluvial attributes are also present (Figures 6.48 & 6.54). These accumulations are common around breaks in slope, on tectonic terraces, surrounding the base of landforms and on gently inclined slopes. In places the colluvial attributes dominate the regolith profile (Figures 6.48 & 6.49). This is particularly common where large quartz veins form rises or protrude at the top of the range.

The low-lying plains surrounding the inliers are dominated by colluvial regolith, namely sheetflow profiles (Figure 6.54). Immediately surrounding the inliers the sheetflow profiles are dominated by clasts of quartz, metasediments and sporadic sandstone clasts. These sediments are associated with fans shedding of the inliers, erosional rises in the fault zones directly associated with the range bounding structures, and in the immediate low-lying plains that halo the inliers.
Figure 6.48. Sheetflow profile shedding off a large quartz vein in the Mt Poole Inlier (57586mE / 671451mN). The vein is exposed along the axis of an asymmetrical anticline, such that the shallower side of the fold hosts the sheetflow accumulation. Karen Hulme for scale.

Figure 6.49. Sheetflow sediments surrounding the north of the Mt Browne Inlier. Sheetflow sediments are dominated by sub-angular quartz and metasediments with bands of red-brown, fine-grained sands and silts (578010mE / 6710424mN). Photo is looking southeast.

Further into the basin the colluvium is dominated by sandstone clasts and sub-angular to rounded quartz (Figure 6.50). The banding is typically less prominent in these areas. In the south of the area between the Gorge and Mt Browne inliers, where the plains are undulating and in places low rises, this zone is void of banding, such that it is colluvial not a sheetflow accumulation. Dispersed in amongst the clasts in the sandstone dominated colluvium and sheetflow is orange-brown sands and silts.

Figure 6.50. Colluvial profile dominated by sandstone clasts with abundant quartz fragments and minor exposures of sandstones and conglomerates (584461mE / 6705011mN). The profile is being sampled for regolith carbonate accumulations that are dispersed within the colluvium.
In the far plains around the southern edge of the Tibooburra Dome, the sheetflow profiles are characterised by abundant clasts of rounded and very highly polished silcrete pisoliths (Figure 6.51). The silcrete bands are dominated by orange-brown silts with abundant disseminated and acicular gypsum. These landforms also have minor exposures of the poorly lithified shales identified from around Tibooburra and Warratta inliers as pertaining to the Wittabrenna Shale.

![Figure 6.51. Rounded and highly polished silcrete clasts in the plains surrounding the Mt Poole Jump-ups (570024mE / 6710145mN).](image)

Similar to the indicators in the Warratta Inlier, changes in the general dominance in the sheetflow clasts characterise subtle exposures of bedrock and Mesozoic sediments. Accumulations of angular quartz clasts in the basins indicate low-lying exposures or metasediments and quartz veins, while exposures of the silcrete pisoliths indicates exposures of the Eyre Formation type sediments. While the general distribution of the sheetflow clasts indicates that the constituents in these regolith profiles are a combination of proximally and distally sourced, the indicator clasts describe here indicate that the underlying bedrock controls the dominate clast lithology in most profiles.

Aeolian sediments also dominate a large portion of the undulating plains in the Milparinka area, dominatly in the northwest and in the south (Figure 6.54). These regolith profiles are characterised by accumulations of red-brown fine sands and silts hosted either in extensive sand plains or in small parabolic dunes. Small, predominantly rounded quartz have been washed into many of these areas, and have been winnowed in with the aeolian sediments such that they too are a part of the unit, despite coming from a different transport medium. In places the sand plains and dune fields abut exposures of Mesozoic sediments, such that small wind ramps have formed (Figure 6.52).

![Figure 6.52. Aeolian sand accumulation abutting exposures of Mesozoic sediments along the New Bendigo Fault in the east of the area (589963mE / 6715546mN).](image)
The major drainage in the area is controlled by the Evelyn Creek system flowing down from the west of the Warratta Inlier. The channel is dominated by anastomosing and anabranching streams. The morphology of the channel is controlled by the uplifted blocks from the Mt Browne and Mt Poole inliers. The parts of the channel that correspond to the uplifted blocks are where the channel profile is relatively straight. The down thrown blocks correspond to the meandering parts of the channel. This association is attributed to the channel incising to base level in the up-lifted block, and forming a meandering profile in the down thrown block where channel is already at base level. Drainage within the inlier is characterised by steep gorge like channels, often with strath terrace formation around the edges of the gorges (Figure 6.54).

Figure 6.53. Drainage within the inlier at Depot Glen in the Mt Poole Inlier. View facing northwest (574237mE / 6708206mN).
ACah1 (active channel sediments / active channel): grey-brown, fine to coarse-grained sands, sub-rounded to rounded gravels, sporadic, rounded, lithic clasts hosted with in broad ephemeral channels. Vegetation is dominated by *Eucalyptus camaldulensis*. Exposures of Sandstone and metasediments

ACah2 (active channel sediments / active channel): red brown, fine sands to coarse pebbles, overlying slight to moderately weathered bed rock, hosted in steep channels. Vegetation is dominated by *Eremophila* spp.

Aap1 (alluvial sediments / erosional drainage): grey-brown, fine to coarse-grained sands, sub-rounded to rounded gravels with minor exposures of slight to moderately weathered sandstones and shales in shallow incised channels. Vegetation is dominated by chenopod shrubs.

Aed1 (alluvial sediments / erosional drainage): grey-brown, fine to coarse-grained sands, sub-rounded to rounded gravels hosted in low angled elongated fans. Vegetation is woodland species with minor chenopod shrubs.

Afa1 (alluvial sediments / alluvial fan): orange brown, fine sands and silts with minor sandstones, shale and silcrete exposures, hosted on a shallow, low-lying alluvial plain. Minor shallow drainage throughout. Vegetation is dominated by woodland species.

CHer1 (Sheetflow sediment / erosional rise): Subrounded to subangular lithic phyllite gravels, angular lithic quartzite fragments and rounded to subrounded silcrete and sandstone clasts with minor orange-brown, fine sands associated with moderate slopes of moderate to low relief (9-30 m).

CHep1 (Sheetflow sediment / erosional plain): Subangular to sub-rounded, slightly ferruginised, lithic and quartzose sandstone, matrix supported conglomerate and mudstone with sub-rounded silcrete clasts and sub-rounded to sub-angular quartz clasts and minor orange-brown, calcareous, fine sands.

SSep1 (Slightly weathered bedrock / erosional plain): Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Low relief, undulating landform (90-300 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts).
Figure 6.54. Regolith-landform map of the Milparinka Inlier. Legend on previous page, detailed legend in Appendix 5.
6.4.3. Mesozoic Sediments
The Milparinka area hosts abundant exposures of the Mesozoic sediments. These sediments have previously been interpreted to be lateral equivalents of the Gumvale Formation and the Wittabrenna Shale from around the Tibooburra and Milparinka inliers (Davey 2005; Davey & Hill 2005; McAvaney 2006; Davey et al. 2008). The Milparinka area also has extensive exposures of unconsolidated sediments also interpreted to be Mesozoic (Morton 1982; Davey 2005). Throughout the area the Mesozoic sediments have been exposed as a result of the areas intense tectonism (Davey 2005; Davey & Hill 2005). However, in places the saprock and unconsolidated sediments have been interpreted to be in their approximate original landscape context (Davey 2005).

Mesozoic sediment exposures within the area are dominated by the sandstones and conglomerates from the Gumvale Formation. These sediments are exposed along fault zones and planes, within creek beds, and in shallow, low-lying exposures within the undulating plains and rises that surround the inliers.

Vertical profiles of the Gumvale Formation are common along many faults within the basin, and in fault zones surrounding the inliers, particularly the Mt Browne, South Warratta and New Bendigo inliers. The most extensive vertical exposure of the Gumvale Formation is near the southern extension of the Warratta Fault (Figure 6.55) to the east of the South Warratta and New Bendigo inliers. Here, extensive cliffs of sandstones, siltstones and conglomerates have been exposed along a trend concordant with the fault trace. Where the Warratta Fault has caused uplift in the basins, the fault plain has undergone scarp retreat, such that the contemporary landscape is now a result of lithology as opposed to the faulting. Along the Warratta Fault the retreat has been minimal, approximately 5-10 m to the west (Figure 6.55) of where geophysical imagery places the fault. Lithological variations have resulted in the irregular nature of the scarp, as the more resistant lithologies have been preserved. This exposure contains the type section for the Gumvale Formation, previously defined in many studies including Morton (1982), Chamberlain (2001) and McAvaney (2006).

![Figure 6.55. View south of the stepped expression of the uplifted fault trace exposures of the Gumvale Formation along the Warratta Fault (Photo taken looking south from 588891mE / 6715575mN).](image)

Exposures are characterised by interbedded pebbly conglomerates, medium- to coarse-grained sandstones, pebbly sandstones and sporadic silty claystones (Figures 6.56, 6.58, 5.60 & 5.61). The exposures range from slight to highly weathered, with the differential weathering resulting in stepped expressions of the fault zone. Where sediment exposures are well preserved silicic and ferruginous indurations are present.

Few exposures of the bedrock – Mesozoic unconformity are present along the fault zone. However, where exposed, the base of the formation is marked by a conglomerate sequence. The sequence is characterised by large clasts of metasediments, quartz and occasional granite fragments (Figure 6.56). The attrition of the clasts varies greatly (Figure 6.56), indicating that the clasts have undergone different paths to be deposited in this sequence. The size of the clasts also vary from <1 cm up to 30 cm, with sporadic boulders up to 1 m wide. The
exposures of the conglomerate are often indurated typically ferruginised (Figure 6.56). In places, the apparent ferruginisation is superficial and a product of weathering.

In other areas, a similar conglomerate is exposed at the basal unconformity. In the south of the Mt Browne Inlier, the basal conglomerate is exposed within channels along the Mt Browne Fault and along the fault traces that splay within the basin to the west of Mt Browne. Here exposures of the conglomerate are characterised by matrix supported sequences with abundant metasediment clasts. The matrix component is typically a silty to fine-grained, occasionally calcareous sand. The clasts within the conglomerate beds are dominated by sub-rounded, elongated metasediment clasts (up to 15 cm), angular and rounded quartz clasts (up to 6 cm), minor small silcrete pisoliths (<4 cm) and sub-rounded mafic clasts (<5 cm). These exposures also host granite clasts. The highly weathered nature of these boulders has hindered identifying the provenance of the boulders. Optical mineralogy of the boulders does not highlight any specific features of the granites, such that determining provenance is not possible (Figure 6.57).
The exposures near the Warratta Fault have been previously defined as the type section for the Gumvale Formation. The exposure is dominated by different sandstone units with interbedded siltstones and occasional conglomerate lenses. The sandstone beds are dominated by intercalated packages of poorly sorted, medium-grained, buff-coloured sandstones and coarse- to pebbly, moderately-sorted sandstones (Figure 6.58). These sequences vary from 30 cm up to 2 m thick, with the intercalated packages in some areas exceeding 10 m. This unit is often vertically repeated, and laterally extensive within the profile (Figure 6.61). Planar and trough cross-bedding is present on both the cm scale and the meter scale, with minor microscopic, asymmetrical ripple marks in some of the medium-grained layers. Convoluted bedding is also common, often best highlighted where the sediments have multi-toned primary layering (Figure 6.62). Mineralogy of both the sandstone packages is quartz dominated, with sporadic accumulations of muscovite and pyrite. Thin-section analysis indicated minor plagioclase, opaque minerals and lithic fragments (Figure 6.62). The pebbly fraction is almost uniquely angular quartz clasts, typically no bigger than 1 cm (Figure 6.62 vi). Where the sediments have not been indurated, the matrix component of the pebbly sandstones is highly kaolanic.

![Figure 6.58. Exposure of Gumvale Formation from near the Warratta Fault. Sediments are characterised by interbedded sandstones, siltstones and thin clay beds and show displacement along a prominent small cross cutting fault (588711mE / 6716741mN).](image)

Trough-like lenses of matrix supported conglomerates are a common feature of the sandstones. These troughs range from 1-2 m wide and up to 1 m high, and are characterised by distinct oblate lenticular shapes that often inter-tongue into the surrounding sediments. These troughs also have abundant cross-bedding preserved within the sequence. The clasts within the lenses are dominated by sub-rounded metasediments (up to 20 cm), angular and rounded quartz (<6 cm) and sporadic large (up to 40 cm) granitic boulders and rounded clasts (Figure 6.59). Induration and surficial staining make distinguishing these lenses hard as the induration permeates all packages such that the lenses appear consistent with the surrounding rock.
The sandstone sequences are sporadically interrupted by beds of finer-grained sandy siltstones and silty claystones (Figure 6.60). These sequences are typically less that 2 m thick. In some areas this sequence bulges up to 4-5 m. This sequence is dominated by pale-brown claystones, that are often have leached, pallid zones (Figure 6.60) and pods that have been indurated by siliceous, ferruginous and gypseous cements. Occasionally these sediments have beds that have preserved bioturbation. The small burrows are typically characterised by small (< 4 cm) narrow, vertical pipes that have been in filled by goethitic (predominantly yellow and pale orange) cements. Mineralogy of the claystones are dominated by kaolinite and other clays that are more often than not too highly weathered to determine mineralogy optically. Minor detrital components are present in thin-section (Figure 6.62), typically sub-rounded monocrystalline quartz and lithic clasts. The silty sequences often have an abundance of micas, dominantly muscovite.
Figure 6.61. Normalised log profiles from the extended profiles near the Warratta Fault. All logs are taken from a section of the uplifted block approximately 110 m ASL, with length of exposures occasionally compromised due to colluvial overburden and build up. The log sections were recorded opportunistically along the cliff profile. Logs have been aligned in horizontal profile in the schematic for simplicity.
Figure 6. Normalised log profiles from a 150 m extension of the Warratta Fault. All logs are taken from a section of the cliff at 120 m ASL, with length of exposures occasionally compromised due to colluvial overburden and build up. The log sections were recorded at approximately equal spacing along the cliff profile. Logs have been aligned in horizontal profile in the schematic for simplicity.
1. Fine- to medium-grained, poorly sorted, sub-rounded to sub-angular sands, with pebbly and gravelly lenses. Mineralogy is dominated by monocrystalline quartz with minor muscovite, pyrite and plagioclase. Sandstones are partially indurated, typically siliceous, with occasional ferruginous bands and have a yellow-brown surficial goethitic staining. Photomicrograph of well sorted sandstone: quartz dominated detritus with ferruginous cement indurating. Minor pyrite and muscovite.

2. Medium- to coarse-grained, poorly to moderately sorted, sub-angular to sub-rounded sands within a clay matrix (kaolinite, and occasional smectite). Detrital Mineralogy is dominated by monocrystalline quartz, muscovite, feldspars and occasional lithic fragments. Clays are highly weathered and hard to distinguish in Thin-section, however rock fragments adhere to the tongue when licked indicating kaolinite. Minor calcite and gypsum veinlet throughout. Photomicrograph of poorly sorted sandstone: quartz dominated detritus with weathered clay matrix, and microstructure calcite veinlets. Minor muscovite and plagioclase.

3. Coarse-grained to gravely, poorly sorted, angular to sub-angular, buff to yellow-coloured sandstones. Detrital mineralogy is dominated by monocrystalline quartz grains and milky quartz gravels, minor feldspar clasts and lithic fragments (including pyrite typically <0.5 mm), muscovite and mafic fragments). Photomicrograph of poorly sorted coarse-grained sandstone: quartz dominated detritus with ferruginous induration (opaque matrix). Minor muscovite and plagioclase.

4. Medium-grained, well sorted, sub-angular to sub-rounded, buff-coloured sandstones, with poorly sorted gravely lenses and beds. Mineralogy is dominated by monocrystalline quartz with minor components or polycrystalline quartz and lithic fragments. Sandstones are typically silicified, with a minor yellow-brown surficial staining. Photomicrograph of well sorted sandstone: quartz dominated detritus. Detrital dominance (>95%): quartz arenite.

5. Matrix supported conglomerates with clasts up to 10 cm, with minor pebbly and gravelly beds and boulders. Clasts are dominated by sub-angular metamatrix sediments, angular quartz (typically >6 cm) and rounded quartz (typically <4 cm). Sporadic granitic boulders.

6. Medium- to coarse-grained, occasionally gravelly, sub-angular to sub-rounded, white, red and pale brown sandstones. Mineralogy is dominated by monocrystalline quartz with minor lithic fragments. Sandstones are ferruginised, but often moderately to highly weathered.

7. Interbedded fine-grained, well sorted sandstones and silty to mudstones. Detrital mineralogy is dominated by monocrystalline and polycrystalline quartz, minor lithic fragments and isotopic pyrite. Sediments are typically ferruginised, often forming banded patterns.

Figure 6.62. Log correlation from the described sections. Description of the seven major units have been provided as have some plain polarsied light photomicrograph sections (each section has an associated description). Photo (i) Colluvial slope of highly ferruginised sandstone clasts; (ii) convoluted bedding and surficial staining on a sandstone cave incised into the range front (); (iii) fine-grained sandstone (587115E / 6716741mN); (iv) basal conglomerate (590634mE / 671017mN); (v) gravel units similar to the unit at Tunnel Hill (592372mE / 670594mN); (vi) fine-grained, highly weathered sandstone (590042mE / 671686mN).
Other exposures of Gumvale Formation sediments have been uplifted and exhumed along fault traces in the Milparinka area. Exposures along fault traces include: steep cliff like profiles such as along the Milparinka air strip; low hills and rises as seen to the southwest of Mt Browne where the Banana Finger Fault splay has created an undulating landscape (Figure 6.50); and as discontinuous mesas such as the ones to the east of the Warratta Fault in the plains surrounding the New Bendigo and South Warratta inliers (Figure 5.63).

The Gumvale Formation also forms subtle exposures in the Milparinka area, including: undulating plains of sandstones and conglomerates surrounding the Mt Browne, Gorge and Mt Poole inliers (Figure 6.64); Evelyn Creek channel profile and stream bed; exposures that have been dragged up and overturned against fault planes; small rises within the sand dunes to the east of Mt Browne; minor low-lying exposures surrounding the Jump-ups; and, knick point exposures in channels and incised drainage (Figure 6.65). This saprock consists of buff-coloured sandstones and matrix supported conglomerates. The buff coloured sandstones are dominated by slightly silicified, occasionally ferruginised, medium- to coarse-grained, moderately sorted quartzose sandstones.
Thin-sections of the samples indicate that there are two types of sandstones, including: quartz dominated arenites; and, silty, quartzose sandstones (Figure 6.67). Where the exposures have not been indurated, the sandstones are often calcareous, effervescing when dilute HCl is poured on them.

Gumvale Formation exposed within and surrounding Evelyn Creek is dominated by exposures buff coloured, coarse grained sandstones similar to the exposures throughout the sand plains surrounding Tibooburra (Figure 6.65). These sediments were initially mapped as Gumvale Formation (Rose et al. 1967); however, were revised to Eyre Formation equivalents (Stevens 1988). The revised classification was primarily established because of the sediments are topographically equivalent to the Eyre Formation sediments that cap the Wittabrenna Shale exposure at Peak Hill due east of Milparinka. In the Milparinka area, an exposure of these sediments along a cliff profile at the Milparinka airstrip is capped by ‘jelly-bean’ pebbles, characteristic of the base of the Eyre Formation. The pebbles are unique to the base of the Eyre Formation indicating that the sediments below are in fact older than the Eyre Formation. Furthermore, these sediments are also lithologically equivalent to the coarse-grained sandstone packages from around the south of the Warratta inlier and many exposures around the Tibooburra Inlier that have been dated as late Jurassic (Morton 1982). The sediments are also lithologically different to the Peak Hill Eyre Formation sediments.
For the most part, where the sediments are exposed they are indurated. Ferruginous indurations are most abundant in the basin between the Mt Browne and Gorge inliers and to the north of the Mt Poole Inlier nearing the Warratta field area. The ferruginous indurations are both haematitic (deep red and brown staining) and goethitic (dark purple, green and yellow staining), with occasional manganese contributions, mostly as concretions scattered around as a surface lag. Siliceous indurations are widespread and are very common. Optical analysis indicates that the silcrete has formed as both a relative and an absolute accumulation of silica. The concentric infilling patterns and the preservation of other minerals in the unit are characteristic of the absolute accumulations. This is common in the exposures in the plains surrounding the New Bendigo Inlier in the east (Figure 6.67 vi & viiI). In contrast to this are the silcrete in the fault zones around the Milparinka Township. These indurations are characterised by monocrystalline quartz filling in pore spaces around quartzose sediments, with a slight ferruginous staining. These pods are typically associated with ferruginous, specifically haematitic indurations. These indurations are indicative of a silcrete formed in acidic environments, which leached the rock, leaving behind almost only quartz. The associated ferricrete formation is also a result of the acidic conditions. These indurations occur together around faults and fault zones. This occurs as the fault produces a change in base-level which results in a change in the water table with respect to regolith profile. The causes a change in the redox profile. In areas where the base-level has been uplifted, a relative drop in the water table occurs. This generates an increase in the oxidizing environment, facilitating weathering of the sulphate. The sulphate is suspected to be sourced from the abundant pyrite in the metasediments that is often a detrital component of the Gumvale Formation, and the isometric pyrite found in the Wittabrenna Shale. The oxidation of the pyrite results in ferrolysis and acid-sulphate weathering. Acid sulphate weathering produces high acidity in the ground water. This leads to the leaching of aluminium and other base metals leading to silicification resulting from a relative accumulation of silica. The abundance of gypsum in Wittabrenna Shale sediments supports this mechanism of silcrete formation as gypsum is a sulphate that forms as a bi-product of sulphide weathering.

The top of the Gumvale Formation is marked by a series of interbedded coarse- to fine-grained sandstones and claystones. These sediments are dominated by monocrystalline quartz, with minor lithic fragments dominantly mica, plagioclase and occasional mafic grains. The finer-grained sediments are dominated by clays and occasional silt particles.

A common feature throughout the Gumvale Formation in the Milparinka area is petrified wood fragments. The fragments range from 2 cm up to 1 m long. Some fragments have been weathered and as such are rounded; others still have the fibrous wood textures seen in the fragments around the Warratta Inlier. Plains near the Milparinka Township have clasts present within the colluvial plains. In places, these clasts dominate the colluvium in these plains. Photomicrographs of the wood from around Milparinka indicate that it is the same species as the clasts from Warratta (Figure 6.66). The clasts around the Milparinka Inlier have abundant opal veining.

Associated with these sediments are surficial accumulations of hardpan RCA’s, which form along joints and in small rill weathering crevices.
Figure 6.67. Photographs of Gumvale Formation sandstones and associated photomicrographs: (i and ii) coarse-grained, silicified sandstone exposure (583488 / 6701985). Concentric cementation patterns indicate an absolute accumulation of silica; iii and (iv) Highly ferruginised, liesegang sandstone (591576 / 6716102); (v and vi) ferruginised sandstone. Grains are fractures as a result of fault movement (589869 / 6714844) vii and viii) partially ferruginised sandstone; ix and x) arenaceous sandstone (577557 / 6716102).
Palaeocurrent measurements were obtained from the basal medium- to coarse-grained sandstones from the Gumvale Formation. This particular bed was chosen to take the measurements from as it is in the same approximate lithological and stratigraphical position as the beds that were used to measure the palaeocurrent directions in Tibooburra (Chamberlain 2001). Exposures of this bed are typically confined to the lower-lying positions within the landscape, often associated with stream exposures and the undulating plains to the west. Around the South Warratta and New Bendigo inliers, exposures of these sediments are often limited to vertical profiles, where the sediment and structural relationships are occasionally distorted or poorly exposed as a result of the orientation of the exposure. Where this has occurred, no measurements were taken. The intense structural deformation within the area, has considerably re-orientated the sediments such that the foresets measured do not reflect the actual Mesozoic flow patterns. To account for this, structural corrections were applied based upon the structural measurements obtained during earlier tectonic and structural mapping projects (Davey 2005; McAvaney 2006).

The palaeocurrent measurements were typically consistent, with a general flow vector trends to the NE (Figure 6.68). The consistent flow patterns on both sides of the inliers are indicative that the contemporary topography was not in existence during deposition. However, bimodal flow vectors are common in areas where bedrock is near surface or sub-cropping. This reflective of a localised eddy currents that were flowing around bedrock obstructions. A change of flow direction occurs around the south of the Mt Browne Inlier. Here the flow vectors have a SE trend (Figure 6.68). This change is a result of a change in flow path, most likely as a result of an obstruction, such as a small rise or pediment in the landscape.

Figure 6.68. Palaeocurrent directions for the Milparinka Inliers expressed as directional arrows plotted against the geomorphology map of the Milparinka Inliers.
Regolith mapping within the Milparinka area has identified that the colluvial sediments surrounding the inlier are dominated by sub-angular to angular quartz, metasediments and sporadic igneous clasts with red-brown fine sands and silts and minor exposures of sandstone and metasediments. However, in places, in amongst the dominating clasts are a series of rounded and flattened clasts of quartz, quartzite and various igneous lithologies. The attrition of the pebbles is indicative of one of two options: 1) the quartz veins weather and erode into the small flattened pebbles because the veins are somewhat ‘sheet-like’, and as such the small flattened pebbles form; 2) the clasts have been re-worked in a tidal environment where they have been exposed to a strong ‘swash’ or turbulent current in which the rounded nature of the clast forms, and is then flattened and smoothed by a gentle back-wash or lower velocity current (i.e. a beach environment). Colluvium surrounding the inlier is littered with clasts of quartz that have weathered out of the veins. These clasts are typically angular, often sharp and occasionally have conchoidal fracture patterns on the face of the clasts. The clasts are occasionally sub-rounded, very rarely rounded and often blocky, not flattened. Thus the pebbles are interpreted to be beach pebbles.

The attrition of the clasts is similar to the clasts around the Warratta and Tibooburra inliers. These beach pebbles are typically limited to the edges immediately surrounding the Mt Browne, Mt Poole and occasional exposures around the South Warratta New Bendigo inliers. The pebbles are in greatest abundance around the south east of the Mt Browne Inlier where the clasts lap up onto the gentler slope of the inlier. The location of these sediments coincides as a lateral extension of the Wittabrenna Shale up against the ranges.

Along the western rangefront of the Mt Browne Inlier several generations of tectonic terraces are present. These terraces have been previously attributed to neotectonic reactivation of the Mt Browne Fault (Davey 2005; Davey & Hill 2005). There are three primary terraces along this rangefront. The middle terrace, typically the largest of the three terraces (Davey 2005) hosts the rounded clasts associated with the beach environment. The top terrace and the summit surface of the inlier are void of these pebbles. The presence of the pebbles around the terrace indicates that the uplift occurred post deposition. The lack of pebbles on the summit surface terrace and the high points of the inlier indicate that either clast preservation is not as great on high points of the landscape due to greater erosion or that part of the inlier was uplifted pre-deposition indicating an approximate landsurface from the onset of the marine environments. The complete lack of pebbles and the relatively gentle slope, even after several generations of tectonics of the east side of the inlier favour the pre-Mesozoic uplift. The western side of
the inlier along the Mt Browne Fault is steeper, there has been considerable erosion, and the preservation of the clasts along the terraces is poor.

Wittabrenna Shale exposures are also common in the Milparinka area. The sediments are a combination of different fine-grained sequences, dominantly a micaceous mudstone and a pallid shale. A large exposure of the Wittabrenna Shale is present in the basin to the north of the Mt Browne Inlier where a fault has exhumed a section of the formation. This exposure has also been etched and exhumed since faulting, with trough like depressions exposing a further 1 m of section. The sediments are dominated by a repeating sequence of white-grey, friable mudstones. These sediments are further characterised by an abundance of muscovite and occasional quartz grains. Intercalated with the mudstone sequence are thin beds of shaly claystone. These beds are characterised by white-pale brown clays that in places are sticky to touch. The dryer clay sequences stick to a wet tongue indicating that the sequence has abundant kaolinite.

![Figure 6.70](image-url)  
*Figure 6.70. Exposure of the Wittabrenna Shale along a fault plane in the basins to the west of the Mt Browne Inlier. Exposure shows the fine-grained nature of the dominate sequences and the friable nature of the profile (575766mE / 6705281mN).*

Other exposures of the shale are abundant in the sand plains in the south of the area. Here silicified exposures of siltstones and claystones protrude from the sand plains and in some places have small wind ramps built up on them. Photomicrograph analysis of the sediments shows the different indurations and how they have affected the sediments. Exposures of the silicified sediment are considerably different to the smooth, polished and dense induration common to the Gumvale Formation. The silicification is hard and brittle, in places very crumbly. When struck with a hammer, the exposure breaks off in blocks, rather than the typical concoidal fracture pattern associated with siliceous rocks. The infilling cement is granular, occasionally porous, and sometimes has small grey veins running through it. The cement is easily mistaken for the kaolinitic clays that are abundant in the pallid Wittabrenna Shale sequence, or for a hard-pan regolith carbonate accumulation; however, it does not effervesce or stick to a wet tongue. Photomicrographs of the sediments indicate that the induration is in fact siliceous, dominated by a concentric chalcedony pattern (Figure 6.71). This sequence also has embayed quartz grains with the cryptocrystalline chalcedony infilling both the pore spaces and embayments (Figure 6.71). These features are all indicative of a silcrete formed by an absolute accumulation of silica.

An absolute accumulation of silica is often associated with basic environments. Silica is typically but not exclusively mobilised by alkaline fluids. An absolute accumulation defines a silica body in which the silica is
 deposited opposed to being all that is left behind as with a relative accumulation. A basic environment also supports the embayed nature of the quartz grains.

The porous nature of the cement and the blocky habit of the fractured rock is attributed to the cryptocrystalline nature of the silica and the concentric ‘growth’ patterns. Both of these features indicate that the cement does not have the typical strong silica bonds throughout the entire cement, but rather only with the relative layer that it formed within.

![Figure 6.71. Plane polarised light photomicrograph of the silicified siltstone from the sand plains to the south of the Mt Browne Inlier. (583491mE / 6702429mN)](image)

Wittabrenna Shale sediments are also exposed in incised drainage along the northwest of the Mt Browne and south of the Mt Poole Inliers. These sediments are characterised by the pale-brown claystones and abundant disseminated and acicular gypsum accumulations. The claystones have distinct diagenetic structures preserved, namely cone-in-cone dewatering structures that are a common feature of the marine sediments in the basin. In places the claystones have yellow mottles indicating where pyrite has been weathered out of the formation. These sediments also have minor indurations which are typically ferruginous.

Subtle exposures of the Wittabrenna Shale are difficult to define, as fine-grained beds are common interbedded within the top part of the Gumvale Formation. However, in the plains in the far west of the area where the silcrete pisoliths dominate the landscape, the underlying sediments are characterised by pale-brown silts, muds and clays with abundant disseminated and acicular gypsum and small clay shatter cones all characteristic features of the Wittabrenna Shale.
6.5. Discussion
The Tibooburra-Milparinka Inliers are considered to be a regolith dominated terrain. The landscape is characterised by several Cambrian to Ordovician bedrock inliers surrounded by extensive undulating gibber plains from Sturts Stony Desert. Landscape remnants of the Mesozoic are preserved within the landscape. Some of these features have been uplifted, exhumed and etched, so are estimated to be in a landscape position relative to that of the Mesozoic landscape. The presence of Mesozoic remnants that have been continually exposed within the landscape provides an interesting conundrum as the area is tectonically active and has been since the Mesozoic. These exposures are integral to the understanding of the evolution of the Frome Embayment as they provide a contrast between marginal sediments (for example around the southern Milparinka Inliers) and basinal sediments (for example some of the uplifted profiles along the Warratta Fault) within a landscape context. Palaeo reconstructions of the Mesozoic from the Tibooburra-Milparinka Inliers are focused around constraining the landscape relationships with Mesozoic Remnants.

6.5.1. Pre-Mesozoic Landscape
The general grain of the pre-Mesozoic landscape is attributed to the east verging, meso-scale isoclinal folds that deform the Easter Monday, Jefferies Flat and Canella Beds and the various igneous intrusions. This deformation is responsible for the intense cleavage that has formed within the metasediments and the abundant corestone-tors that have formed from preferential weathering along an extensive joint set within the Tibooburra Suite Granites. Palaeocurrent vectors from the Milparinka area indicate that the inliers in the south did not have their contemporary topography pre-Mesozoic. The flow vectors are consistent across both sides of the Mt Browne and Mt Poole inliers. Had the inliers been uplifted in the pre-Mesozoic landscape there would have been at least some variation in the flow vectors resulting from the deflection a large mountain range would have cause. Beach pebbles overlying tectonic terraces also support that the Warratta Inlier was also low lying during this time. The beach sediments currently sit elevated in the landscape (up to 150 m above ground surface) on one of the three range bounding palaeoterraces along the Warratta Fault. For these sediments to be reflective of the Mesozoic landscape positng would have required at least 150 m of erosion of the marine sequence from the plains surrounding the inlier. While this is possible, it is highly unlikely. The two tectonic terraces that are topographically lower then the one with the beach sediments indicate further uplift, and have no association to distribution of the Mesozoic sediments and as such are interpreted to be younger generating folding. A similar scenario is present along the Mt Browne fault where the pebbles sit within an approximately equivalent landscape position. At Mt Browne regolith profiles and Eyre Formation sediments have been used to date the tectonism that uplifted these terraces (Davey 2005). The terrace formation is attributed to post Eocene deformation, and as such, the current extent of the inliers are a combination of pre – syn – post Mesozoic deformation.

6.5.2. Late Jurassic to Early Cretaceous : Initial basin formation
In the north of the area, determining the nomenclature to assign to a particular body of sediments proved to be very difficult. This is most likely the reason for the many different interpretations and classifications previously assigned to them. The biggest challenge is with the sediments that form the unconformity with the underlying bedrock. These are the sediments that have fluctuated between being classified as Eyre Formation and Algebuckina Sandstone equivalents. However, it is easy to correlate these sediments locally as the units are fairly wide spread, and often lithologically distinct. Because of this, sandstone units that had preserved fossils were easily correlated across the area, and as such general relationships between these sequences and the other sequences made it easier to define formations. A challenging aspect of sediment classification occurred when trying to distinguish the difference between the Gumvale Formation and the Injune Creek (Algebuckina Sandstone equivalents). This was a particular issue around the Tibooburra Inlier, where the sediments are a not as marginal as they are around the Milparinka area. Both successions of interbedded sandstones, conglomerates
and claystones. However, the Gumvale Formation type section along the Warratta Fault shows the Gumvale Formation as being dominated by finer-grained sandstones interbedded with claystones and siltstones with conglomerate and gravel lenses. The exposures of the Injune Creek Formation from Tunnel Hill and Quarry Hill where the sediments have been dated by fossils, are typically very coarse-grained, have large (up to 2 m thick) conglomerate beds and gravels. The Gumvale Formation type section is lithologically equivalent to the Cadna-owie Formation sediments common in drill holes and also from around the Northern Flinders Ranges (see chapter 5).

Distinguishing these sediments from Eyre Formation sediments proved to be simpler than expected due to the widespread presence of the petrified wood fragments. While it is possible that the wood fragments have been reworked into younger unit, the fragments all appear to be relatively unworn, fragmental and somewhat angular with fracture patterns (including choncoidal fracturing) well preserved. If these clasts were distally sourced or had been reworked the attrition of the clasts would typically be more rounded. The angularity and preservation of the fracture patterns indicate that they have not travelled very far, nor have they been reworked.

The detrital component of the fluvial Mesozoic sediments, particularly the Algebuckina Sandstone equivalents and the Gumvale Formation are dominated by monocrystalline quartz, with minor polycrystalline quartz, muscovite, plagioclase and granitic grains and clasts. There are also localised accumulations of K-feldspar, biotite and mafic fragments. Monocrystalline quartz is indicative of an igneous detrital source. Locally the bedrock is dominated by metasediments with only minor igneous intrusions. While the intrusions have contributed some of the detritus, such as the localised feldspar, biotite and mafic accumulations, these intrusions are dominated by mafic and intermediate bodies and thus not a likely source of the quartz detritus. Furthermore, the typical sub-rounded attrition of the grains supports a considerable transportation of the sediments. Palaeocurrent indicators in the south of the area define a flow direction to the northeast. This indicates that the source of the sediments is potentially from the reworking of sediments from the south top southwest of the area, where there are several older volcanic units that the sands could be sourced from.

The depositional environments from the basal Mesozoic to the Gumvale Formation are considerable different. The coarse nature, lenticular sediments bodies and abundant conglomerate and gravel beds in the basal Mesozoic are indicative of extremely high-energy depositional environments. The lenticular sediment bodies are synonymous with channel profiles and river beds. In contrast the Gumvale Formation is characterised by interbedded fine-grained sandstones and claystones with occasional conglomeratic facies. The Gumvale Formation are also highly variant, with the sequences being as small as centimetres, indicating frequent changes in depositional environments. The Gumvale Formation sediments are highly characteristic of a coastal plain setting where the depositional environment fluctuates regularly, and has terrestrial inputs, such as fluvial environments, as well as marine, such as estuaries. The coastal plain environment is also supported by the marine and fluvial sediments interfaces which are reflected within profiles regularly. This indicates the common trait of the Cadna-owie Formation sediments of the cycling marine transgression-regression phase. The Gumvale Formation sediments are wide-spread compared to the Basal Mesozoic. The Injune Creek Formation and equivalents are limited in exposure to the Tibooburra Inlier. A similar scenario was seen in the Northern Flinders Ranges where the initial interpretation of the Algebuckina Sandstone Equivalents were thought to be limited to the far north of the area. This was based upon a time correlation of the sediments and not a lithological association. This lead to the reclassification of many thought to be Cadna-owie Formation profiles being reclassified as Algebuckina Sandstone. However, in the Tibooburra Milparinka Inliers, the correlation is a lithological association. The basal sediments further south around Milparinka and Warratta are dominated by the transitional natures sediments with the claystone units and the finer-grained sandstones. Exposures around the Mt Browne and Gorge inliers have abundant conglomerate sequences; however, exposures shoe these to be more lobes rather than channel profiles. The conglomerate sequences are interpreted to be more of a debris flow than a channel flow.
6.5.3. Early Cretaceous Marine Environments

The cyclic transgression-regression events represented in the interchanging sequences at the top of the Gumvale Formation were followed by a major Marine Transgression. Evidence for the major marine incursion are seen as far down as the Mt Brown and Gorge Inliers where beach pebbles and shorelines can be tracked lapping up onto the inliers. The main marine transgression culminated in the deposition of the main part of the Rolling Downs group, which is represented within the area as the Wittabrenna Shale. These sediments are exposed within the sand sheets further north around the Mt Browne Homestead. As with the other areas within the basin, the beach pebbles are seen to be a lateral landward extension of the main marine succession. The presence of these sediments around the various inliers, with the Wittabrenna Shale sediments clearly extending past them indicates that the shore lines are onlapping in the middle of the sea (Figure 6.72). This indicates the presence landforms interfering with the general flow of the sea that is intra-basinal highs.

The Wittabrenna Shale sediments are limited in exposure, primarily due to their friable nature and poor lithification leaving them to be unstable and easily eroded. This is particularly evident within the plains surrounding the Mt Poole inlier where the selenite veins and disseminated gypsum are spread within a grey-brown silt with abundant rounded silcrete clasts, indicating where the sediments are so highly weathered it would
be easy to mistake them for an aeolian contribution to the landscape or a poorly formed soil. Exposures of the Wittabrenna Shale around Milparinka where fault plains have exposed them indicate a relatively homogeneous silty claystone unit. This is concordant with exposures around the Tibooburra inlier.

Following the deposition of the Wittabrenna Shale, a reduction in sedimentary influx occurred, particularly within the south of the area. Some studies have suggested that there is the second phase of the main marine transgression around Tibooburra (the Oodnadatta phase); however, that was not recognised within this study. Winton Formation sediments are exposed further north out of the scope of this study around Olive Downs. During this time the metasedimenst and Eromanga Sediments underwent weathering, induration and deformation.

6.5.4. Contemporary Landscape

The perplexing factor with the exposures of the Mesozoic sediments surrounding the Tibooburra-Milparinka Inliers are the abundant landscape remnants that have been exposed since the Mesozoic. The most common and wide spread is the beach sediments that are scattered in profile across the area. These sediments are shown to be lapping up on to contemporary rises and seem to support the approximate shore line profiles that would have been expected when accounting for all the tectonism. While some of these sediments have been uplifted within the landscape and sit topographically higher than they initially did, the general profile and structure of the sediments still mimics a shoreline that you would see at a contemporary beach. One of the contributing factors to this is that the dominant and in places only pebble in these formations are vein quartz. Quartz is highly resistant to weathering and subsequent erosion and as such has survived the landscape. Furthermore, the area has experienced an increasing in aridity since the regression of the seaway, and as such has not been exposed to environmental condition that would accelerate movement and re-distribution of these sediments. While there has been considerable tectonics in the area, the uplift has occurred over a great period of time. Previous studies have shown no evidence of cataclysmic tectonics (for example Anderson 2004; Davey 2005; McAvaney 2006). Slow and small amounts of uplift have not resulted in disruption of the sediments, indicating another key factor in their preservation.

In places, the beach pebbles have also helped to preserve the exposures of several other Mesozoic sediments such as in the plains surrounding the Warratta Inlier where they cap sandstone exposures. The quartz pebbles act as an armour protection the remnants from being eroded away.

Several exposures have been silicified or ferruginised and as such have been preserved by the reinforcing of the secondary cement.
Chapter Seven: Landscape Evolution of the Frome Embayment

The regional and localised studies across the Frome Embayment indicate that the morphology, extent and sedimentological trends in the southern Eromanga Basin are largely a product of morphotectonic, climatic and eustatic processes that have been active since the Proterozoic. Subsurface profiles and surface exposures of the sediments indicate that many of these processes have continued to effect the basin after the Mesozoic, and as such the contemporary landscape holds keys to the long term geological evolution of the area. The five major divisions in the basin’s history are discussed here, and include: 1. the pre-depositional landscape, referred to as the pre-Eromanga landscape as not to confuse it with a pre-Mesozoic landscape which may have had a different form to what is preserved directly prior to the onset of the Eromanga Basin sedimentation; 2. the initial basin formation stage; 3. marine deposition; 4. the final stages of basin formation; and, 5. the contemporary expression of the Eromanga Basin.

7.1. Pre-Eromanga Landscape

The pre-Eromanga structural grain of the embayment is a product of a series of deformation and epeirogenic generations. The general characteristics and attributes of the bedrock underlying the embayment is controlled by the Curnamona Province, Arrowie Sub-basin, and the Delamerian Orogen to the east and centre of the embayment, the Wonnaminta Block and Thomson Orogen to the west. The seismic, magnetic and gravity show that the Curnamona Pluton defines the east and central portions of the embayment. While the province is considerably older than the embayment, it controlled features such the distribution patterns of the Arrowie Sub-basin and the Benagerie Ridge. Both of these features have been deformed by considerable tectonic events that occurred pre-Eromanga, such as the Delamerian Orogen, that have been interpreted to be preserved within the pre-Eromanga land surface that was present at the onset of basin formation.

In the west of the area, the bedrock and pre-Eromanga landscape is controlled by a post-Proterozoic orogenic structure and deformation that is associated with the Delamerian Orogen. This was one of the areas of great contention prior to this study because of the several schools of thought on the evolution of the Flinders Ranges. A common belief was that the landscape was relatively flat lying, with the contemporary topography being a recent feature (for example: Paul et al. 1999; Celerier et al. 2005; Quigley et al. 2007 a & b). Structure associated with this orogenic zone, has a typical N-S trend. The presence of fans and channel sediments within the Algebuckina Sandstone equivalents (basal Mesozoic unit) within and surrounding the ranges, support alternative interpretations that there was at least some relief within the Mt Painter Inlier during the first phase of basin formation. The sediments in the Paralana Valley recognised as remnants of a palaeo-channel were also recognised to have been deposited in a valley that had a similar morphology to that of the current valley. While it is unclear as to the amount of relief across the valley at the time of deposition, the extent of the sediments is limited by the contemporary valley walls, with no evidence of sedimentation within the inlier beyond the walls of this valley. It is entirely possible that sedimentation did exceed these bounds, and has simply been eroded or has...
not yet been recognised within the contemporary landscape. However, evidence of these features is yet to be found despite extensive studies within the area (Blight 1981; Wilson 2007; Hector 2007). Such morphology would require there to be some uplift within the ranges at the time of deposition.

Further north, around the Mt Babbage Inlier, the Algebuckina Sandstone equivalents are preserved within the landscape onlapping the small granitic rises in the Mt Babbage Inlier. These exposures preserve the original onlap patterns in the sediments, particularly within vertical exposures along fault zones showing the typical onlap sediment patterns. The onlap patterns indicate the exposure of the granitic bedrock during the Mesozoic around Mt Babbage. It was shown that the sediments do not entirely cover the small granitic rises, and as such they were exposed as intra-basinal highs. This is supported by the presence of the shorelines around the small granitic rises near Mt Babbage and around the Mt Babbage Inlet. The shorelines onlap the polished granite and flank them, indicating the extent of deposition and the presence of small intra-basinal highs.

Seismic interpretation on surveys to the east of the ranges further confirms that there was uplift at the onset of the basin formation in the west of the embayment. The sediment profiles are defined by the wedged distribution against the Flinders Ranges in which the sediments in-filled the landscape before a syn-depositional re-activation along the now range bounding fault. The initial landscape in which this was hosted had highlands (the ranges) against an elongated trough (the Moorowie Syncline or the Poontana Trough). A similar trough is evident in the seismic data in the east of the embayment on the western side of the Barrier Ranges. The troughs have limited expression within the contemporary landscape because of the basin cover and regolith profiles. The Strzelecki Desert dune fields mask most evidence of these features. Within the ranges, the pre-Eromanga structure has been considerably altered by the neotectonics and contemporary stress fields. In the northern Flinders Ranges, tear faults and scissor structures have resulted in the reactivation of the range bounding and major structures as a result of a stress transfer ‘wrenching’ processes. From field exposures it is evident that this process is younger than the Palaeogene sediments in the area. A similar displacement of the pre-Mesozoic fabric is evident within the Tibooburra-Milparinka Inliers in the west.

Two major post-Proterozoic orogenic zones define the bedrock trends in the east of the embayment. In the northeast of the embayment, around the Tibooburra-Milparinka Inliers, the bedrock trends are controlled by the Thomson Orogen. The typical structural grain of this area is orientated approximately NW-SE, with neotectonism occasionally re-orientating and reactivating these structures such that it has a contemporary trend approximate to a N-S axis. Beach pebbles, shore lines and sandstone units onlap the Tibooburra-Milparinka Inliers similar to that of the Flinders Ranges. This indicates that there was also some topographic relief along the Grey Ranges at the onset of the sedimentation. The poor quality seismic data limits the recognition of subsurface features in this area that may otherwise help to further characterise the pre-Eromanga landscape.

In the southeast of the area, the general structural trends seen in the north are maintained throughout the Koonenberry and Wonnaminita blocks. These blocks are defined by the NW-SE trending faults and folds that are relatively continuous with the structure from the Thomson Orogen. These structures define the extent of sedimentation within the embayment, and as such must have had defining features within the landscape at the onset of sedimentation. This area is limited by poor quality seismic data, and is limited in extent in representation from the airborne magnetic data, as the Curnamona Pluton dominates the image and prevents the recognition of the more subtle anomalies. However, the distribution of sediments within the wells and surface exposures define the last known extent of Mesozoic sediments around this area.

This structural trend also controls one of the largest structural features in the east of the embayment, the Bancannia Trough. The Bancannia Trough is one of the few features that is distinguishable on the regional airborne magnetic data that is not associated with the Curnamona Province. This feature is defined by a late to
early Proterozoic metamorphic complex east of the Barrier Ranges. Sediment distribution patterns indicate that the trough had some expression during the Mesozoic, as the limits of sedimentation in that area are channelled down a similar trend. Abundant Willyama Supergroup clasts from the Broken Hill complex are included in the Mesozoic sediments indicating that the Broken Hill Domain had clear path of transport to the area. The current topography and morphology of the Barrier Ranges inhibits this. This indicates that the pre-Eromanga bedrock relief around the Barrier Ranges was not as high as it currently is. However, the presence of the Willyama Supergroup clasts indicates that there was some uplift in the area as the clasts would have required considerable potential energy to be transported into the Eromanga Basin.

The southern margin of the basin is only seen in seismic data, as the Lake Eyre Basin sediments cover the Eromanga Basin sediments. The pre-Eromanga landscape is defined by an unconformity with the Marree Subgroup. Seismic surveys show the Marree Subgroup onlapping, as opposed to the sharp boundaries in the east and west.

Intra-basinal features are also defined by the bedrock trends. The most prominent of this is the Benagerie Ridge in the south central portion of the embayment. Seismic surveys from the central portion of the embayment indicate that the Benagerie Ridge was a prominent feature of the landscape throughout the first phases of deposition in the basin. Sediments from the Cadna-owie Formation and the lower Marree Subgroup (Bulldog Shale equivalents) onlap the ridge, indicating that it was sub-aerially exposed during the basal deposition in that area. This indicates that it was a feature of the pre-Eromanga landscape.

In the north of the area, intra-basinal bedrock highs alter the thickness of sediments packages. These intra-basinal highs are typically structurally controlled, generating up to 200 m of variation in thickness of the basal sediments.

### 7.2. Stage Two: Initial Basin Formation

The initial phase of basin formation is represented by the Algebuckina Sandstone and its lithological equivalents. The deposition of the Algebuckina Sandstone in the embayment was initially thought to be limited to the far north of the field area. However, the Northern Flinders Ranges field study indicated that the deposition extended at least as far south as the Mt Painter Inlier. The sediments used to establish this had been previously identified as Mesozoic; however, were classified as Cadna-owie Formation due to associations with fossils that have been used to determine age correlations (Norton 1983; Wilson 2007). While these basal sediment profiles around the ranges are technically chronologically equivalent to the Cadna-owie Formation, they are lithologically equivalent to the Algebuckina Sandstone as defined by Ambrose (1980) and Green et al. (1989). This highlights that the Algebuckina Sandstone is more laterally extensive than originally thought, as well as more time transgressive. In the northeast of the area, the Algebuckina Sandstone crops out around the Tibooburra Inlier. There are no further accounts of the sediment sequence further south. The formation is dominated by fluvial sediments, including multiple channel profiles and associated flood plains, alluvial plains, fans and sand bars. Drill core of the unit indicates stacking of coarse-grained sands interpreted to be channel sediments. Exposures of the formation around Tibooburra show the profile of the channels as lenticular bodies of coarse-grained sediments, often characterised by gravel and conglomerate beds. Around the northern Flinders Ranges, isolated pods of very-fine-grained sediments are nestled amongst the coarser-grained sediments. These sediments were determined to be spring deposits bound by syn-depositional faults. Such a feature indicates the presence of active tectonics during the early phases of basin formation in the embayment as well as the varying terrestrial inputs to the Algebuckina Sandstone succession.
The Algebuckina Sandstone grades into the transition unit, the Cadna-owie Formation. Distinguishing between the Algebuckina Sandstone and the Cadna-owie Formation is difficult due to the gradational nature of the sediments. The Cadna-owie Formation is characterised by interbedded sandstones (dominantly fine to medium-grained), claystones, and occasional conglomeratic units. In places such as around the Milparinka Inliers, the Barrier Ranges and in part around the northern Flinders Ranges, these sediments overlie bedrock. Typically the base of the Eromanga Basin sequence is represented by the Algebuckina Sandstone; however, in these places, the basal Mesozoic unit is characterised by the finer-grained sediments and the distinct abundance of claystone interbeds. The sandstone sequences are typically well-sorted, quartzose sandstones with minimal lithic or exotic grains. They are characteristic of low-energy fluvial environments. However, occasionally the sediments have rhythmic patterns in the successions indicating a tidal influence. Rhythmic successions are characteristic of coastal plain environments in which the sediments are being deposited within proximity to the marine environment, with some marine influence. Rhythmic sediments may also be associated with seasonal glacial outwash in which the melt waters at the terminus of the glacier result in the deposition of sand and gravel-sized grains in irregular interbeds and sediment sequence fluctuations. Tillite packages have been identified around the northern Flinders Ranges (Alley & Frakes 2003). The tillites indicate that glacial deposition has contributed to the sedimentation in the embayment. However, conclusive evidence of glacial deposition as a wide spread depositional environment for the Cadna-owie Formation is limited to the margins of the basin. The interbedded finer-grained sediments are characteristic of marine environments, and the sandstone of high-energy fluvial sediments, and as such the main depositional environment is interpreted to be coastal plain. Around the ranges it is; however, recognised that glacial inputs did occur, possibly from fluvial systems transporting glaciers.

The occasional conglomerate packages typical to exposures around the Mt Browne and Mt Poole inliers in the east of the embayment are indicative of the higher energy faces of these environments such as the feeder channels or the debris flows. The other major component of this formation is the claystone sequences. These sediments are characterised by homogeneous silty-claystones and occasional mudstones interpreted to be marine. At the base of the unit the claystones are typically thin and separated by thick sequences of the sandstones. Towards the top of the unit the sandstones are thinner and the claystones are more abundant, occasionally being thicker than the sandstone sequences. The interbedded terrestrial sandstones and marine claystones indicate a dynamic marine incursion within the area in which a cyclic transgressive and regressive sea migration occurred.

The Cadna-owie Formation is more widespread than the Algebuckina Sandstone, extending as far south as the Barrier Ranges, and part way down the Benagerie Ridge. Despite this, the sediment profiles are typically thinner than the Algebuckina Sandstone. This represents three primary phases of basin formation:
1. Initial fluvial deposition including incision and grading to base level associated with new sediment accommodation space;
2. Fluvial system maturing and developing a graded longitudinal profile; and,
3. Landward migration of the marine profile and sediment "back-filling" due to a raised baselevel.

The initial deposition within the basin was limited in extent within the embayment as the basin was a narrower profile. The initial fluvial regime was consumed by incising streams and channels and the associated overflows. This accounts for the dominant high-energy environments represented by the sedimentary facies that characterise this unit, and the vertical, opposed to lateral, deposition of sediments. As the channel system ‘matures’ and grades to the new base level the energy dispersed from the fluvial system is funnelled into the channel migrating across the landscape. At this stage, the channel system dimensions broaden as the flow patterns start to become meandering, anabranching and anastomosing profiles with several different flood-outs, plains and associated landforms attached. The onset of the marine incursion also contributed to a broader basin profile, with the basin extending southward, such that as the marine incursion occurred, the transgressive phase of the basin stepped landward to the south. This pushed the land-sea boundary and as such, the coastal plain further south, helping to extend the margin of the basin further south. This area, known as the coastal plain, has influences from both the marine and terrestrial deposition, and fluctuates between dominance of these processes. This accounts for the presence of the Cadna-owie Formation further south than the Algebuckina Sandstone.

7.3. Stage Three: Marine Environments

The most extensive sedimentation phase within the basin and the embayment was the marine sequence. The marine succession is characterised by the Marree Subgroup, a multiphase marine incursion in which the basin transformed from continental to marine. The Marree Subgroup can be divided into three stages in the embayment. These include:

1. The initial transgression that resulted in the incursion of the Eromanga Sea into the embayment and resulted in the deposition of the Bulldog Shale and lateral equivalents;
2. A regression phase in which the Eromanga Sea briefly retreated; and,
3. A second phase transgression with a new maximum flooding surface in which the Oodnadatta Formation and lateral equivalents were deposited.

The first major transgression is marked basin wide by a transgressive lag deposit consisting of rounded pebbles and clasts. This unit is present in the wells and exposure, demonstrating that it is not only laterally extensive but also widespread. While the Cadna-owie Formation has several marine sequences interbedded with the sandstone, the Bulldog Shale equivalents are the first major marine transgression. The Bulldog Shale sediments...
are characterised by the blue-green glauconitic shales that are abundant throughout the basin. The sediments are characteristic of a shallow to proximal marine environment with some sediment sequences indicating a deeper marine system. The presence of glauconite indicates that the deposition was slow, and that there was abundant decaying organic matter within the system.

In the west of the area, the Bulldog Shale sediments abruptly flank the northern edge of the Mt Painter Inlier. Sediment profiles of up to 10 m are exposed against the inlier. These profiles are characteristic of the shallow marine Bulldog Shale and have no indication of shore line profiles or grading in the beach environment that is common in other parts of the basin. This abrupt boundary is not a later stage tectonic juxtaposition, as the sediments have been uplifted with the ranges, and have not been displaced against the ranges. There is also no evidence of sedimentation south of the Mt Painter Inlier, which from exposures overlying the Mt Babbage Inlier, would be expected. This further supports considerable elevation of the Mt Painter Inlier at the time of deposition. The graded profile and bevelled terraces that form at margins of the Mt Babbage Inlier have been interpreted to be the base-level at the time of the marine phase. The palaeo-base-level is now elevated within the landscape indicating the amount of uplift since then is approximately 200-300 meters. The amount of uplift in the contemporary Mt Painter Inlier is approximately 500-600 meters. The inliers have both been affected by similar contemporary stress and uplift, as evident by the sediment profiles deformed and caught up in the faulting in both inliers (for example the deformation of the Mesozoic sediments at Parabarana and the Pimples in and around the Mt Painter Inlier, compared to the deformation of the Algebuckina Sandstone equivalents overlying Mt Babbage and the overturned profiles in the Birthday Well fault).

The southern limit of these sediments within the embayment is a gradational profile in which the seismic data shows the Bulldog Shale onlapping a gentle bedrock incline in the south of the embayment, approximately 25 km south of Lake Frome.

The zone between the two major transgressive phases is a regressive phase in which the sea partially retreated from the area. Seismic data indicates that this retreat was a natural regression in which the Bulldog Shale sediments infilled the available accommodation space and as such there was no longer the space to host the sea. This unit is best identified on the seismic data as a high-amplitude continuous reflector which is deformed by the intraformational faults.

The second transgression phase in which a new maximum flooding surface covered the embayment is interpreted to be the most laterally extensive phase of deposition within the embayment. This depositional phase is equivalent to the Oodnadatta Formation. These sediments cover areas in the south of the basin in which no other Eromanga Basin sediments have been deposited. The sediments range from clays to shales and occasional sandstones. The southern limit of the sediments is seen in the seismic data extending beyond that of the Bulldog Shale equivalent sediments. However, due to a gap in the seismic data the exact location of this is unknown. This is the first sediment package within the embayment to cover the Benagerie Ridge, such that it was no longer a feature of the landscape.

The overall onset of the marine incursion in the area is attributed to the syn-depositional tectonism that was abundant within the area. Both field studies and seismic data indicate that there were several generations of faulting and subsequence subsidence during this time. The intra Marree Subgroup deposition was the result of sediment capacity, opposed to tectonism; however, the return of the inland sea to the area was resulted from a relative sea level rise or a forced transgression, that is, tectonically controlled subsidence. Seismic data in the west of the area indicate that the structures bordering the Flinders Ranges were active at this time, and that this was a controlling factor in the increased subsidence in the Poontana Trough subsidence history.

Lateral extensions of these sediments are beach deposits preserved in exposures around the basin margins. Rounded and flattened pebbles and shell hash halo small rises and in some places have been uplifted such that they are now elevated within the embayment. In places, the beach sediments overlie older Mesozoic sediments indicating that the marine deposition did not extend far beyond that of the basal Mesozoic.
It is widely accepted that the global climate is largely controlled by the ocean-atmospheric circulation (Miall 1997). This in turn dictates humidity, rainfall and temperature, and also has a large control on sedimentation (Miall 1997, Boggs 1987; Allen et al. 2006). Climate regulates sediment influx by contributing to weathering and erosion and contributing to sediment transport mechanisms (Miall 1997, Boggs 1987; Allen et al. 2006). The importance of climate in some aspects of weathering, particularly in the formation of duricrusts and the association to the degree of weathering has been recently challenged (for example: Taylor et al. 1992; Bourman 1993), as factors such as chemical weathering and physical processes can contribute to this. However, these studies still recognise the importance of climate in contributing to sediment supply and distribution.

The first transgression phase (the Bulldog Shale) has been associated with cold environments. The drop-stones and glendonite assemblages scattered throughout the Bulldog Shale are both indicative of near freezing and freezing conditions within the sea as well as ice-rafting. Syn-depositional mineral assemblages within the shale sequences, dominantly the abundant glauconite indicate that the sedimentation during this time was slow and calm. This contrasts with the climate and depositional environment interpretations from the Cadna-owie Formation and Algebuckina Sandstone. At the time of deposition, the global sea level did not show a considerable rise (as defined by Haq et al. 1987, see Figure 2.2). In both transgressive phases in the embayment, the marine incursion was forced by a relative sea leave rise. The relative sea level rise was driven by tectonic subsidence in the Moorowie and Yalkalpo Synclines creating accommodating space in which the Eromanga Seaway flowed down. While the first transgression phase is associated with the cold climate, the marine incursion is not necessarily what caused it. The second transgression phase has no association with cold environments, and is formed by the same base-level drop as the first phase. Wide spread sand lenses indicate higher-energy deposits in the Oodnadatta Formation (second phase).

**Figure 7.3 schematic of the two transgressive phases of basin formation: (i) Bulldog Shale depositional environments; and (ii) Oodnadatta Formation depositional environments. PN=Palaeo-north.**

### 7.4. Final Deposition: Return to Fluvial Environments

Following the deposition of the Marree Subgroup there was a short hiatus in major sedimentation within the basin, in which weathering and some erosion occurred. This is expressed on the seismic data as a minor erosional unconformity. Following this short hiatus, a further subsidence event resulted in the deposition of the Winton Formation. The Winton Formation is limited to the far north of the area, and is not exposed in either of the field study sites. Preserved drill core of the formation is limited, and as such the inferences drawn about it are limited mainly to the seismic interpretation. The Winton Formation is often exempt from the deformation seen on the seismic data within the underlying sediment packages. This indicates that there were deformation events within
the basin pre-dating the Winton Formation deposition. These deformation events are assumed to have rejuvenated subsidence within the area. The limited extent of Winton Formation is marred by the extreme depth of the sediment profiles. Despite the far north of the field area being the southern limit of the deposition of the formation, the sediment profiles exceed 400 m thick. As with the Algebuckina Sandstone, the succession is defined mainly by coarse-grained sequences. Stacked successions of sands dominate the wells. These have been interpreted to be stacked channel profiles. The stacking of channel profiles indicates a continual change of base-level, in which the channel fills up with sediment, and then a new channel forms. The Winton Formation also has abundant finer-grained sediments, including claystones and some silts and mudstones. These sediments are interpreted to be aspects of the fluvial plains that surrounded the channel systems. The wells that intersect the Winton Formation are too widely spread to correlate many of these features. The final stages of basin sedimentation closely mimics that of the Algebuckina Sandstone time; however, there was no further subsidence associated with this basin.

7.5. The Post Mesozoic Landscape

Following the deposition of the Winton Formation, there was no substantial sedimentation preserved within the sedimentary record until the onset of the Lake Eyre Basin. During this time the landscape underwent weathering and erosion such that clasts of the Mesozoic sediments have been reworked in the basal Eyre Formation sediments. The morphology and distribution of the Lake Eyre Basin was not a focus of this study, and as such will only be briefly discussed further in the context of the Eromanga Basin.

The contemporary landscape hosts remnants of the Mesozoic sediments scattered around the basin margins. Many of these remnants have been uplifted and exhumed by the recent tectonism throughout the embayment. However, some of the remnants have been preserved sub-aerially since the Mesozoic. Many of these exposures have been indurated or have been covered by quartzose lags, such as the beach pebble lags, which have essentially formed armour on the sediments.

The contemporary landscape also forms analogues for the Mesozoic landscape. The fans shedding out of the Terrapinna Corridor are a similar morphology to the dual lobe fan system from the Algebuckina Sandstone equivalents from the northern Flinders Ranges. The structurally controlled lake chain (Lake Frome to Lake Blanche), particularly the small spring deposit at the Montecollina Bore are analogues to the spring deposit from Gunpowder Bore around Mt Babbage. The ephemeral channels and the associated fluvial systems also provide insight into how fluvial systems may have been forming in a similar intracontinental setting during the initial and final phases of the basin.

In contrast, the Mesozoic landscape provides an insight into the contemporary landscape and its evolution. The Flinders and Grey Ranges had some uplift at the time of the Eromanga Basin sedimentation. The Uplift in the Mt Painter Inlier in the Flinders Ranges is estimated to have been within the realm of 100-200 m, indicating that the land surface in that area was not flat lying as previously though. However, the Mt Babbage Inlier had minimal relief, only the small archipelago islands in the east. This indicates that he rest of the uplift in that area occurred post-Mesozoic deposition. Similarly, only the upper-most (summit surface) terrace of the Tibooburra-Milparinka Inliers was exposed during the Mesozoic, such that they too have undergone considerable uplift during this time.
A critical component of this project was to identify a technique by which active and dynamic geological evolution models can be established, particularly for intracontinental interiors. Currently, no standard application for palaeogeological reconstructions is widely available. Methodology previously employed has focused on two main approaches: a regolith-geomorphic approach in which detailed and precise mapping of the surface and shallow subsurface are used to infer geological evolution; and, a typically petroleum exploration-based approach in which wells and complex geophysical techniques are used to assess subsurface sedimentology and structure. While both methodologies have considerable benefit, neither provide a complete and accurate evolution model for intracontinental interiors. This project assessed different techniques and combinations of techniques to ascertain the benefits and limitations of the different methods.

8.1. Geomorphic and Regolith Mapping

Understanding the contemporary landscape provides an initial basis for a geological evolution model. Active geology and environmental factors control the preservation of the landscape, and ultimately what can be interpreted from it. Understanding the potential for preservation, and conversely, destruction or burial of features not only provides a basis for the evolution model, but also analogies for past geological processes. The subtle nature of landscapes within intracontinental interiors poses a considerable challenge for creating regolith maps that contribute to geological evolution models. The Frome Embayment is no exception, with the extensive dune fields and gibber plains from the Strzelecki Desert covering a majority of the landscape. These features were initially thought to be hindrances to geological interpretations, as they bury landscape expressions of structure and rocks. Exposures within the ranges highlighted aspects of the areas tectonic history, as well as discrete and prominent exposures of the Mesozoic sediments which were initially thought to be absent in the low-lying plains of the embayment. After constructing the regional regolith profiles, relationships, structure and Mesozoic exposures previously obscured information was discovered. These features were exposed by conducting extensive fieldwork as well as in the recognition of signatures of features already identified in other areas of the embayment in the remotely sensed imagery. From this, channels were used to define structure, neotectonics was recognised in fan profiles and lake chains, and specific features of gibber plains were used to identify exposures or sub-cropping saprolite.

Remotely sensed imagery available for the embayment included Landsat-7 images in both pseudo and natural colour, Landsat Brovey imagery in the east, Pseudo colour SRTM imagery, 90 m digital terrain models and a 30 m synthetic aperture radar image. Quickbird Imagery was available for the whole of the Northern Flinders Ranges and for the Tibooburra Inlier, as was localised radiometric images. Initial regional mapping of the embayment was
conducted using the pseudo colour Landsat imagery draped over the 90 m resolution DTM. These data sets were used because they had regional coverage and the best image preservation when loaded in the mapping packages. While the 90 m DTM provided a basis for identifying landforms, the 30 m SAR image was able to discern landforms at greater resolution and precision than the DTM. However, this data set only became available in 2009 and as such was not incorporated into the main mapping component of the project.

The regolith and geomorphic maps, as well as the remotely sensed imagery, had different influences on the regional and local scales. Regional mapping identified features of interest within the landscape that tended to affect the constraints of the embayment both in the Mesozoic and contemporary landscapes as well as the general distribution of sediments. The localised mapping provided more detail on morphotectonic relationships and classification of regolith features, especially the exposed Mesozoic sediment profiles. These maps uncovered detail within the landscape that was not recognisable at a regional level. This detail was typically applicable to the large-scale evolution models. The features from the localised maps clarified many unconstrained attributes that arose with the regional mapping, as well as identified new aspects of the basin and landscape morphology during the Mesozoic.

A considerable disadvantage of the regolith and geomorphic mapping and the remotely sensed imagery is that it typically defines the lateral extent of structure but not the horizontal extent. Important relationships between structural age, reactivation and depth cannot always be identified from these studies. This project also showed that older generations of structure are also not always evident at surface as a result of younger generations of sedimentation (be that contemporary sediments, for example the dunes, or the blanketing affect of successor basins such as the LEB).

8.2. Sedimentology, Stratigraphy and Mineralogy

Sedimentological studies in the embayment were conducted using three primary sources, including: surficial exposures; wells and bores; and down-hole geophysics.

Wells provide a conclusive link to subsurface geology. They provide the only real lithological tie to the mechanical signatures of geophysical surveys targeted at subsurface features. As well as this, they are the most accurate insight into lithological properties that can otherwise only be inferred from surface exposures and signatures and by manipulating geophysical data. While the well profiles form the basis of the subsurface study and ties to geology for the seismic data, the wells presented several challenges. One of the biggest constraints was the availability of core, cuttings and chips from the wells. Several wells in New South Wales do not have any preserved rock from drilling. Because of this, data from well completion reports, tenement reports and down hole geophysical logs were the primary source of data. However, these reports come from different sources, with different standards and definitions for interpretation, and as such the data could not be taken at face value. Rather than assume that the data was of high quality, data for the formation tops for distribution maps and the seismic ties were obtained from the detailed lithological logs and gamma logs. The classical signatures of the Eromanga Basin sediment facies and formations could be picked out. Where possible, photos of the core were also used. Wells from South Australia were more readily available for viewing and logging, with several petroleum and stratigraphic wells having preserved core or cuttings. Formation tops from the South Australia wells were picked directly from the core. However, original lithological logs were still used as it was obvious that several sample trays and core runs had been mixed up over time. Some more recently drilled core was not available for
logging, so lithological logs were the only source of data. This highlighted two considerable issues with basin study method:

- Rock samples from wells are not always preserved, accurately presented at correct depth markers, or oriented correctly.
- Data originally collected from wells is highly interpretative and as such can be littered with errors and incorrect assumptions.

The exposures of the Mesozoic sediments proved to be one of the most useful components of this project. Rock exposures provide an expression of features such as sedimentary structures and mineralogy that are otherwise limited to very small core slices or cuttings. The exposures also provide an environmental and structural context for the sediments, preserving aspects of the Mesozoic landscape.

A key factor recognised in the surface exposures was that the ages of sediments did not necessarily categorise sediments in a formation, but rather this was based on lithology. This was particularly evident in the basal Mesozoic, where Algebuckina Sandstone lithological equivalents were time equivalents of the Cadna-owie Formation from further north. This resulted from the lateral broadening and thus southerly growth of the basin over time. While age of a sediment package is important, it does not define the mechanisms which determine the sediment type and distribution. Because of this, sediment mapping was conducted on lithological distribution as opposed to age. Logging of exposures in the localised studies helped to identify patterns in sedimentation which could be correlated across the area. This allowed for the recognition of larger scale depositional environments and morphotectonic relationships that attributed to the understanding of the state of the syn-depositional landscape.

Mineralogy of the Mesozoic sediments was a very small component of this work, and as such was only conducted using hand-sample identification and photomicrographs of selected rocks. The primary use of the photomicrographs was to determine the typical lithological composition of different units, particularly ones hard to identify as hand specimens and samples of interest in the localised study areas. Approximate provenance was able to be determined based on the abundance of feldspar (particularly k-feldspar); however, this was only used to determine if the detrital component of the rock was locally derived. This is not a precise provenance technique, as it requires potential source regions to initially host feldspar. The photomicrographs were also used to determine relative ages of chemical growths and indurations highlighting crystallographic relationships and overgrowth. This helped with defining provenance and in some instances depositional environments and relative timing of crystal growth.

However, like the feldspar analysis, this is an opportunistic technique. Due to the size of the basin, depth of the profiles and lack of access to core, mineralogical analysis of the sediments in the regional study was not looked at in enough detail to determine if this technique was of use on a more extensive scale. The localised studies showed that where sedimentary growths are present they are invaluable contributors to understanding the general depositional environment. The lithological analysis at the micro-scale was also useful. If at all possible it would be recommended that this technique be applied on a regional scale.

General sediment provenance was also determined from palaeo-flow analysis determined from palaeo-current measurements in exposures around the basin margins. The primary source of the measurements was from exposed cross-bedding in the basal sandstones, and occasional ripple marks and sole casts. In the marine
sediment, general current directions were determined by clast attrition distribution. While these techniques
provided a simple means of deterring flow paths, several problems arose from this analysis. Initially, identifying
structures suitable to be measured proved to be difficult due to weathering, and thus partial destruction of the
rocks being analysed. As well as this, over-printing and authigenic indurations hindered such features as they
partially destroy the sedimentological characteristics of the rocks and in places over-printed new characteristics.
Furthermore, because palaeo-flow measurements are azimuth measurements, they must be taken from specific
planes of the rock, with respect to the original depositional surfaces. The required surfaces and planes are not
always exposed, and when exposed are not always obvious. In places where tectonism is abundant, these
exposures may also be re-oriented or even just slightly tilted. Because of this, the measurements were collected
with coinciding bedding measurements in areas where there was a good constraint on tectonism. To account for
some of these errors, several measurement were taken from the one location, on equivalent parts of the
sequence to try and eliminate localised variations or outlier recordings.

Around the basin margins, sediment provenance was also determined by analysing the clast lithologies from the
basal Marree Subgroup beach sediments. This methodology was assumed to be a high risk task, as the
contemporary expression of the beaches has a large impact from recent regolith features. This task required
good knowledge of the localised regional geology as to be able to determine the source of clasts. Identifying
beach environments was conducted by analysing clast attrition and any other characteristic features that may be
present. For example, in the west of the embayment, shell hash and shells were a common occurrence within the
sediments. In the east, shells were less abundant; however, the rounded and flattened beach pebbles were
abundant. Many of the Mesozoic beach environments have been re-worked by contemporary processes such
that they are now elevated within the landscape, or have later regolith materials incorporated into with the
sediments. Determining the lithology and the source of that lithology was the most difficult part of the analysis.
For example, in the west of the area, a Neo-Proterozoic-Cambrian metasedimentary unit contains abundant and
thick tillite beds containing lithologies derived from as far away as the Gawler Ranges and some clasts that were
unidentified volcanoclastics that were not known to be proximally sourced. Many of the clasts from the tillite are
reworked within the Mesozoic beach sediments and have the characteristic beach pebble morphology indicating
that they are beach sediments. However, upon face value, these clasts would be assumed to have come from as
far away as the Gawler Ranges. Exposures of the tillite in the ranges showed the abundance of these clasts, and
the size ranges from which it could be identified that the clasts had been proximally sourced during the Mesozoic,
and most likely distally sourced upon initial deposition of the tillite.

8.3. Geophysics

The abundance of geophysical data in the embayment greatly aided the interpretation. Potential field geophysics
(magnetics and gravity) best highlighted basement terrains and general regional structural trends. These images
were of particular use in determining the pre-Mesozoic structural grain of the area because they so closely image
basement terrains. Features not seen at surface, such as the extent of the Curnamona Province, the Bancannia
Trough and the Benagerie Ridge, are all expressed within these data sets as prominent features. However, the
magnetics and gravity data alone posed considerable challenges within the interpretation as the data set
accounts for the lateral extent of regional structure, but not the horizontal extent. Because of this, they could not
be used on their own as tools of interpretation. Linking these surveys to the well geology was useful as it
accounted for any affects of the basin sediments within the images, for instance the anomaly in the west of the
area on the gravity data which is the Poontana Trough and the anomaly in the centre of the image which
corresponds to the Yalkalpo Syncline. However, the comparison with the wells has limited ability to determine the complete effects of the structure from the interpretations.

In the embayment, many subsurface structural and morphological features were identified through the seismic analysis. As a result of this, the source and cause of sedimentological variations were readily identified, and new variations and attributes were recognised. The data set in the east was of poor quality and sparse in distribution, so therefore the data set was only used to identify individual features, as opposed to a basin-wide structural model. This highlighted that the quality and availability of seismic data dictates the success of it in geological reconstructions. Problems with the seismic data were dominated by the variations in state survey databases and the resultant availability of high quality seismic data in New South Wales. The TIFF formatted lines were difficult to interpret; however, valuable contributions could still be made for the subsurface interpretation. The natural attenuation of the signal in the south also impeded deep interpretation; however, it identified areas in which the thick sequence of clays represented as high amplitude reflectors high up in the surveys were present. The lack of check-shot data (time-depth relationships) complicated the conversion of the seismic time sections to depth. The relatively shallow nature of the sediments in the south where there was the least check-shot meant that this was not such an issue.

Other challenges with using the seismic data set were the attenuation of the signal at the top of the surveys because of the high amplitude response of the Cainozoic sediments. This compromised the quality of the reflectors lower in the sequence such that in places no reflectors were preserved. While this anomaly was diagnostic of a specific sediment and regolith pattern, the hindrance that it caused on a number of lines added to the general poor quality of the seismic. Another issue faced with the seismic was the availability of time depth data (check-shot data) such that the seismic could be converted from standard TwT into a referenceable depth equivalent. In South Australia, 6 lines from a possible 189 had recorded check-shot. In New South Wales the 5 lines from a possible 134 have check-shots. While it is common to only have one check-shot per survey set, there are more than 11 seismic surveys. Limitations in the check-shot data compromised the velocity calculations and as such the conversion of the seismic to depth. The relatively shallow nature of most of the sediments means that this typically will not affect the data set. However, in the north the Eromanga Basin sediments are quite deep and thick, pushing them past the transition-depth of time to depth (Hughes & Fitzgerald 1995; Meyers et al. 2006). Because the seismic data was used to define features rather than create models, the seismic data was presented and referenced in TWT, with a depth equivalent also provided.

8.4. Reliability and Risk

By analysing all aspects of a technique, table 8.1 was generated. All techniques have been assigned a value out of 18 summed from six factors: relevance, reliability (risk factor), application to regional studies, application to local studies and efficiency by which the application can be applied (time consumption and ease of achieving the task, i.e. is a specific skill set required to achieve the task) and finally if the outcome of the method can be worked in with other techniques. Each category is given a rank from 0-3, with zero being the lowest rating, and 3 being the highest. Total scores higher than 15 are considered to be successful tools for geological reconstructions, values of 12-15, recommended tools, 10-12 useful but often opportunistic, 9-10 beneficial but only in some terrains, 9 and below may contribute minor aspects.

Several techniques employed were of specific relevance to the localised areas, and not to the regional analysis (Table 8.1). However, in some cases, such as with the mineralogy of the formations, this was because the
analysis was not able to be conducted on a basin-wide scale. In contrast, aspects such as well interpretations do not have a great impact on localised studies as they have poor context when there are not several for comparison.

Table 8.1. Reliability and risking of the methods employed in the geological reconstruction of the Frome Embayment.

<table>
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<th>Relevance</th>
<th>Regional</th>
<th>Local</th>
<th>Reliability</th>
<th>Efficiency</th>
<th>Amalgamation</th>
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8.5. Proposed Work-flow

After conducting this study, a general idea of how methodologies and processes fit together was established (Figure 8.1). This methodology was designed such that the evolution process can be systematically evaluated in terrains, ranging from regional to local scales.

Despite whether the project is conducted at a regional or local scale it is proposed that it be conducted within a regional context. Understanding the general area and geological terrain provides a sound basis for understanding the localised terrains. This was best conducted using remotely sensed imagery, seismic data and potential field data interpretations. While many of these features may not be available for all areas, where possible they are a useful baseline of techniques to employ. The regional surface map also provided an essential base for the rest of the analysis as it established the contemporary state of the landscape as well as reviling sites of potential interest. Seismic data provided an essential insight into the subsurface; however, seismic data is not available for all areas. The potential field interpretations were only a small part of this analysis; however, could be refined to take the place of seismic data if such a need arises. This would involve modelling the surveys either by inversion or attribute modelling.
8.6. Future Work

This project focussed on the surface and geophysical aspects of geological evolution. No geochemistry was involved. A proposed future study was to assess the mineralogy and whole rock geochemistry to advance provenance and development history. Included in this study it is suggested to incorporate a zircon U-Pb series isotope analysis to determine source locations of the detrital components. Further work on the crystallographic growth patterns, stress migration since the Mesozoic and a detailed localised regolith study intra-basin is recommended to try and determine subtle expressions of the geological reconstructions. To assess the ability of the potential field surveys to take the place of the seismic data in areas that are lacking in detail, it is also proposed that a potential field inversion and attribute model be conducted over the area. This could aid the development of a more complex structural model in which to define the basin inversion and original basinal terrains better. Once such features were done, extending the methodology into the main basin would help to define areas of structural instability, potential economic benefit and environmental importance.
Chapter Nine: Conclusions

The Frome Embayment in the south of the Eromanga Basin was formed by a culmination of tectonic subsidence, climatic fluctuations and eustatic response to these processes. The resulting evolution model sees the embayment transition from an intracontinental basin to a marine basin, and finally back to an intracontinental basin.

- The pre-Eromanga landscape defined initial deposition, and extent of sedimentation within the basins. This landscape and the pre-Eromanga landforms affected the distribution of sediments in the embayment up to the Albian.

- Eromanga Basin sediments are more time extensive than previously described. The embayment formed at a later stage to most of the basin, primarily as a result of it being the far margin, in which sedimentation was not as extensive as the main portion. Lithologically the entire Eromanga Basin succession is present at some point within the embayment. However, in places, particularly around the western margin, the chronological and lithological interpretations do not match standard Eromanga Basin.

- Initial sedimentation in the embayment was triggered by a tectonic subsidence in the two main troughs that bounded the Benagerie Ridge. This same subsidence drove the other phases of sedimentation within the embayment. This deposition was laterally limited, being confined to the north of the field area.

- An extensive transition zone between the fluvial and the marine sedimentation is present across much of the basin. The Cadna-owie Formation sediments characterise a repetitive transgressive-regressive cycle. Determining the base and top of this unit is difficult as it is a gradational unit; however, features such as sand dominance in the lower Cadna-owie Formation and the widespread transgressive lags provide benchmarks for this definition.

- The basin underwent two major marine transgressions which resulted in two very extensive maximum flooding surfaces. The associated sediments, the Bulldog Shale and the Oodnadatta Formation are the most extensive and wide spread units in the embayment. Both transgression phases were 'forced' such that they were the result of tectonic subsidence and a relative rise in sea-level.

- The Benagerie Ridge remained emergent until the second transgressive phase.

- Small archipelago systems were prevalent in the landscape syn-deposition. Of at least the Marree Subgroup. These small islands were Mesozoic expressions of the Grey Ranges and the Mt Babbage Inlier.
• Uplift in the Mt Painter Inlier was between 100-200 m above the basins. The uplift in the Mt Babbage Inlier was limited to the small archipelago systems located near the Moolawatana Homestead. The planed base level from the Marine incursion is uplifted and now forms the bevelled ‘table top’ of the Mountains and hills in the Mt Babbage Inlier. The Mt Babbage Inlier has almost been entirely uplifted since the Mesozoic.

The methodology employed during this project highlighted several points:

• Seismic surveys provide key insight into sub-surface structure and sediment distribution patterns. The seismic also shows the morphological properties of the basin, and preserve features such as angular unconformities. The seismic also provides an extension of information gained from wells by correlating the well sediments with the seismic signature. While distribution may be irregular, the seismic proved to be useful as ‘one line’ interpretations as this identified key structural sense and refined surface mapping.

• Potential field surveys are useful for regional scale analysis, where shot locally at very high resolution they are useful on a localised scale.

• Boreholes, wells and drill holes provide instantaneous accounts for the subsurface geology; however, must be recognised as limited when correlations are being drawn. Down hole gamma logs provide an excellent substitute for core, where the core is not preserved or available. The general lithological associations are.

• Many contemporary landforms and sediment distribution profiles were used as analogues of past geologic processes (such as the fan complex at Terrapinna for the Late Jurassic – fan system, proving that the knowledge of regolith type and distribution and the landforms on which the regolith is hosted is crucial for the understanding of a geological evolution.

• Combining the subsurface techniques with the surface techniques refined the ability to construct geological models by analysing the whole system.
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References


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References


References


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Appendix One: Seismic quality

The complete Arrowie Basin survey set from PIRSA and surveys from the Tibooburra seismic set from the NSW DPI were merged and loaded into Move and the basic navigation in to ArcGIS for interpretation and map purposes. In total, 323 2D seismic surveys were loaded for the embayment, totalling 3689.2 km. However, several surveys in both data sets had poor representation of the reflectors, which in places were not even present. To account for this, a quality assessment was made on the lines before interpretation to determine data quality and the lines that are adequate for interpretation and also to determine what the seismic could be used for. This assessment was based upon the visibility of reflectors, migration attributes and processing quality, as well as scanning the quality of data that had been transcribed from paper. Four categories of quality were assigned, including:

- **Good:** clear reflectors, minimal survey noise, minimal migration effects - survey easily interpreted;
- **Moderate:** reflectors present, some survey noise, migration patterns; however, minimal interference with data - survey interpreted with minor difficulty;
- **Poor:** minimal reflectors, extensive survey noise, migration effects masking data visibility, parts of survey missing - difficult to interpret survey; and,
- **Bad:** migration patterns, noise and missing data dominate section - interpretation impossible

Only survey lines with good or moderate classifications were used. An example of the data classification is shown below. This details the differences between lines, and highlights some issues with the data set. In total there were 114 lines of good quality, 94 moderate, 113 poor and 2 bad. The poor quality lines were dominantly the 1960's lines from the Tibooburra surveys and the lines in the south of the area where the clays attenuate the seismic signal shallow.

Figure. Examples of the different quality seismic lines from the Arrowie and Tibooburra data sets.
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## Appendix Three: Regolith-Landform Unit Codes

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Chapter four: South Lake Frome

Alluvial Channels

ACah1 (Channel Sediments / Active Channel): Sub-rounded to rounded, grey-brown, quartzose sands and silts, sub-rounded sandstone, plagioclase and quartz gravels hosted in a broad, shallow ephemeral channel. Sporadic larger clasts of rounded, highly polished silcrete (up to 15 cm), sub-rounded to rounded granite (up to 30 cm), sub-angular to sub-rounded sandstones and reworked tilite/conglomerate clasts (including volcanics, quartzites and psammites). Channel banks are unstable, often having notches (up to 20 cm high) worn out of the base of the wall. Vegetation is river red gums (*Eucalyptus camaldulensis*) and chenopod shrubs including thorny saltbush (*Rhagodia spinescens*) and bluebush (*Maireana spp*). Accumulations of bark, leaves and sticks forming litter dams against trees and depressions in the channel.

Alluvium

Afa1 (Alluvial sediments / alluvial fan): Red-brown coarse to fine grained sands with minor silts and gravels in small broad fans. The landform has very small and low-lying apex at the base of the broad ephemeral channels. Small channels are incised in the fan lobes, typically less that 1 m wide and 30 cm deep. Vegetation is sparse, dominated by small grasses and forbs.

Apd1 (Alluvial sediments / depositional plain): Sub-rounded to rounded, quartzose sands with minor gravels. Low relief depositional landform (0-9 m), with associated with the shallow channels and flood out plains. Minor manganese ventifacts around the far edges of the landform. Vegetation is Mexican poppy bush (*Argemone mexicana*) and velvet potato bush (*Solanum ellipticum*), bluebush (*Maireana spp*). with minor *Acacia spp*.

Aeolian Regolith

ISu1 (Aeolian sands / lunette): Brown-red-buff coloured, fine-grained sands and silts hosted in a parabolic dune. Minor exposures of partially lithified sandstone around the base of the landform. Landform is up to 15 m high, asymmetrical with an oblate curvature around the northeast side of the lake. Vegetation includes white teatree (*Melaleuca glomerata*) mulga (*Acacia aneura*), dead finish (*Acacia tetragonophylla*).

ISul1 (Aeolian sands / longitudinal dunefield): Red-brown fine sands and silts hosted within elongated, asymmetrical dunes. Clay pans and small lakes forming in the lower parts of the landscape, Vegetation is dense, typically dominated by white teatree (*Melaleuca glomerata*) mulga (*Acacia aneura*), dead finish (*Acacia tetragonophylla*), with abundant chenopods, small grasses and forbs.

ISps1 (Aeolian sediments / sands plain): Low relief landform with coarse to medium grained, red-brown sands forming on a low relief landform. Minor clay pans and salt lakes forming in localise playa plains. Minor ‘crab-hole’ depressions forming in the clay areas. Vegetation is dominated by woodland species, predominantly mulga (*Acacia aneura*).
Mount Babbage Inlet

Alluvial Channels

ACh, (Channel Sediments / Active Channel): Sub-rounded to rounded, grey-brown, quartzose sands and silts, sub-rounded sandstone, plagioclase and quartz gravels with minor exposures of sandstone, conglomerates and shales. Sporadic larger clasts of rounded, highly polished silcrete (up to 15 cm), sub-rounded to rounded granite (up to 30 cm), sub-angular to sub-rounded sandstones and quartz gravels with minor exposures of sandstone, granites and gneisses. Low relief landform associated with ephemeral drainage and minor swamps. Vegetation is river red gums (Eucalyptus camaldulensis) and chenopod shrubs including thorny saltbush (Ragodia spinescens) Mexican poppy bush (Argemone mexicana) and bluebush (Maireana spp). Minor native apricot (Pittosporum angustifolium) and pods of white teatree (Melaleuca glomerata).

ACh2, (Channel Sediments / Active Channel): Sub-rounded to rounded, grey-brown, quartzose sands and silts, sub-rounded sandstone, plagioclase and quartz gravels with minor exposures of sandstone, granites and gneisses. Low relief landform associated with ephemeral drainage and minor swamps. Vegetation is river red gums (Eucalyptus camaldulensis) and chenopod shrubs including thorny saltbush (Ragodia spinescens) Mexican poppy bush (Argemone mexicana) and bluebush (Maireana spp).

Alluvium

Aaf, (Alluvial Sediments / Alluvial Fan): Red-brown-grey, rounded to sub-rounded, quartzose sands and silts with minor small lithic pebbles. Low relief, elongated landforms associated with the dissipation of considerable slopes. Elongated ephemeral swamps up to 3 m wide within the fans, typically associated with large zones of sediment collapse. Vegetation is sparse, dominated by chenopod shrubs, typically bluebush (Maireana spp.), salt bush (Atriplex spp.) and velvet potato bush (Solanum ellicotticum). Vegetation within swampy units is dense, typically mulga (Acacia aneura), dead finish (Acacia tetragonophylla) and saltbush (Atriplex spp.), with minor grasses and forbs.

Aed, (Alluvial Sediments / Erosional Drainage): Sub-rounded to rounded, quartzose sands, sub-rounded sandstone and quartz gravels with minor exposures of sandstone, conglomerates and quartz veins associated with poorly developed, shallow drainage. Minor powdered regolith carbonate accumulations in stream beds, hardpan regolith carbonate accumulations on knick point in sandstone exposures. Vegetation is Mexican poppy bush (Argemone mexicana) and velvet potato bush (Solanum ellicotticum), bluebush (Maireana spp.) with minor Acacia spp.

Aed2, (Alluvial Sediments / Erosional Drainage): Sub-rounded to rounded, quartzose sands, sub-rounded granite, feldspar and quartz gravels with exposures of highly polished, slightly weathered granites, gneisses and pegmatites associated with poorly developed, shallow drainage. Vegetation is sparse, typically velvet potato bush (Solanum ellicotticum), bluebush (Maireana spp.) with minor rock emubush (Eremophila freelingii).

Aap, (Alluvial Sediments / Alluvial Plain): Sub-rounded to rounded, quartzose sands, sub-rounded sandstone and quartz gravels with minor exposures of sandstone, clast supported conglomerates, and rounded silcrete clasts. Low relief landform (0-9 m), with a shallow slope associated with poorly developed,
shallow drainage and flood out plains. Minor fragmented regolith carbonate accumulations associated with sandstone exposures. Vegetation is Mexican poppy bush (*Argemone mexicana*) and velvet potato bush (*Solanum ellipiticum*), bluebush (*Maireana spp.*) with minor Acacia spp.

**Colluvium**

CHpd1 (Sheetflow Sediments / Depositional Plain): Sub-angular to angular, silicified sandstone (up to 8 cm), rounded quartz (up to 4 cm), sub-angular to sub-rounded lithic clasts (2-8 cm) with red-brown-orange, fine-grained sand and silts. Low relief depositional landform (0-9 m) with subtle contour banding defined by irregular distribution of small clasts (predominantly quartz). Sporadic exposures of sandstone, associated with shallow drainage. Vegetation is dense, typically black bluebush (*Maireana pyrmaidata*), thorny saltbusht (*Rhagodia spinosae*) bladder saltbush (*Atriplex vesicaria*) with minor Mexican poppy bush (*Argemone mexicana*), paddy melon (*Cucumis myriocarpus*) and velvet potato bush (*Solanum ellipiticum*). 

CHep1 (Sheetflow Sediments / Erosional Plain): Sub-angular to sub-rounded, sandstone clasts (up to 8 cm), angular to sub-angular and rounded quartz, sub-angular to sub-rounded lithic clasts on a shallow to moderate plains (0-9 m). Minor red-brown, fine-grained, sands and silts. Low relief landform (9-30 m) with prominent relief landforms (9-30 m) with a shallow to moderate slope. Minor exposures of sandstone, typically in pods less that 3 m wide. Accumulations of salt in localised shallow depressions (up to 10 m wide). Minor drainage incision, up to 3 m wide and <1 m deep. Vegetation is dominated by chenopod shrublands, typically black bluebush (*Maireana pyrmaidata*), bladder saltbush (*Atriplex vesicaria*) with minor forbs and grasses. Sporadic large sugar wood (*Myoporum platycarpum*) around fault related exposures.

CHep5 (Sheetflow Sediments / Erosional Plain): Sub-angular to sub-rounded, sandstone clasts (up to 8 cm) with red-brown-orange, fine-grained, quartzose, sands and silts with an abundance of disseminated gypsum. Low relief landform (0-9 m) with irregular contour banding. Sporadic exposures of moderately to highly weathered sandstone, highly weathered shales and mudstones, exposed in small drainage depressions. Minor salt accumulations around sandstone exposures. Vegetation is sparse, typically erect mallee bluebush (*Maireana pentatropis*), black bluebush (*Maireana pyrmaidata*) and bladder saltbush (*Atriplex vesicaria*) with minor forbs and grasses.

**Eolian Regolith**

ISps1 (Aeolian Sediments / Sand Plain): Sub-rounded to rounded, quartzose sands and silts. Low relief landform hosted on a low relief plain. Minor fragements of partially silicified sandstone and some clay supported conglomerates. 

**In Situ Regolith**

SMer1 (Moderately Weathered Saplrite / Erosional Rise): Slightly to moderately weathered, coarse-grained sandstones, pebbly sandstones and conglomerates with minor angular sandstone clasts and red-brown sands and silts. Low to moderate relief landform (9-30 m) with a shallow slope. Minor ferruginisation and silicification of some sandstones. Vegetation is sparse, dominated by black bluebush (*Maireana pyrmaidata*) and pearl bluebush (*Maireana sedifolia*).

SMer2 (Moderately Weathered Saplrite / Erosional Rise): Moderately to highly weathered, poorly consolidated, grey-green shales, khaki-yellow mudstones and matrix supported conglomerates. Low relief landform (9-30 m) with a shallow to steep unstable slopes. Minor gypcrete and calccrete...
throughout the highly weathered shales, with silicification pods throughout some mudstones. Rises are typically unstable, with small gully incision common. Vegetation is rare, typically erect mallee bluebush (Maireana pentatropis) and velvety potato bush (Solanum ellipcicum).

SSel (Slightly Weathered Saprolite / Low Hill): Slightly weathered, highly polished, rounded granites and granite tills. High relief landforms (30-90 m), with very steep slopes. Minor surficial hardpan and fragmental calcrete in joints and depressions. Sporadic highly weathered mafic intrusives, up to 4 m wide. Vegetation is dominated by open shrublands, typically rock emu bush (Eremophila freelegii) with minor chenopods growing in joints.

SSeh (Slightly Weathered Saprolite / Erosional Hill): Slightly weathered tillite and quartzites, slightly to moderately weathered, blue-green dolomite and graywacke with Minor colloval clasts, typically reworked, rounded and ridged volcanic and quartzitic tillites. High relief landform (90-300 m), with very steep slopes and deep incised gullies. Surficial hardpan calcrete along breaks in slope and in filling cracks and veins. Vegetation is sparse, typically rock emu bush (Eremophila freelegii), with sporadic Acacia spp. in shallow drainage.

SSep (Slightly Weathered Saprolite / Erosional Plain): Slightly weathered, coarse-grained, ferruginised sandstones with conglomeratic beds throughout, and intercalated partially silicified angular, gravelly sandstones and medium-grained sandstones with minor sub-angular to sub-rounded sandstone clasts. Low relief landform (0-9 m), with a slight slope. Minor goethite surface staining on some sandstone surfaces. Vegetation is sparse, dominated by black bluebush (Maireana pyrmaidata) and bladder saltbush (Atriplex vesicaria). Blue-green and orange lichen on western and southern exposures of ferruginised sandstones.

SSep1 (Slightly Weathered Saprolite / Erosional Plain): Slightly weathered, highly polished, rounded, feldspathic granites and potassic augen gneisses with Minor angular to sub-angular plagioclase and quartz clasts. Low relief landform (0-9 m), with moderately steep slopes. Vegetation is dominated by open chenopod shrublands, typically black bluebush (Maireana pyrmaidata). Orange lichen growing on some ferruginised saprolite.

SSer (Slightly Weathered Saprolite / Erosional Rise): Slightly weathered, highly polished, rounded granites and granite tills with minor colloval clasts, typically litchi, angular to sub-angular plagioclase and quartz. Low to moderate relief landforms (9-30 m), with moderately steep slopes. Sporadic pods of moderately weathered sandstones. Vegetation is dominated by open shrublands, typically rock emu bush (Eremophila freelegii) with minor chenopods and forbs growing in joints.

SSer1 (Slightly Weathered Saprolite / Erosional Rise): Slightly to moderately weathered, highly polished, rounded, feldspathic granites and potassic augen gneisses with minor angular to sub-angular plagioclase and quartz clasts. Low to moderate relief landforms (9-30 m), with a moderately steep slope. Vegetation is dominated by open chenopod shrublands, typically black bluebush (Maireana pyrmaidata). Orange, pale green-blue and blue pink lichen growing on haematitic and goethitic saprolite.

SSer2 (Slightly Weathered Saprolite / Erosional Rise): Slightly to moderately weathered, highly polished, rounded granites and potassic augen gneisses with minor orange-brown, fine-grained, sands and angular to sub-angular plagioclase and quartz clasts. Low to moderate relief landforms (9-30 m) with high angled, steep slopes. Pink-red-purple surficial staining common. Vegetation is dominated by open chenopod shrublands, typically rock emu bush (Eremophila freelegii) with minor velvet potato bush (Solanum ellipcicum) and sturt desert pea (Swainsona formosa).

Parabarana

Alluvial Channels

ACah (Active channel sediments / active channel): orange-brown-mustard, sands and silts, quartz, litchi and silcrete pebbles; quartz and silcrete clasts, minor exposures of sandstones and shale. Vegetation is dominated by river red gums (Eucalyptus camaldulensis) with minor velvet potato bush (Solanum ellipicicum), thorny saltbush (Rhagodia spinescens) and Mexican poppy (Argemone mexicana).

ACah (Active channel sediments / active channel): slightly weathered, highly polished granite exposures in steep, narrow valleys. Abundant granite and quartz clasts line the base of the channel. Vegetation is dominated by emu bush (Eremophila spp.).

Alluvium

Aap (Alluvial sediments / Alluvial Plain): Sub-rounded to rounded, and minor gravels in a low relief landform (0-9 m), with a shallow slope associated with poorly developed, shallow drainage and flood out plains. Sandstone exposures common. Minor fragmental regolith carbonate accumulations associated with sandstone exposures. Narrow drainage depressions are incised throughout the landform. Vegetation is Mexican poppy bush (Argemone mexicana) and violet potato bush (Solanum ellipcicum), bluebush (Maireana spp.). Woodland species are widespread with minor Acacia spp.

Aap (Alluvial sediments / Alluvial plain): orange-brown, sands and silts in a low relief landform (0-9 m). Densely vegetated landform, with Mulga (Acacia aneura), white teatree (Melaleuca glomerata) bluebush (Maireana spp.) and dense saltbush (Atriplex spp.). Some Mexican poppy bush (Argemone mexicana) and small grasses and lily's.

Aap (Alluvial sediments / Depositional Plain): Sub-rounded to rounded, quartzose sands, sub-rounded sandstone and quartz gravels. Low relief depositional landform (0-9 m), with poorly developed, shallow drainage and flood out plains. Minor. Vegetation is sparse, dominated by velvet potato bush (Solanum ellipcicum), bluebush (Maireana spp.).

Afa (Alluvial sediments / Alluvial fan): orange-brown, sands and silts and sub-rounded to rounded quartz, sandstone and granite pebbles in a shallow ephemeral fan. Fan apex are low-lying and lobes are broad.

Colluvium
**In Situ Regolith**

**SSen (Slightly weathered saprock / erosional rise):** slight to moderately weathered shales, highly silicified sandstones and conglomerates exposed in small mesas, slight rises and in exposures along channel banks. In places sediments are very highly weathered and poorly consolidated. Minor regolith features include rounded clasts of sandstone and quartz, sub-rounded to angular fragments of silcrete. Abundant disseminated and accicular gypsum crystals are present within the shale units. Vegetation is sparse, dominated by black bluebush (Maireana pyrmidata) and occasional pearl bluebush (Maireana sedifolia).

**SSel (Slightly weathered saprock / low hill):** slightly weathered, polished and rounded highly polished and rounded granite low hills, with some granite tors. Granite has a distinct red colour, with abundant phenocrysts of feldspar. 'Skins' of granite colluvium accumulating on the breaks of slope and the base of the landform. Minor attributes of red-brown, fine-grained sands and silts. Vegetation is dense, dominated by emu bush (Eremophila spp.) with minor velvet potato bush (Solanum ellipticum) and Sturt desert pea (Swainsona formosa).

**SSeh (Slightly weathered saprock / hill):** slightly weathered, highly polished and rounded granite hills, with some granite tors. ‘Skins’ of granite colluvium accumulating on the breaks of slope and the base of the landform. Vegetation is dense, dominated by emu bush (Eremophila spp.).

**Chapter Six:**

**Milparinka**

**Alluvial Channel**

**ACah1 (Alluvial channel sediments / alluvial channel):** orange-brown-grey, rounded to sub-rounded, quartzose, sands and silts with sub-rounded to sub-angular lithic gravels in an active stream bed. Exposures of slightly to moderately weathered coarse-grained sandstones and some conglomerates in the bed and walls of the channel. Minor accumulations of highly rounded silcrete clasts and sub-angular to sub-rounded quartz, granite and sandstone clasts. Vegetation is dominated by river red gums (Eucalyptus camaldulensis) with a mixture of under story chenopod shrubs around the boundaries of the streambed.

**ACah2 (Alluvial channel sediments / alluvial channel):** slightly to moderately weathered metasediment exposures hosted in steep gorge-like valleys with ephemeral channels flowing through. Minor accumulations of fine-grained sands and some silts. Vegetation is dominated by emu bush (Eremophila spp.) with minor velvet potato bush (Solanum ellipticum). In some of the sandier areas abundant river red gums (Eucalyptus camaldulensis) dominate the vegetation species.

**Alluvium**

**Aap (Alluvial sediments / alluvial plain):** orange-grey-brown, rounded to sub-rounded sands and silts with sub-rounded quartz, sandstone, silicified sediments and metasediment gravel clasts. Low relief land form with shallow incised channels associated with intersection point flood outs from large channels. Vegetation is riparian woodlands dominated by river red gums (Eucalyptus camaldulensis) with an understory of chenopod shrubs and forbs, typically thorny saltbush (Rhagodia spinescens) and Mexican poppy (*Argemone mexicana*).
Afa. (alluvial sediments / alluvial fan): orange-brown, rounded to subrounded quartzose sands and silts with minor small (<1 cm) lithic gravels, associated with low relief land surfaces at the base of stream channels and creeks. Vegetation includes silky cobbeach (Bassia eriaca), and thorny saltbush (Rhagodia spinescens) with some mulga (Acacia aneura).

**Colliuvium**

**Chen** (Sheetflow sediment / erosional rise): Sub-rounded to subangular lithic phylite gravels, angular lithic quartzite fragments and rounded to subrounded silcrete and sandstone clasts with minor orange-brown, fine sands associated with moderate slopes of moderate to low relief (9-30 m). Subcropping and exposed moderately weathered sandstones, conglomerates and metasediments. Chenopod shrublands dominated by pear bluebush (Maireana sedifolia) and black bluebush (Maireana pyramidata) with grey cobbeach (Sclerolaena diacantha) and silky cobbeach (Bassia eriaca).

**Chen** (Sheetflow sediment / erosional rise): Sub-angular to sub-rounded, slightly ferruginised, lithic quartzite sandstone and quartzose sandstone, matrix supported conglomerate and mudstone with sub-rounded silcrete clasts and sub-rounded to sub-angular quartz clasts and minor orange-brown, calcareous, fine sands. Low to moderate slopes with low relief (9-30 m). Exposures of slightly weathered, slightly ferruginised sandstone and coarse grained conglomerate in areas of low relief. Nodular ferricrete, hardpan regolith carbonate accumulations exposed in incised streams and channels. Some exposures of steep, highly weathered mudstone. Low woodlands, typically including cabbage tree wattle and chenopod shrublands dominated by pear bluebush (Maireana sedifolia).

**Chep** (Sheetflow sediment / erosional plain): Sub-angular to sub-rounded, slightly ferruginised, lithic sandstone and mudstone, matrix supported conglomerate and mudstone with sub-rounded silcrete clasts and sub-rounded to sub-angular quartz clasts and minor orange-brown, calcareous, fine sands. Low-lying, undulating landform with abundant small drainage depressions incised. Exposures of slightly weathered, slightly ferruginised sandstone and coarse grained conglomerate in areas of low relief. Nodular ferricrete, hardpan regolith carbonate accumulations exposed in incised streams and channels. Low woodlands, typically including cabbage tree wattle and chenopod shrublands dominated by pear bluebush (Maireana sedifolia).

**Chep** (Sheetflow sediment / erosional plain): Rounded to sub-rounded silcrete clasts (1-7 cm) and angular to subangular lithic quartz and ferruginised sandstone clasts with minor orange-brown quartzose, fine sands and silts associated with shallow slope and low relief (0-9 m). Sporadic exposures of locally shedding sandstones and metasediments. Pods of clay-rich soils forming "crab-hole" depressions in less lag covered contour bands. Chenopod shrublands dominated by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia).

**Chep** (Sheetflow sediment / erosional plain): Rounded to sub-rounded silcrete clasts (up to 12 cm) and minor orange-brown, quartzose sands with moderate slopes and low to moderate relief (9-30 m). Contour banding dominated by thick (up to 3 m wide) bands of larger, highly polished, slightly ferruginised silcrete nodules. Open chenopod shrubland with bluebushes (Maireana spp.) and grasses.

**Chpd** (Sheetflow sediment / depositional plain): Sub-angular to sub-rounded, slightly ferruginised, lithic sandstone and mudstone, sub-rounded to sub-angular quartz clasts and petrified wood fragments with minor orange-brown, calcareous fine sands and silts associated with low relief. Exposures of highly silicified and ferruginised sandstones and conglomerates shedding locally. Chenopod shrublands dominated by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia). Thorny saltbush (Rhagodia spinescens) and velvet potato-bush (Solanum ellipticum) abundant in drainage depressions.

**Aeolian Regolith**

**ISps** (Aeolian sediment / sand plain): rounded, orange-brown-red, quartzose sand and rounded to sub-rounded well-sorted lithic gravels with pods of rounded to subrounded quartz, sandstone and silicified clasts. Low relief with hardpan regolith carbonate accumulations. Vegetation is mulga (Acacia aneura) and bastard mulga (Acacia clivicola) with some black bluebush (Maireana pyramidata).

**ISps** (Aeolian sediment / sand plain): rounded, orange-brown-red, quartzose sands and rounded to sub-rounded, well sorted lithic gravels. Low relief associated with partially silicified sandstone exposures. Vegetation includes Christmas tree mulga (Acacia aneura var. confinera) and bastard mulga (Acacia clivicola), rock sida (Sida petrophilia) with some black bluebush (Maireana pyramidata).

**In Situ Regolith**

**SSeh** (Slightly weathered bedrock / hill): Highly silicified interbedded sandstones, siltstones and matrix supported conglomerates with minor brown-grey-orange, quartzose sands and silts. High relief landform (90-300 m) associated with locally shed rounded silicified clasts (up to 10 cm). Vegetation includes wide spread chenopod shrubs.

**SSeh** (Slightly weathered bedrock / hill): Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. High relief (90-300 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phylite clasts). Minor exposures of slightly weathered phylitic tuff and basalt sills. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Vegetation includes emu bush (Eremophila sp.), mulga (Acacia aneura) and grey cobbeach (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

**SSer** (Slightly weathered bedrock / erosional plain): Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Low relief, undulating landform (90-300 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phylite clasts). Minor exposures of slightly weathered phylitic tuff and basalt sills. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Vegetation includes emu bush (Eremophila sp.), mulga (Acacia aneura) and grey cobbeach (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

**SSen** (Slightly weathered bedrock / erosional rise): Slightly ferruginised, interbedded calcareous sandstones and mudstones with orange-brown, rounded to sub-rounded, calcareous, sand and silts with moderate relief (9-30 m). Occasional matrix supported conglomerate lenses. Minor locally derived subrounded colluvium. Vegetation is chenopod shrublands, dominated by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia). Orange and green lichen on some exposures.
SSer1 (Slightly weathered bedrock / erosional rise): Slightly ferruginised, highly cleaved, interbedded metasedstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Moderate relief (8-30 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllice clasts). Minor exposures of slightly weathered rhyolitic tuff and basalt silts. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Vegetation includes emu bush (Eremophila spp.), mulga (Acacia aneura) and grey copperburr (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

Warratta

Alluvial Channel

ACah1 (Alluvial channel sediments / alluvial channel): orange-grey-brown, rounded to sub-rounded, quartzose, sands and silts with sub-rounded to sub-angular lithic gravels in an active stream bed. Exposures of slightly to moderately weathered coarse-grained sandstones and some conglomerates in the bed and walls of the channel. Minor accumulations of highly rounded silcrete clasts and sub-angular to sub-rounded quartz, granite and sandstone clasts. Vegetation is dominated by river red gums (Eucalyptus camaldulensis) with a mixture of under story chenopod shrubs around the boundaries of the streambed.

ACah2 (Alluvial channel sediments / alluvial channel): slightly to moderately weathered metasediment exposures hosted in steep gorge-like valleys with ephemeral channels flowing through. Minor accumulations of fine-grained sands and some silts. Vegetation is dominated by emu bush (Eremophila spp.) with minor violet potato bush (Solanum ellipticum). In some of the sandier areas abundant river red gums (Eucalyptus camaldulensis) dominate the vegetation species.

ACah3 (Alluvial channel sediments / alluvial channel): orange-brown-grey, rounded to sub-rounded, quartzose, sands and silts with sub-rounded to sub-angular lithic gravels in an active stream bed. Exposures of slightly to moderately weathered metasediments, coarse-grained sandstones and some conglomerates in the bed and walls of the channel. Abundant accumulations of gravels and highly rounded clasts, dominated by metasediments and sandstone. Vegetation is dominated by river red gums (Eucalyptus camaldulensis) with a mixture of under story chenopod shrubs around the boundaries of the streambed.

Alluvium

Aap1 (Alluvial sediments / alluvial plain): orange-grey-brown, rounded to sub-rounded sands and silts with sub-rounded quartz, sandstone, silicified sediments and metasediment gravel clasts. Low relief land form with shallow incised channels associated with intersection point flood outs from large channels. Vegetation is riparian woodlands dominated by river red gums (Eucalyptus camaldulensis) with an understory of chenopod shrubs and forbs, typically thorny saltbush (Rhogodia spinescens) and Mexican poppy (Argemone mexicana).

Afa1 (alluvial sediments / alluvial fan): orange-brown, rounded to subrounded quartzose sands and silts with minor small (<1 cm) lithic gravels, associated with low relief land surfaces at the base of stream channels and creeks. Vegetation includes silky copperburr (Bassia eriacantha), and thorny saltbush (Rhogodia spinescens) with some mulga (Acacia aneura).

Afa2 (alluvial sediments / alluvial fan): orange-brown, rounded to subrounded quartzose sands associated with low relief land surfaces at the base of stream channels and creeks. Vegetation is very sparse, including thorny saltbush (Rhogodia spinescens) with some mulga (Acacia aneura).

Colluvium

Chep1 (Sheetflow sediment / erosional plain): Subrounded to subangular lithic phyllice gravels, angular lithic quartzite fragments and rounded to subrounded silcrete clasts with minor orange-brown, fine sands associated with low-lying undulating plains (0-9 m). Sub-cropping moderately weathered sandstone and metasediments, locally shedding sediments. Chenopod shrublands dominated by pearl bluebush (Maireana sedifolia) and black bluebush (Maireana pyrmidata) with grey copperburr (Sclerolaena diacantha) and silky copperburr (Bassia eriacantha).

Cher1 (Sheetflow sediment / erosional rise): Subrounded to subangular lithic phyllice gravels, angular lithic quartzite fragments and rounded to subrounded silcrete clasts with minor orange-brown, fine sands associated with moderate slopes of moderate to low relief (9-30 m). Sub-cropping moderately weathered saprock, locally shedding sediments. Chenopod shrublands dominated by pearl bluebush (Maireana sedifolia) and black bluebush (Maireana pyrmidata) with grey copperburr (Sclerolaena diacantha) and silky copperburr (Bassia eriacantha).

CHfs1 (Sheetflow Sediments / Sheetflow fan): Angular to sub-angular metasediments (up to 9 cm), lithic quartz (up to 4 cm), sub-angular to sub-rounded sandstone clasts with minor red-brown, fine-grained, quartzose, sands and silts. Moderate angle, elongated fans, with narrow lobes and highly inclined apex. Vegetation is sparse, dominated by bluebush (Maireana pyrmidata) and bladder saltbush (Atriplex vesicaria).

CHfs2 (Sheetflow Sediments / Sheetflow fan): Angular to sub-angular metasediments (up to 9 cm), lithic quartz (up to 4 cm), sub-angular to sub-rounded sandstone clasts with minor red-brown, fine-grained, quartzose, sands and silts. Moderate angle, elongated fans, with wide lobes and moderately inclined apex. Vegetation is sparse, dominated by bluebush (Maireana pyrmidata) and bladder saltbush (Atriplex vesicaria).

CHpd1 (Sheetflow sediment / depositional plain): Rounded and highly polished silcrete clasts, sub-angular to sub-rounded, slightly ferruginised, lithic sandstone and mudstone, sub-rounded to sub-angular quartz clasts and petified wood fragments with minor orange-brown, calcareous fine sands associated with low relief. Exposures of highly silicified and ferruginised sandstones and conglomerates shedding locally. Chenopod shrublands dominated by black bluebush (Maireana pyrmidata) and pearl bluebush (Maireana sedifolia). Thorny saltbush (Rhogodia spinescens) and velvet potato-bush (Solanum ellipticum) abundant in drainage depressions.

Aeolian Regolith
I Śwps: (Aeolian sediment / sand plain): rounded, orange-brown-red, quartzose sand and rounded to sub-rounded well-sorted lithic gravels with pods of rounded to subrounded quartz, sandstone and siliciied clasts. Small ventifacts scattered around the landform. Low relief with hardpan regolith carbonate accumulations. Vegetation is mulga (Acacia aneura) and bastard mulga (Acacia clivicola) with some black bluebush (Maireana pyramidata). Small sand wind ramps have accumulated on the west of large Chenopods and some of the woodland species.

I Śwps: (Aeolian sediment / sand plain): rounded, orange-brown-red, quartzose sands and rounded to sub-rounded, well sorted lithic gravels. Low relief landform associated with partially siliciided sandstone exposures. Some small dunes formed around the edges of the unit. Vegetation includes Christmas tree mulga (Acacia aneura var. conifera) and bastard mulga (Acacia clivicola), rock sida (Sida petrophila) with some black bluebush (Maireana pyramidata).

In Situ Regolith

SSel: (Slightly weathered bedrock / low hill): Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. High relief (90-300 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts). Minor exposures of slightly weathered diorite and basalt silts. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Some exposures of moderately weathered metasandstones with green and purple staining. Vegetation includes emu bush (Eremophila spp.), mulga (Acacia aneura) and grey copperburr (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

SSer: (Slightly weathered bedrock / erosional rise): slightly ferruginised, interbedded calcareous sandstones and mudstones with orange-brown, rounded to sub-rounded, calcareous, sands and silts with moderate relief (9-30 m). Occasional matrix supported conglomerate lenses. Minor locally derived subrounded colluvium. Vegetation is chenopod shrublands, dominated by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia). Orange and green lichen on some exposures.

SMep: (Moderately weathered bedrock / erosional plain): slightly ferruginised, interbedded calcareous sandstones and mudstones with orange-brown, rounded to sub-rounded, calcareous, sands and silts with low relief (0-9 m). Occasional matrix supported conglomerate lenses. Abundant colluvium, dominated by sub-rounded silcrete clasts and sub-rounded to sub-angular quartz clasts and minor orange-brown, calcareous, fine sands. Vegetation is sparse, conforming to contour bands, and dominated by chenopod shrublands, typically by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia).

SMel: (Moderately weathered bedrock / low hill): Slightly to moderately weathered, highly cleaved, interbedded metasandstone, metasiltstone, shale and slate with minor orange-brown, quartzose fine sands and silts. Moderate to high relief (30-90 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts). Minor exposures of slightly weathered rhythmic tuff and basalt silts. Large protruding quartz veins intruding the metasediments. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Vegetation includes emu bush (Eremophila spp.), mulga (Acacia aneura) and grey copperburr (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

SMer: (Moderately weathered bedrock / erosional rise): Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts. Moderate relief (9-30 m) associated with sheet-like exposures and minor angular colluvium (predominantly quartz and phyllite clasts). Minor exposures of slightly weathered rhythmic tuff and basalt silts. Hardpan regolith carbonate accumulations on some exposures in incised channels and infilling joints and fractures. Vegetation includes emu bush (Eremophila spp.), mulga (Acacia aneura) and grey copperburr (Sclerolaena diacantha). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures.

North Mt Browne

Alluvial Channels

ACah: (Channel sediments / Active Channel): Active ephemeral channel, dominated by channel sediments, predominantly fine-grained silts, quartzose coarse-grained sands and proximally and distally sourced clasts of metasediments, sandstones and quartz. Occasional exposures of moderately weathered sandstones and conglomerates. Vegetation dominated by woodland species with abundant chenopods.

ACah: (Channel sediments / Active Channel): slightly to moderately weathered metasediment exposures hosted in steep gorge-like valleys with ephemeral channels flowing through. Minor accumulations of fine-grained sands and some silts. Abundant hardpan regolith carbonate accumulations. Vegetation is dominated by emu bush (Eremophila spp.) with minor velvet potato bush (Solanum ellipticum). In some of the sandier areas abundant river red gums (Eucalyptus camaldulensis) dominate the vegetation species.

Colluvium

Chen: (Sheetflow sediment / erosional rise): Subangular to angular phyllite and slate clasts with angular lithic quartz, rounded, quartzose sands associated with landforms of moderate to steep slopes and low to moderate elevation (9-30 m). Exposures of slightly weathered basalt and small rounded microclitic monzonite tors with locally ferruginised fine to medium-grained sands. Hardpan regolith carbonate accumulations and silcrete typically associated with areas of lower relief. Chenopod shrubland dominated by black bluebush (Maireana pyramidata) and pearl bluebush (Maireana sedifolia) with copperburr and occasional woodland species such as whitewoods (Atalaya hemiglauca) and rosewoods (Alectryon oleifolius). Beefwood (Grevillea striata) near sub-cropping saprock exposures.

CHfs: Sheetflow fan sediments on a low-angle, broad fan shedding of the Mt Browne Inlier. Clasts dominated by sub-rounded to sub-angular metasediments, rounded quartz, minor silcrete, sandstone and quartz clasts. Small exposures of sandstone in small incised drainage and contemporary channels red-brown sands and silts. Chenopod shrublands dominate vegetation profiles.
**Appendix**

**Cfc (Colluvial sediment / colluvial fan):** Angular to sub-angular metasiltstone and metasandstone clasts and angular lithic quartz clasts (1-10 cm) with minor orange-brown, rounded, fine, quartzose sands associated with moderate to low angle fans. Vegetation is sparse including grey copperburr (*Sclerolaena diacantha*). Blue-green lichen on some larger clasts of metasediments.

**In Situ Regolith**

**SSeh (Slightly weathered bedrock / hill):** Slightly ferruginised, highly cleaved, interbedded metasandstone, metasiltstone and quartz veins with minor orange-brown, quartzose fine sands and silts on high relief (90-300 m) landform. Exposures of intrusives including diorite, basalt and rhyolite intrusives hosted in the lower lying parts of the landform. Minor component of localised colluvium accumulating in breaks of slope and in amongst changes of cleavage profiles. Slopes are typically unstable, with the cleaved sediments often shearing off when trod on. Vegetation includes emu bush (*Eremophila* spp.), mulga (*Acacia aneura*), and grey copperburr (*Sclerolaena diacantha*).

**SSer (Slightly weathered bedrock / erosional rise):** Highly cleaved, slightly weathered interbedded metasandstone and metasiltstone with minor orange-brown, quartzose fine sands and silts on high relief (90-300 m) landform with minor quartz and basalt intrusives and rhyolitic tuff exposures hosted on low to steep rises with a minor component of localised colluvium accumulating in breaks of slope and along fault planes. Vegetation includes emu bush (*Eremophila* spp.), mulga (*Acacia aneura*) and grey copperburr (*Sclerolaena diacantha*). Blue-green lichens are on the southern and eastern aspects of larger exposures of metasediments and orange and green lichens on more ferruginised exposures and pink lichen on rhyolitic tuff.

**SSep (Slightly weathered bedrock / erosional plain):** Highly cleaved, slightly weathered interbedded metasandstone and metasiltstone with minor orange-brown, quartzose fine sands and silts minor quartz and basalt intrusives hosted on undulating plains, with occasional incised drainage depressions. Drainage depressions host abundant colluvium, dominated by angular metasediments clasts (up to 20 cm) and angular to sub-angular quartz clasts (up to 6 cm). Minor component of localised colluvium, rounded quartz pebbles and red-brown, fine-grained sands and silts. Sparse vegetation, dominated by *Eremophila* spp, occasional woodland species such as whitewoods (*Atalaya hemiglauca*) and rosewoods (*Alectryon oleifolius*). Beefwood (*Grevillea striata*) near sub-cropping saprock exposures.

**SMep (Moderately weathered bedrock / erosional plain):** Moderately weathered sandstones, siltstones and conglomerates hosted on undulating plains, low rises and in incised drainage systems in which cliff profiles are up to 20 m high. Dark purple-red ferruginisation with some leisengange weathering pattern. Minor component of colluvium, fragmented hardpan calcrete and red-brown sands and silts. Vegetation is chenopod shrublands, dominated by black bluebush (*Maireana pyramidata*) and pearl bluebush (*Maireana sedifolia*). Orange and green lichen on some exposures.