# The Adelaide Rift Complex in the Flinders Ranges: Geologic history, past investigations and relevant analogues

John W. Counts


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# The Adelaide Rift Complex in the Flinders Ranges: Geologic history, past investigations and relevant analogues


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## ABSTRACT

**The Adelaide Rift Complex, a sedimentary basin in South Australia, has a long history spanning over 300 million years from the Neoproterozoic to the Cambrian. Over 100 individual formations make up the basin fill, documenting its geologic evolution from incipient rift to passive margin and recording a wide range of depositional environments. The basin is significantly affected by syndepositional salt tectonics and later structural deformation, creating a well-exposed natural laboratory in which to examine sedimentary systems that are rarely exposed elsewhere. This publication briefly summarises the basin's geology (focusing on sedimentology), and provides a starting point for further research through reviews of both recent and older literature. The deposits discussed here may serve as analogues for similar depositional systems in the subsurface during petroleum exploration and development; some relevant analogues are also discussed, focusing on those that also have a component of salt-sediment interaction.**


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## INTRODUCTION

This paper provides a general overview of the geologic history of the Adelaide Rift Complex (also known as the 'Adelaide Geosyncline' and 'Adelaide Fold Belt') in South Australia, as well as a summary of published literature on the basin to date. It focuses primarily on the sedimentology, stratigraphy, and depositional environments of lithostratigraphic units and depositional sequences within the basin fill, as well as the connections to relevant surrounding provinces and other coeval basins within Australia. This information provides the background necessary to fully understand the spatial, temporal, and stratigraphic context of a given stratigraphic unit, and demonstrates the need for future investigations. Preiss (1987) covers the Adelaide Rift Complex in substantially more detail; this publication is intended to supplement and summarise that work, and to provide an updated reference list that includes important works published in the 30 years since its release.

This report is based on the literature review for the author's Ph D thesis titled *Sedimentology, provenance, and salt-sediment interaction in the Ediacaran Pound Subgroup, Flinders Ranges, South Australia* and is available online from the University of Adelaide Library (https://digital.library.adelaide.edu.au/dspace/handle/2440/105869).

## PRESENT-DAY GEOGRAPHY AND RECENT HISTORY

The Adelaide Rift Complex is spatially coincident with the modern Flinders and Mount Lofty Ranges. It extends over 600 kilometres across South Australia from the Willouran Ranges in the north, to Kangaroo Island in the south. Today, the Flinders Ranges are in continuity with the genetically related Mount Lofty and Willouran Ranges to the south and northwest, respectively (Fig. 1). The modern topographic expression of the Flinders Ranges is the product of 'Sprigg's Orogeny', a somewhat enigmatic intraplate episode taking place over the last several million years related to the transfer of stress from the margins of the Australian plate (Dyksterhuis and Muller

2008). Uplift continues today; the ancient basin and fold belt provides a zone of weakness in which to accommodate ongoing compression. The region is thus one of the most seismically active zones in Australia (Célérier et al. 2005).

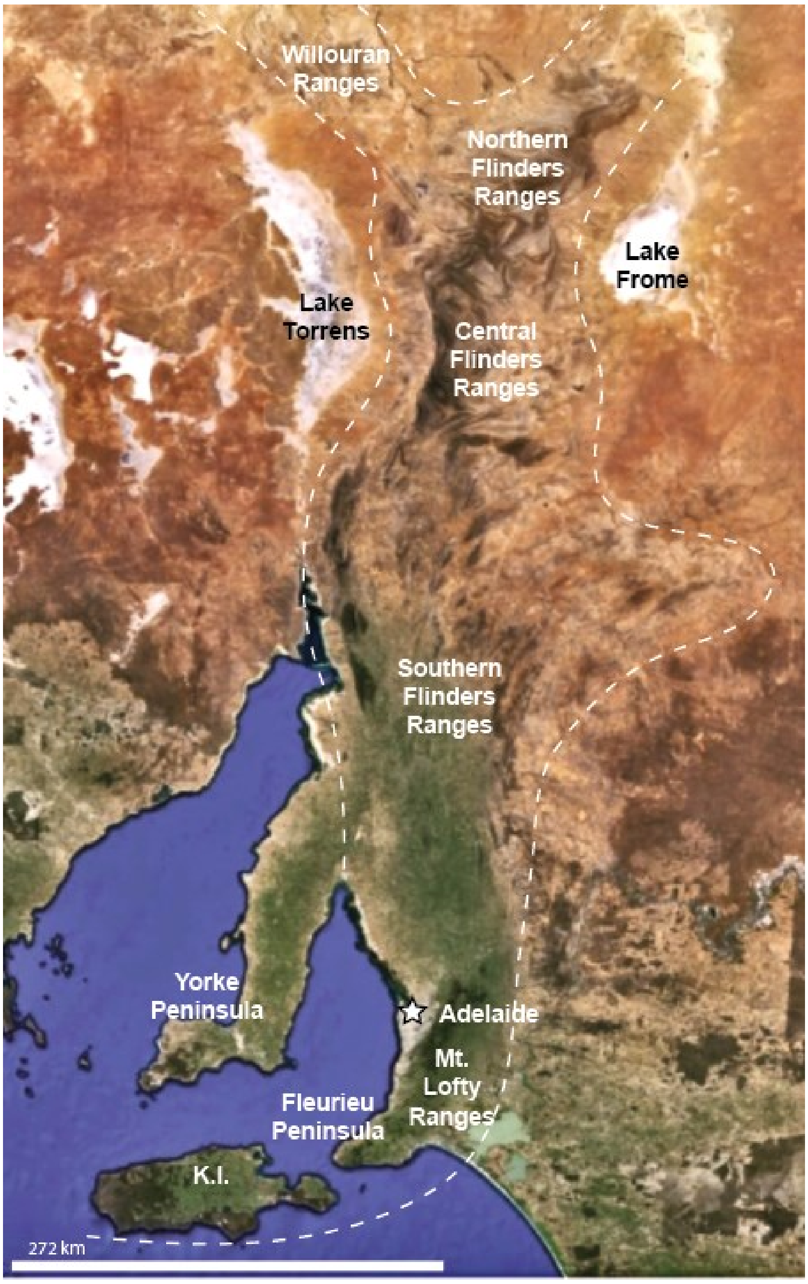


**Figure 1. Present-day satellite view of the Flinders Ranges and surrounds, with geographic regions labelled.**

In the Flinders Ranges, the excellent exposures of Neoproterozoic basin fill sediments are afforded in part by the arid climate and lack of substantial vegetation cover (Fig. 1). The region receives around 250–350 mm rainfall on average per year, and is classified as semi-arid (Preiss 1987). This was not always the case, even in the recent past; Pleistocene valley fill deposits preserved in some catchments show the occurrence of permanent or semi-permanent wetlands between 33 and 17 ka (Williams et al. 2011). Numerous creeks now flow through the area, which are usually dry but are periodically (although rarely) inundated by major floods. These creeks provide access to many of the area's bedrock exposures, including many of the sections measured here. Outcrop exposure is also promoted by extensive pastoral land use, primarily for livestock grazing. European settlement began in the mid-19th century, with the establishment of sheep and cattle stations and the granting of mining leases. Both of these activities continue until the present, although most of the copper mines in the region were largely uneconomic due to low yields and unsustainable transport costs, and did not last past the early 20th century (Mincham 1977). The last substantial working mine in the Flinders Ranges, the Leigh Creek Coal Mine, produced low-grade Triassic coal and closed in 2016.

Today, tourism is an important part of the Flinders Ranges economy. Much of the region is protected by Ikara-Flinders Ranges and Vulkathunha-Gammon Ranges National Parks, as well as the privately held Arkaroola Wilderness Preserve. Geologic investigations in the area have been ongoing since the mid- to late 19th century, beginning in earnest with the identification of Flinders Ranges strata as Precambrian in age by R.C. Tate at the University of Adelaide in the late 19th century. This initiated many decades of further research, led by Walter Howchin, Sir Douglas Mawson, Reg Sprigg, and many others (e.g. Howchin 1900; Mawson 1939, 1941). Official mapping of the PARACHILNA sheet (comprising the central portion of the ranges) was completed by Dalgarno and Johnson in 1966, and in the northern Flinders (COPLEY sheet) by Coats in 1973. In the late 1970s through early 1990s, a number of more detailed sedimentary studies of individual units in the basin fill were completed by PhD candidates from Flinders University, the University of Adelaide, and elsewhere (e.g. Plummer 1978; Uppill 1979; Haines 1987; Clarke 1988). However, in the past 20 years, most research in the Flinders Ranges has focused instead on the structural, salt tectonic, and paleontological (rather than sedimentary) aspects of the basin.

# PALEOGEOGRAPHIC CONTEXT OF THE ADELAIDE RIFT COMPLEX

There have been at least three supercontinents in Earth history: Nuna and Rodinia in the Proterozoic, and Pangaea in the Paleozoic to Mesozoic (Meert 2012). Supercontinent formation throughout earth history may be cyclic; it is hypothesised that the amalgamation of continents into a single landmass insulates the asthenosphere and causes a build-up of heat that leads to breakup shortly after formation (Gurnis 1988). Much of the Proterozoic sedimentation and basin formation throughout Australia is related to the breakup of the supercontinent Rodinia and the formation of an Australia-Antarctica subcontinent. Compared to other intervals in Earth history, Proterozoic paleogeography is poorly understood. The exact nature and location of Rodinia and the former geographic position of modern-day continental cratons remains under debate.

## CONFIGURATION AND BREAKUP OF RODINIA

Piper (2000, 2007, 2009) has criticised the entire idea of Rodinia's existence, favouring instead a different supercontinent, Paleopangaea, which is hypothesised to have been a generally coherent landmass from 2700–600 Ma. In this view, Rodinian continental reconstructions are seen as unlikely based on the improbability of the proposed continental movements (among other reasons), as these reconstructions require the individual landmasses to be isolated and move independently until their assembly. The Paleopangaea hypothesis, however, is problematic for several reasons (detailed in Li et al. 2009) and is not widely supported.

Most researchers agree that evidence points to Rodinia's existence. The supercontinent was most likely assembled from the fragments of Nuna/Columbia around the beginning of the Neoproterozoic between 1050 and 900 Ma (Bogdanova et al. 2009). Assembly likely took place in numerous stages, with Laurentia, Siberia, and Amazonia being incorporated prior to Baltica, India, and Australia. Breakup began shortly after assembly, between 825 and 700 Ma. It was during this phase that much of the sediment fill of the Centralian Superbasin and Adelaide Rift Complex were deposited, and the assembly of Gondwana began from the individual continental cratons (Hoffman 1999).

Several competing models for the configuration of Rodinia have been proposed since the supercontinent was first named (McMenamin and McMenamin 1990). The configuration of continental cratons within the supercontinent is the subject of much debate, and has implications for sediment provenance and paleogeographic reconstruction in Australia. Each Rodinian paleogeographic reconstruction is known by an acronym: SWEAT, AUSMEX, and AUSWUS (Zhao et al. 2006; Fig. 2), with some configurations having modifiers as both the ideas and configurations change through time. The AUSWUS (Australia-Western U.S.) hypothesis (described by Brookfield 1993; Karlstrom et al. 1999; and others) places eastern Australia next to the western United States instead of near Canada. This hypothesis is based on the correlation of tectonic belts formed during the breakup of Rodinia, which may be shown to continue across North America into Australia (Fig. 2B). These correlations, however, have been questioned based on the reliability of paleomagnetic data used in both the SWEAT and AUSWUS reconstructions, resulting in an alternative configuration, AUSMEX configuration, (Australia-Mexico; Fig. 2C, Wingate et al. 2002) which places Australia on the Laurentian margin in the relative position of present day Mexico, although both continents were rotated relative to their current orientation. Some evidence for this hypothesis comes in the form of recent Officer Basin well data that confirms a low latitude position for Australia between 810 and 750 Ma (Pisarevsky et al. 2007).

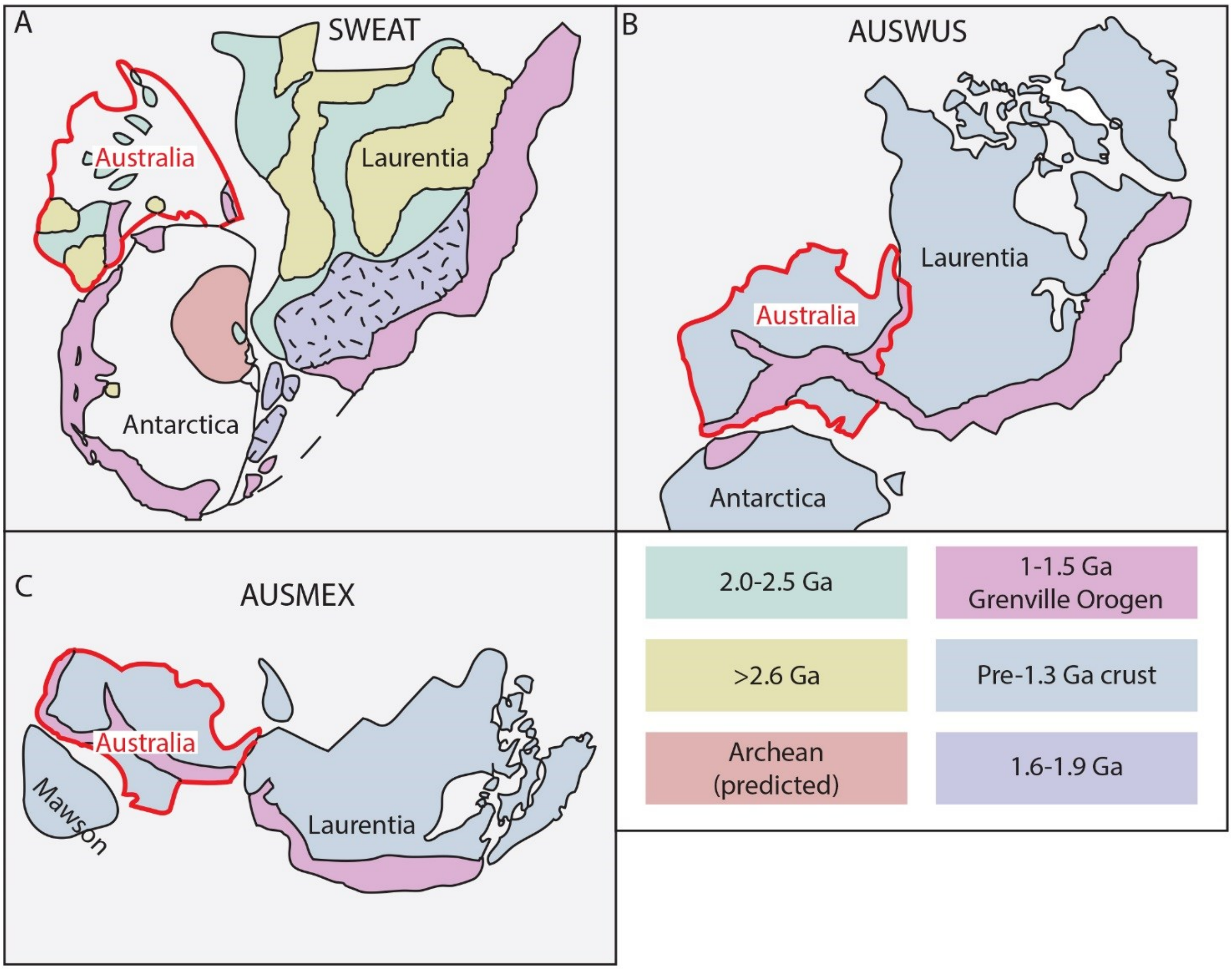


**Figure 2. Major proposed reconstructions of cratonic configurations within the Rodinian supercontinent.** Modified from Zhao et al. (2006).

The SWEAT (Southwest US-East Antarctica) hypothesis (Fig. 2A) generally has the most support; it puts Australia and Antarctica in connection with the western margin of Laurentia. In this configuration, eastern Australia is in close juxtaposition to modern day Canada. Evidence also exists for a connection between the Shackleton Range of Antarctica and the rocks formed during the Grenville Orogeny in the southwestern United States around 1 Ga, giving the model its name and providing the primary evidence for this particular reconstruction. Li et al. (2008) undertook a comprehensive study of Rodinian continental reconstruction as part of a UNESCO-IGCP project to further investigate the supercontinent, concluding that the SWEAT hypothesis is most likely, but modifying it to place south China between Laurentia and Australia/Antarctica. They note the difficulty of reassembling Rodinia with the limited data available, and acknowledge that other hypotheses may also agree with available evidence. Giles et al. (2004) also modified the SWEAT configuration by rotating Australia relative to Laurentia.

Rifting and breakup of Rodinia began about 840 Ma and continued until around 750 Ma. According to Li et al. (2008) the cratons forming Australia and east Antarctica (and possibly south China) remained attached to one another and drifted away from the primary landmass (Fig. 3). The Adelaide Rift Complex was initiated during this time, as part of a tripartite aulacogen that ultimately resulted in an isolated Australia-East Antarctica subcontinent. This aulacogen formed part of what would ultimately become the continental margin; the eastern third of the current Australian continent would not accrete until the Phanerozoic. These original subcontinent boundaries are reflected in the distribution of Proterozoic rocks in Australia, which occur only to the west of the Tasman line (Fig. 4). Australia remained in low latitudes (<20°) throughout the remainder of the Precambrian, including the time during which much of the basin fill (discussed here) was deposited. The paleogeographic position of Australia throughout the Neoproterozoic is determined in part by reliable paleomagnetic data from units in the Adelaide Rift Complex discussed below (Hoffman and Schrag 2002; Hoffman and Li 2009).

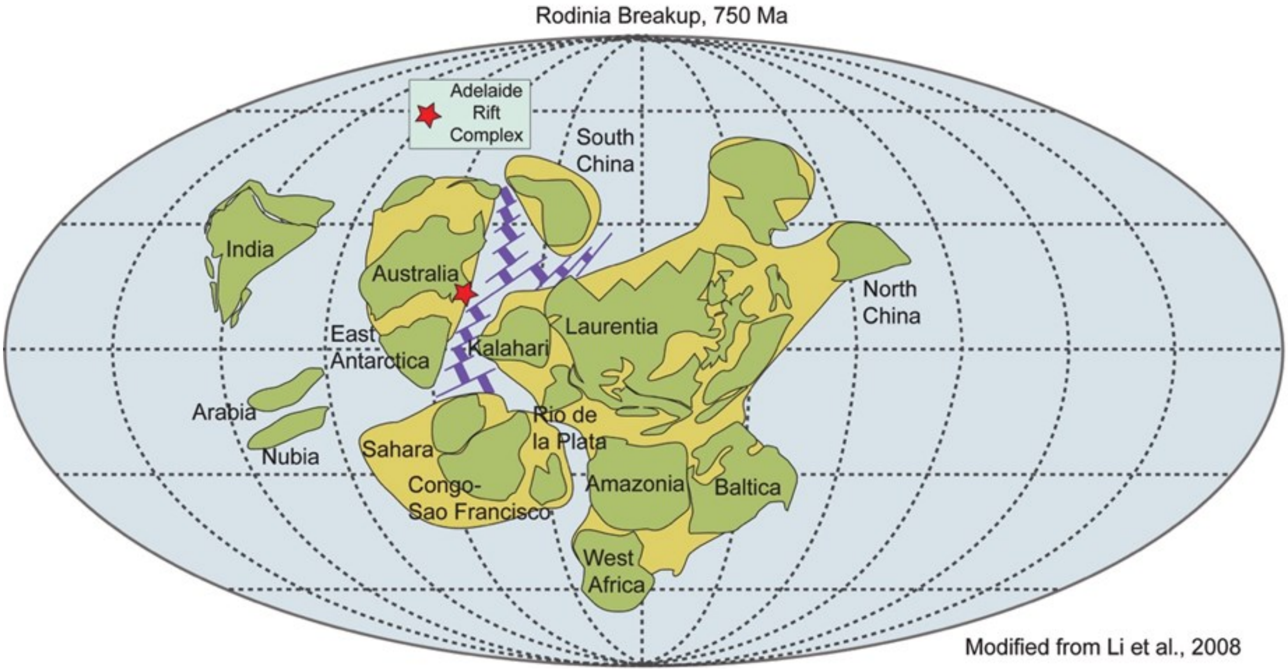


**Figure 3. Global palaeogeography at approximately 750 Ma.**

The basin currently exists as a narrow, north-south trending trough bounded to the west by the relatively undeformed sediments of the Stuart Shelf, which lie unconformably atop the Paleoproterozoic and Early Mesoproterozoic volcanics, granites, and highly metamorphosed sediments of the Gawler Craton. To the east, the Adelaide Rift Complex is adjacent to the Curnamona Province, which is also composed of older igneous and metamorphic continental crust (Preiss 1987). The northern extent of the basin may have been limited by the Muloorina Ridge, a gravity anomaly known only from the subsurface that likely represents Proterozoic basement (Von der Borch 1980). The ultimate southern extent of the basin and surrounding provinces is unknown; potentially correlative sediments of Adelaidean age are found in Antarctica, but the exact relationships are unclear (Wysoczanski and Allibone 2004). The basin was deformed through compression and shortening in the Cambrian Delamerian Orogeny, which exaggerated existing salt-tectonic deformation and resulted in the upturned, folded and faulted sediments seen today.

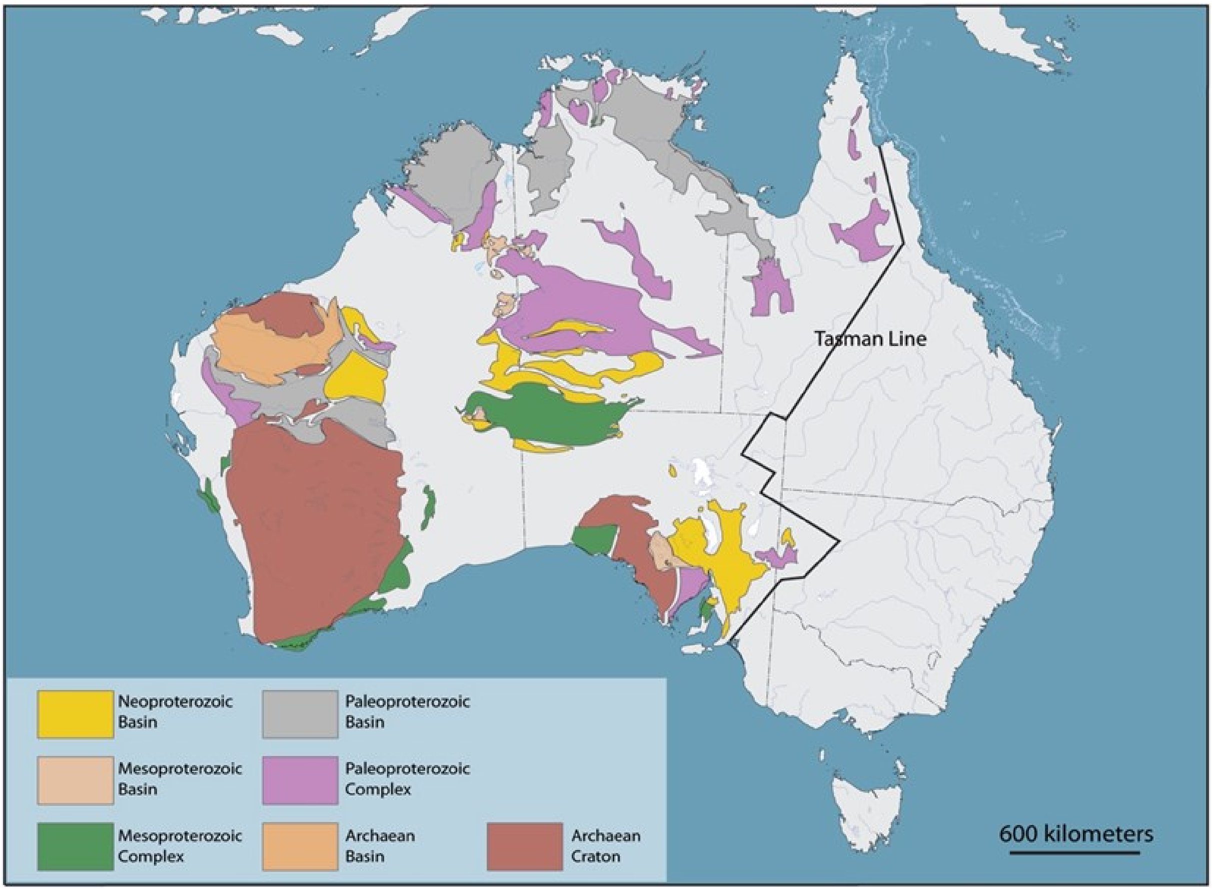


**Figure 4. Present-day Australia, showing the position of the Tasman line and the locations of Proterozoic cratons and basins.** From Parker (1993).

# GEOLOGY OF THE CENTRALIAN SUPERBASIN

## OVERVIEW

The Adelaide Rift Complex shares many similarities with a larger intracratonic basin known as the Centralian Superbasin, which covered much of the Australian Subcontinent during the Neoproterozoic. The superbasin covered over 800,000 square miles, and compromised the present-day Officer, Amadeus, Ngalia, Savory, and Georgina Basins (Fig. 5; Lindsay and Levin 1996). These were likely connected to the Adelaide Geosyncline to at least some degree, as the sedimentary sequences in each of these basins share many similarities. Formation began roughly 800 Ma, and deposition continued until the Peterman Ranges Orogeny fragmented the once-continuous basin around 540 Ma (Walter et al. 1995). Basin formation was related to the breakup of Rodinia, and the termination of subsidence and breakup of the basin was related to the collision of India and Australia during the assembly of Gondwana (Devries et al. 2008). Lindsay et al. (1987) interpreted basin formation to have taken place during two periods of crustal extension, at 900 and 600 Ma. Grey and Calver (2007) attempted to correlate the Ediacaran period across Australia; while absolute ages were difficult to determine, correlations were possible using an integrated approach that combined biostratigraphy, sequence stratigraphy, Carbon isotopes, and the ejecta layer from the Acraman impact.

Evidence for the Centralian Superbasin today exists in the form of lithostratigraphic similarities between existing, smaller structural basins. Unlike continental margin basins where mechanisms of formation can be readily explained, intracratonic basin formation may be more enigmatic. The enormous scale of the Centralian Superbasin cannot be explained by local tectonic processes, and has been hypothesised to have been formed due to crustal thinning associated with a large mantle plume (Zhao et al. 1994).

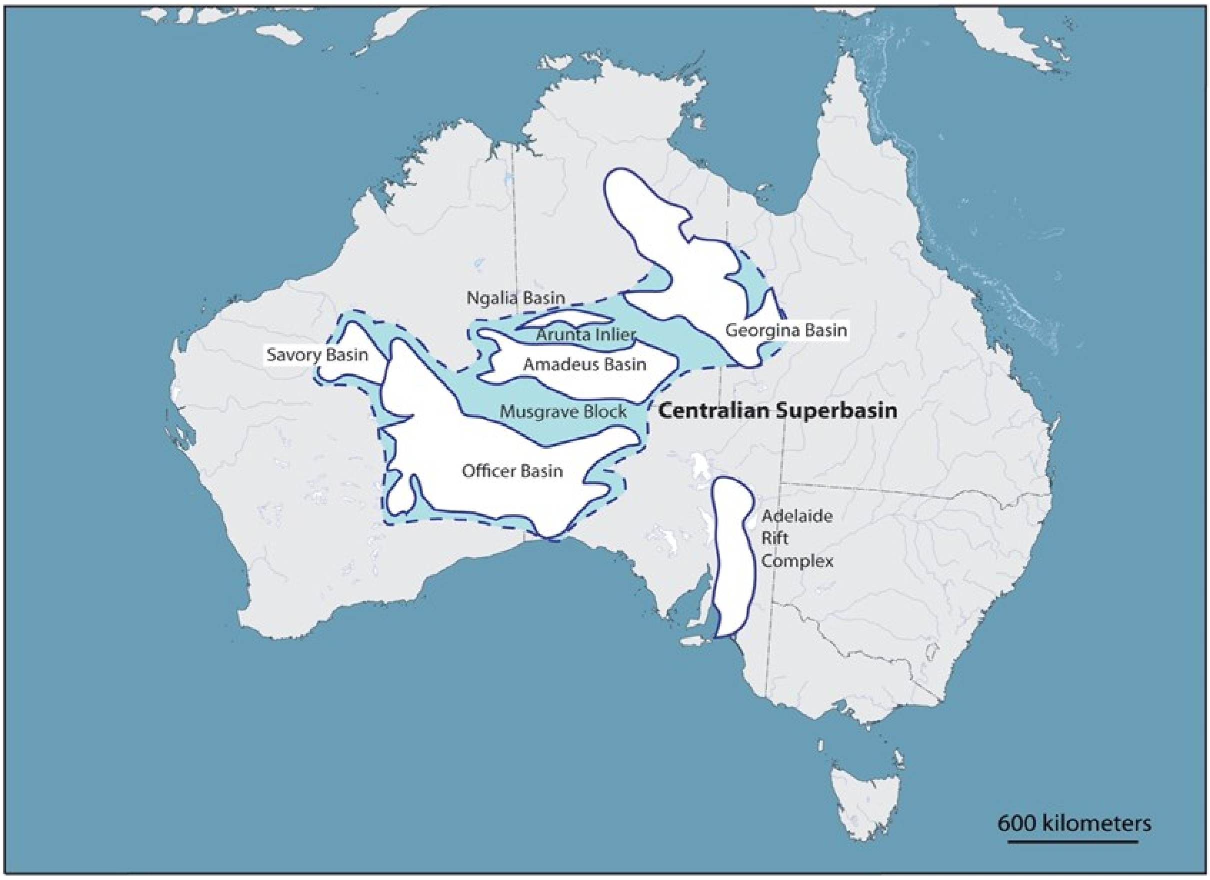


**Figure 5. Map showing location of Centralian Superbasin, cratonic provinces and constituent basins.** Modified from Walter et al. (1995).

## BASIN FILL

Walter et al. (1995) divided the Centralian Superbasin into four supersequences based on distinctive sedimentation patterns, and attempted to correlate strata across several basins (Fig. 6). Supersequence 1 often contains a thick quartzitic sand that consistently lies at the base of the basin fill of each sub-basin. Supersequence 2 is defined by the beginning of the Sturtian Glaciation, and is thus coincident with the Umberatana Group in the Flinders Ranges area. Lithologies in this supersequence are generally poorly sorted, glacially derived diamictites. Supersequence 3 likely correlates with the Marinoan/Elatina glaciation at the base, and continues into stratigraphic equivalents of the Wilpena Group in the Adelaide Rift Complex. Glacial deposits are widespread, and are capped by a dolomitic unit in the Amadeus and Ngalia Basins. Preiss and Forbes (1981) believe that both the Sturtian and Marinoan glacial episodes can be correlated across central Australia, although in the Georgina Basin, the Marinoan episode is represented only by arkosic sands, Calver (2000) correlates the Wonoka Formation in the Adelaide Rift Complex to the Munyarai Formation on the basis of isotope stratigraphy. Supersequence 4 contains trace fossils and the Ediacaran biota, and is generally sand-dominated. Although sedimentation within individual sub-basins continued well into the Phanerozoic, they were no longer connected.

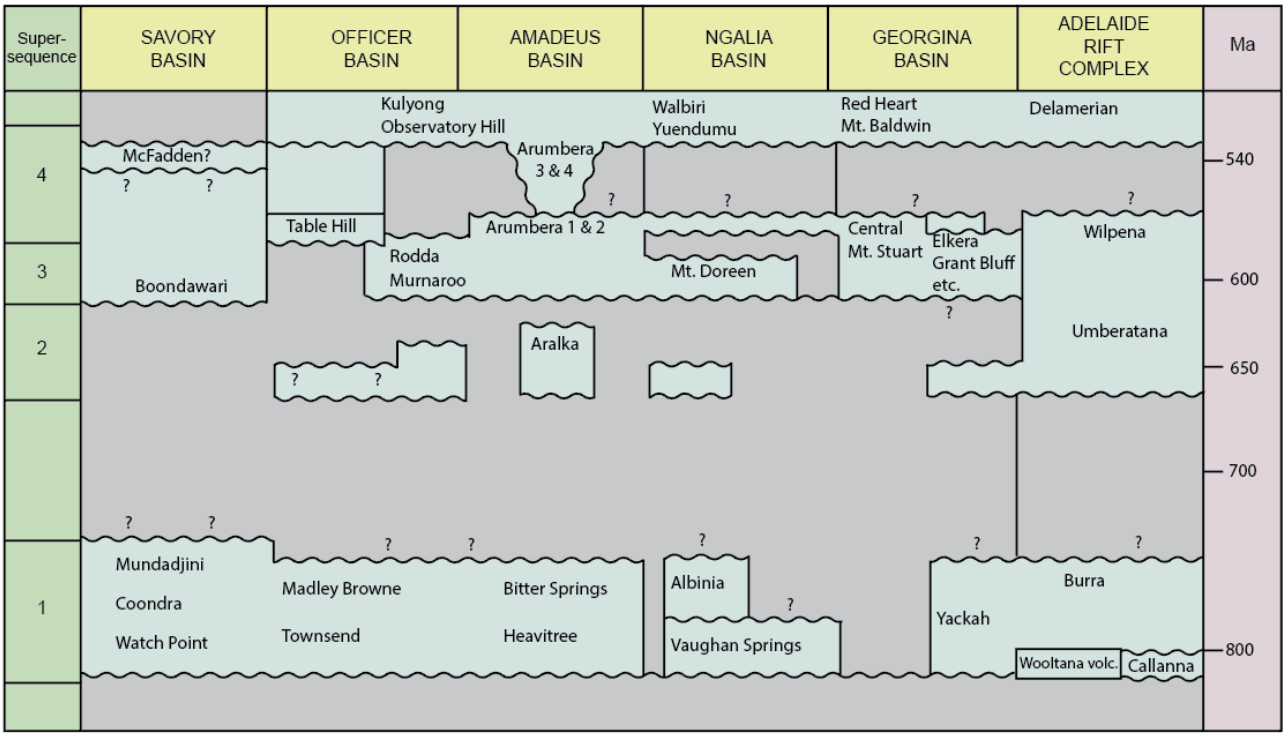


**Figure 6. Correlations across the Centralian Superbasin.** Modified from Walter et al. (1995).

Most sediments filling the Centralian Superbasin during the Neoproterozoic were largely sourced from the 1000–1800 Ma Paleoproterozoic-Mesoproterozoic Arunta Inlier (Collins and Shaw 1995; Maidment et al. 2007) adjacent to the Amadeus and Officer Basins. Later, during the Peterman Orogeny in the Early and Middle Cambrian, the Musgrave Block was uplifted and became the predominant source for the Amadeus Basin sediments. Thick accumulations of sediment were also deposited during this time, and again shortly afterward in the Palaeozoic Alice Springs Orogeny where sediments filled syntectonic foreland basins. In the late Cambrian and Early Ordovician, sediments became sourced from a place elsewhere in Gondwana, with a provenance consistent with Africa or Antarctica.

# STRATIGRAPHY AND SEDIMENTOLOGY OF THE ADELAIDE RIFT COMPLEX

Initial deposition in the Adelaide Rift Complex is hypothesised to have begun around 840 Ma, based on isotopic work in the Wooltana Volcanics (Wingate et al. 1998), a thick sequence of basalts in the upper Arkaroola Subgroup. Rifting is related to the Rodinian breakup, of which the western 2/3 of Australia was a part. The basin is believed to have gone through at least five separate rift cycles throughout its history, each of which is separated by a period of tectonic quiescence and nondeposition, followed by sag-phase deposition. In each of these rift-sag cycles, reactivation of rifting coincides with the top of one of 16 sequence-sets defined by Preiss et al. (1993). The stratigraphy of the Burra and Umberatana Groups was later revised to better reflect sequence boundaries (Preiss et al., 1998; Preiss and Cowley 1999). In addition to these larger-scale rifting episodes, extension was likely ongoing throughout deposition of most of the fill, as syndepositional faulting is recognised throughout the basin.

The lithostratigraphic units that comprise the fill of the Adelaide Geosyncline are divided into three Supergroups, and numerous Groups, Subgroups, and Formations (Fig. 7). Stratigraphic units are discussed here in stratigraphic order from oldest to youngest, organised at a group level.

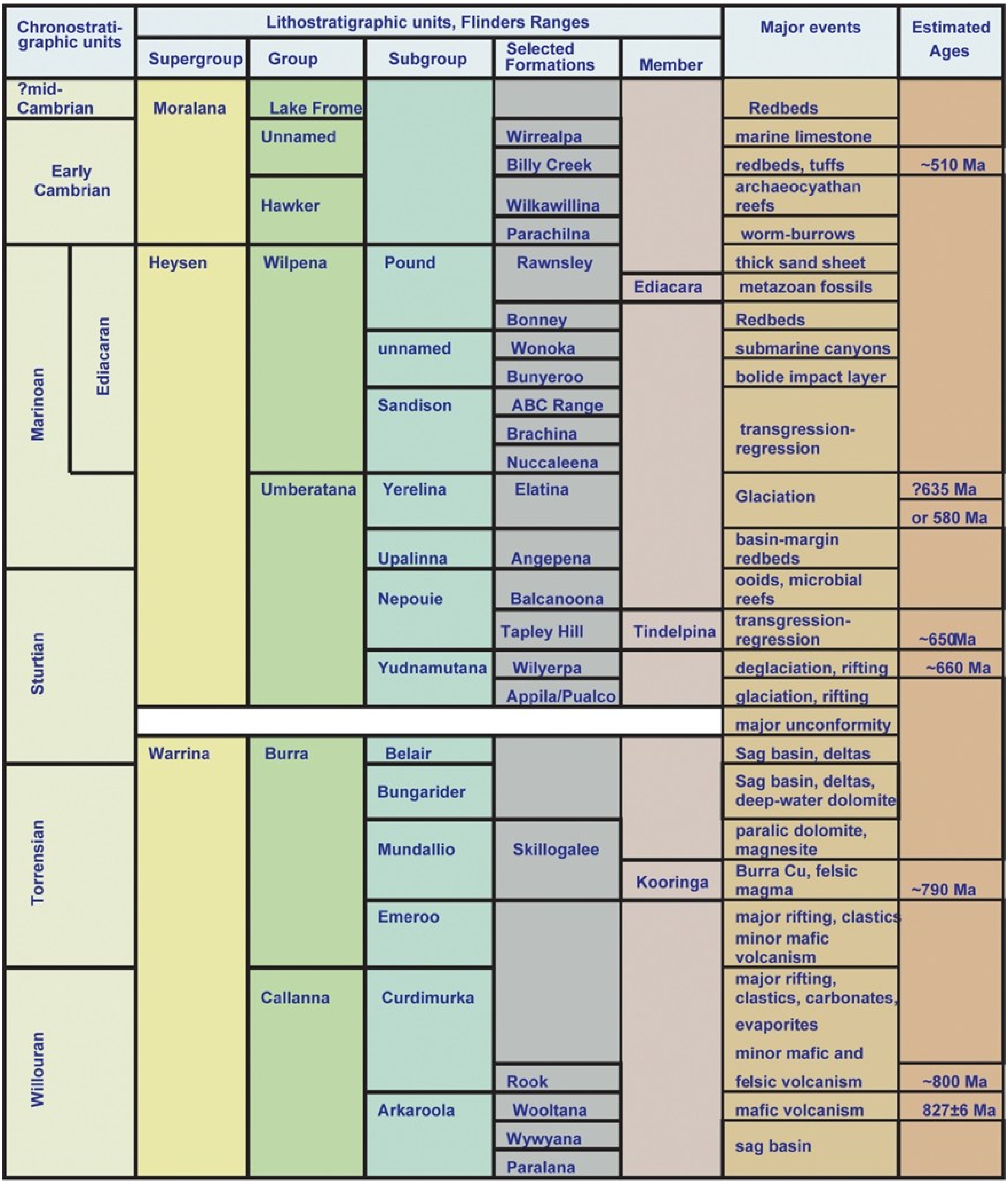


**Figure 7. Generalised basin-fill stratigraphy of the Adelaide Rift Complex.** Modified from Preiss (2010).

## CALLANNA GROUP

Perhaps the least studied interval in the Adelaide Rift Complex, the Callanna Group is poorly exposed in comparison to younger units in the basin. The Adelaide Geosyncline during this time was generally a fault-bounded rift basin, as opposed to the passive continental margin it would become during most of its subsequent history (Preiss 1987). The abundant salt diapirs in the basin originated from evaporites in the Callanna Group, and created topographic relief at the surface that influenced deposition in several areas (Dalgarno and Johnson 1968). The sedimentary units in the

Callanna Group are therefore exposed most often as allochthonous block within diapirs (Preiss 2000). Detailed sedimentological studies are rare; however, general lithologies have been worked out, and the stratigraphic sequence has been pieced together from numerous disparate outcrops.

The oldest in situ sedimentary unit that is exposed in situ in the basin fill is the ~1000 m thick Paralana Quartzite in the Arkaroola Subgroup (part of the Callanna Group), which was unconformably deposited onto exposed basement (Thomson 1966) in the northeast part of the Flinders Ranges. It consists of a lower conglomeratic member of limited extent, deposited only in fault-related depressions and consisting of cobble-sized grains of mixed lithology, and two upper sandstones that abruptly change from cross-bedded, poorly sorted sands at the base, to well sorted massive quartzites in the upper member. This sequence has been proposed to represent a deepening upward trend, beginning with the talus-slope deposition of the conglomerate and culminating in a shallow marine environment near the top of the formation — some areas near the top of the Paralana also contain columnar stromatolites (Preiss 1987). Well-sorted quartzites are the most dominant and widespread lithology in this sequence, and may predate large-scale rifting. Above the Paralana lies the Wywyana Formation, a metamorphosed carbonate unit composed of marble and calc-silicates. It likely had a dolomitic precursor and is folded and intruded into the overlying unit, and thought by some (e.g. Coats and Blissett 1971) to be the source of the diapirs in the region. Preiss (1987) considers the the Wywyana to be deposited in deeper water, away from wave influence, but also considers that it could have been lacustrine. Turner (1976) notes that most sedimentary structures in the Paralana and Wywyana have been destroyed by metamorphism and tectonic deformation, at least in the Mount Painter region of the Flinders Ranges.

The uppermost Arkaroola Subgroup contains a laterally consistent package of extrusive igneous rocks, known in the northern Flinders Ranges as the Wooltana Volcanics. These are approximately correlative to several other igneous formations that are variably present across 250,000 $km^2$ in central Australia (Preiss 1987). These rocks are predominantly basalts and were deposited during a period of regional tensional stress that resulted in widespread igneous activity. Relative sea level was low during this interval, forming a significant sequence boundary that marks the base of the Curdimurka Subgroup at approximately 810 Ma (Preiss 2000). The Curdimurka Subgroup is best exposed in the Willouran Ranges just north of the Flinders, and contains a number of cyclical lithologies that are found throughout the basin but cannot be confidently correlated with one another throughout the entire Adelaide Geosyncline. Repetitive deposition of siltstones, sandstones, and stromatolitic carbonates likely took place in multiple sub-basins that were semi-connected at different times (Mackay 2011). The Curdimurka is known only in the northern part of the Adelaide Rift Complex; it is likely that other areas within the basin were topographic highs and areas of erosion (Preiss 1987).

In the north, the lowermost unit of the Curdimurka is the Dome Sandstone, which contains a number of sand-rich lithologies that range from ~200 to ~1500 m thick. Channels, crossbedding, and local halite and dolomite suggest a fluvial or marginal marine environment. The felsic Rook Tuff lies atop the Dome and is one of the few units that can be dated with some degree of certainty (802 Ma; Fanning et al., 1986), constraining the ages of other early formations in the basin fill. Together with the overlying Dunns Mine Limestone and Recovery Formations, this interval represents a sustained period of marginal marine deposition. The Hogan Dolomite, with its evaporite pseudomorphs, tepee structures, and polygonal cracks, along with the siltstone-rich Cooranna and Boorloo Formations, record similar environments stratigraphically upward. The Curdimurka Subgroup therefore contains a number of transgressive-regressive cycles that reflect only minor changes in the basin environment. Lack of widespread continuity indicates that cyclicity is most likely tectonically controlled (Mackay 2011). The top of the subgroup (and the Callanna Group) is marked by a significant lowstand that forms a sequence boundary between the Willouran and Torrensian sequence sets, as defined by Preiss (2000).

## BURRA GROUP

The Burra Group, defined by Thomson et al. (1964) and revised by Preiss and Cowley (1999) is more widespread than the Callanna Group, and is better exposed and better studied. It is present throughout the Adelaide Rift Complex, and generally can be correlated in some detail across the basin. In the Flinders Ranges, the Burra contains a predominantly clastic Subgroup at its base (the Emeroo Subgroup), which is overlain by the dominantly carbonate Mundallio Subgroup and often fine-grained Bungarider Subgroup. The Belair Subgroup, present to south, is absent in the Flinders Ranges. The Burra, like the Callanna Group, displays repeated depositional cycles of similar lithologies. Many sediment packages are interpreted as having been deposited in lacustrine or restricted environments.

The Emeroo Subgroup is present in the North Flinders as the Humanity Seat Formation, Woodnamoka Phyllite, Opaminda Formation, Wortupa Quartzite, and Blue Mine Conglomerate. The Humanity Seat has been interpreted as having been deposited in a shallow-water and fluvially influenced environment, possibly in a braided river system with associated sheet-flooding and drainage into a shallow restricted body of water (O'Halloran 1992). It is partially correlative with the Woodnamoka Phyllite to the west. The overlying Blue Mine Conglomerate contains mudcracks and ripple marks, and larger clasts of mixed lithology, and is thought to have been deposited on a fluvially influenced shoreline (Coats and Blissett 1971; Preiss 1987). O'Halloran (1992) looked at these formations in a sedimentological and geochemical context, and placed the Blue Mine Conglomerate in braided stream and alluvial fan environments. He also noted evidence for tidal influence in the Emeroo Subgroup due to an increasing connection with the larger ocean. The dolomitic shales and siltstones of the Opaminda Formation, and the sandy Wortupa Quartzite near Arkaroola make up the top of the Formation in the northern Flinders. Job (2011) examined the provenance in some of these formations, finding a potential variety of sources including the Mt. Painter Complex, Gawler Craton, and Musgrave Province.

To the south, the Emeroo Subgroup changes in lithostratigraphic character.  The basal unit  in the Adelaide region is the Rhynie Sandstone, a thick quartzite known for heavy mineral laminae that was deposited in a more landward, fluvially influenced setting than its' northern equivalents. Above the Rhynie Sandstone lies the Blyth Dolomite, fine-grained, laminated carbonate which has not been studied in detail from a sedimentological perspective. The River Wakefield Formation, formerly of Subgroup status, is present from the central Flinders Ranges to the Torrens Hinge Zone and was deposited after Rhynie time during an overall transgressive interval; facies suggest a depositional environment that is generally more marine-influenced than those below. These formations are dominantly silty or dolomitic, and represent at least two fining-upward sequences that are consistent throughout the basin. Numerous members make up the River Wakefield Formation, described in detail by Preiss (1987; at the time these were of Formation status) and Preiss and Cowley (1999). The top of the Subgroup is is coincident with the top of the Torrensian 1 sequence-set in the terminology of Preiss, (2000).

In contrast to the underlying strata, the Mundallio Subgroup (as well as most of the remaining upper basin fill) has been relatively well-studied due to better exposures and less intense metamorphism. The Skillogalee Dolomite is the most widespread unit. In the Flinders Ranges, the Skillogalee dominates the upper part of the sequence, whereas the lower portion of the Subgroup is composed several different formations. Uppill (1979) interpreted the lower half of the Subgroup to have been deposited in a variety of clastic-dominated environments, with minor dolomite-rich units deposited in a low-relief ramp-type setting that records numerous noncyclic facies changes. These sediments represent marginal marine and shallow marine conditions. The Skillogallee itself includes recrystallised dolomites, Magnesite, and terrigenous clastics. These were thought by Uppill (1979) to have been deposited in shallow, subaqueous mudflats with intermittent subaerial exposure and variable clastic supply. Nodular and intraclastic Magnesite beds are interpreted to be sedimentary in origin and were deposited in ephemeral, nearshore lakes.

More recently, Frank and Fielding (2003) re-examined Magnesite in the Skillogalee to better understand its origin. As primary Magnesite is not extensively deposited as a sediment in the present-day, the precise origin of extensive deposits in the Neoproterozoic has been a longstanding controversy (the ‘Magnesite problem’), and is thought to be related to the differing geochemistry of the Precambrian oceans. Unlike Uppill (1979) and von der Borch and Lock (1979), Frank and Fielding support a marine rather than lacustrine origin for Skillogalee-type deposits. Recent analyses support this idea (Kah et al. 2001; Hurtgen et al. 2002) suggesting that the Proterozoic oceans were carbonate-enriched and sulfate-poor, a chemistry that would promote Magnesite precipitation. Skillogalee equivalents (‘ER4-ER7’) in the Willouran Ranges described by Heithersay (1979) are interpreted as a generally shallowing upward cycle, from dark shales at the base, coarsening upward to sands, and finally to heterogeneous lithologies capped by cryptalgal and stromatolitic dolomites. This sequence is interpreted to represent the transition from a reducing, offshore environment below wave base, through an interval of progradation of deltaic and marginal marine strata, to nearshore and subtidal environments closer to the top. Primary Magnesite is absent in higher-energy environment of the Willouran Ranges, in keeping with the idea that its formation is related to restricted or lacustrine deposition in quieter water.

After a significant lowstand toward the end Skillogalee deposition, clastic deposition resumed with the Bungarider Subgroup, which occurs in the northern Flinders Ranges as the Myrtle Springs Formation and several unnamed siltstones and quartzites (Murrell, 1977). Here, these are poorly known, but to the south the unit becomes more well-defined, with the Woolshed Flat Shale, Undulya Quartzite, and Saddleworth Formation outcropping south of Hawker. These are sandy, silty, and locally dolomitic units deposited in a series of three major transgressive-regressive intervals, prograding eastward. The Undulya Quartzite equivalent in the south near Adelaide is the Stonyfell Quartzite, but the Woolshed Flat and Saddleworth Formations persist, albeit with some lateral facies change. The Subgroup thickens considerably to the south, from 1100 to 5000 metres (Preiss and Crowley, 1999) forming a significant portion of the total thickness of Precambrian sediments in the Adelaide region.

The Belair Subgroup is earliest Sturtian in age, but is lithologically more similar to the preceding Burra Group deposits rather than those above. Composed primarily of fine-grained clastics and immature sands, it is well-exposed in the southern Flinders Ranges, including much of the Clare Valley where it is economically important for mining and viticulture. The Mintaro Shale may represent the earliest glacial deposits in the basin, as it contains rare lonestones that indicate the presence of sea ice, at least intermittently (Preiss et al. 2010). It is frequently used as commercially in the Clare area for flooring and interiors. A significant unconformity exists at the top of the Burra Group separating these sediments from the Sturtian glacials above.

## UMBERATANA GROUP AND CRYOGENIAN GLACIATION

Lying unconformably above the Burra Group, and comprising the lower Heysen Supergroup, Umberatana Group stratigraphy was most recently revised by Preiss et al. (1998). The unit records the onset of significant glaciation in the basin. Sediments deposited during Umberatana time (Sturtian and Marinoan ages) have been reliably constrained to low paleolatitudes by paleomagnetic data (Hoffman and Schrag 2002, and references therein), while also containing sediments clearly derived from nearby glacial activity. Glacial sediments in the area were first recognised by Howchin (1900), and have since been the focus of much research in South Australia. These deposits were integral in formulating the original ‘Snowball Earth’ hypothesis, i.e. the idea that Earth during this time was completely covered in glacial and sea ice during the Cryogenian period of the Neoproterozoic. Alternative views of the Snowball Earth hypothesis abound. Many of these call into question the reliability of paleomagnetic latitude data (e.g. Meert and van der Voo 1994; Meert and Torsvik 2004), suggesting that Neoproterozoic glaciations were not as extensive as initially thought because continents were actually in higher latitudes. More recent studies have questioned whether ice cover was complete or only partial, based on sedimentary structures within glacial periods that require ice-free conditions (e.g. Williams et al. 2008; Le Heron et al. 2011a; 2011b). Eyles and Januszczak (2004) question instead whether many of the global ‘glacial’ deposits are indeed glacial at all — they interpret many of the poorly sorted diamictites in numerous formations around the world to be mass-flow deposits that do not originate from a glacial source. They are specifically skeptical of several intervals in the Marinoan sequence previously interpreted as glacial, referring striated exotic clasts to tectonic and diapiric processes, while still acknowledging the presence of ice wedges in Elatina-correlative strata. Despite the controversy, the view that currently prevails is one of at least periodic glacial activity in low latitudes, but not the complete global ice cover that was initially proposed by Hoffman et al. (1998). Two distinct glacial periods are found in the Umberatana Group, referred to as the Sturtian and the Marinoan.

## STURTIAN GLACIAL INTERVAL

The lowermost units of the Umberatana Group are a laterally variable, correlative set of glacially deposited strata that are recognised as the beginning of the Sturtian Glaciation, the earlier of two distinct glacial periods in the Neoproterozoic. The age of Sturtian glacial sediments is constrained by a tuffaceous bed in the Wilyerpa Formation, a thick succession of clastic sands, silts and diamictites at the top of the glacial succession. Since glacial sediments occur both above and below the tuff unit, glaciation is known to have happened in and around 659 Ma, a date consistent with other ages obtained in post-glacial sediments elsewhere in Australia (Fanning and Link, 2008). Preiss et al. (2011) recently reviewed many aspects of the geology of the Sturtian glaciation. They note that during Sturtian time, active rifting in the Adelaide Geosyncline led to the deposition of 3–5 km of siltstones, sandstone, conglomerate, diamictite, and ironstone in the eastern and northern Flinders Ranges. Relationships between these lithofacies are complex; many interfinger and are laterally variable. Thicknesses are controlled by underlying tectonics, where extensional troughs act as depocentres and result in thousands of metres of increased thickness (Preiss, 1999; Busfield and Le Heron, 2014). In the southern Flinders, the Appila and Pualco Tillites and the Holowillena Ironstone form thick successions of diamictite and fine-grained hematite containing glacial dropstones. In the Northern Flinders, the Merinjina Tillite in the Yudnamutana Subgroup contains striated, basement-derived clasts, dropstones, and other evidence of glaciation (Link and Gostin 1981). These units record repeated glacial advancement and retreat, rather than a single episode. Lithologies during the Sturtian glacial episode were interpreted by Preiss et al. (2011) as glacial-marine outwash deposits, and core through the Sturtian sequence described by Eyles et al. (2007) also regard several Sturtian glacial sediments as being submarine in origin. They emphasize the contribution of glacial meltwater to the depositional processes in the Sturtian section, which has implications for the 'snowball earth' hypothesis, wherein the 'snowball' is less 'hard' and did not completely shut down the hydrological cycle. Other authors (e.g. Le Heron et al. 2011a) agree that the abundance of sedimentary structures in the Sturtian sequence that require moving water (e.g., hummocky cross-stratification in the Wilyerpa Formation) are important evidence for a glacial event that was not completely global. Young and Gostin (1988; 1989; 1990; 1991) worked extensively on many of these sediments, and interpret them as glacially influenced subaqueous mass flow deposits. To the north, late Sturtian sediments of the Lyndhurst Formation are clast-poor, suggesting a changing degree of glacial influence. Massive diamictites to the south are instead replaced by laminated silty mudstones and turbidites that Young and Gostin (1989) interpreted as mass flow deposits with occasional ice-rafted debris. Sturtian deglaciation is recorded in the Wilyerpa Formation through decreasing sand beds and increased abundance of lonestones within silts and shales, terminating in a dominantly fine-grained interval at the top of the glacial sequence (Le Heron, 2012) and Sturtian 2 sequence set (Preiss, 2000).

## INTERGLACIAL FORMATIONS

Above these units, the overlying Tindelpina Shale Member of the Tapley Hill Formation contains no glacial debris and therefore marks the end of the Sturtian glacial sequence. This formation, in the center of the Umberatana Group, consists of thousands of metres of black shale and marks a sustained period of deposition free from glacial influence. The Sturtian glacial interval here is capped by fine-grained, laminated limestones and peloidal dolomites of the Tindelpina Shale Member, unlike many other Neoproterozoic glacial episodes throughout the world that terminate in a carbonate unit containing a suite of unique sedimentary features ('cap carbonate'; Giddings and Wallace 2009). Based on carbon isotopes, the formation has been interpreted as having been deposited in a stratified ocean that resulted from an influx of glacial meltwater. Several other interglacial formations lie between the Tapley Hill and the onset of the subsequent Marinoan glaciation, recording a series of laminated silty shales and limestones (e.g. the Trezona Formation shown in Fig. 8) that were deposited in various marine environments. Sedimentation during this interval was also influenced by diapiric tectonics — the Enorama diapir was a topographic high (likely forming an island), which may have been scoured by glacial movement and provided a source for much of the increased sedimentation surrounding it (Lemon 2000; Lemon and Gostin 1990). The Yaltipena Formation, the stratigraphically highest interglacial in the Central Flinders, records a shallow marine carbonate environment that is part of the overall regression associated with the onset of the subsequent Elatina/Marinoan glaciation (Lemon and Gostin 1990).

Interglacial Umberatana Group carbonates were described by Wallace et al. (2014), who report the presence of high-relief, progradational reef buildups in the northern Flinders Ranges that are unusual in several ways when compared to later carbonates. These reefs (in the Balcanoona Formation) and associated fore- and back-reef deposits (primarily in the Yankaninna and Angepena Formations) are strongly progradational, yet grow into near-vertical escarpments with up to hundreds of metres of relief from the basin floor. Reef boundstones are formed by stromatolites and other enigmatic organisms (likely non-photosynthetic microbes), which formed dendritic structures and chambered or clotted fabrics. Forereef deposits consist of breccias composed of large allochthonous blocks of reef-derived material. The authors propose that reef geometries are a product of increased saturation of carbonate in deeper anoxic ocean water, which has been hypothesized to have been the case in Cryogenian oceans (Higgins et al., 2009).

**Figure 8. Large stromatolite in the Trezona Formation, a fine-grained unit in the upper interglacial interval.** Photo 415208

## MARINOAN GLACIAL INTERVAL

The Marinoan (Elatina) glacial interval comprises a single formation and its equivalent strata in the Flinders Ranges area, the Elatina Formation (Fig. 9). The formation is generally sandy in the lower half and heterogeneous in the upper half (Le Heron et al. 2011a), with the lower interval interpreted to be the product of fluvially deposited glacial outwash, and the upper portion representing a mix of environments, including outwash plains and tidal flats. The sequence begins with a major sequence set boundary (Marinoan 1) and records progressive deglaciation overall, with smaller-scale fluctuations of glacial influence internally. Williams et al. (2008) and Williams et al. (2011) examined the sedimentology and depositional environments of the Elatina Formation throughout the basin. They found numerous sedimentary facies, including terrestrial, ice-free permafrost zones on the adjacent Gawler Craton, fluvial-deltaic and shallow marine deposits in the central Flinders, and thick, glacially derived deeper-water sediments in the north Flinders. Like the Sturtian interval below, the presence of wave and tidal indicators, as well as laminated sediments with exotic dropstones, indicate that ice cover was intermittent during this period. Periglacial structures (e.g. sand wedges) in some facies indicate that climate during this time was strongly seasonal but generally arid. Williams et al. (2011) also found paleomagnetic data to be reliable based on fold tests, recording a mean paleolatitude of 6.5°. Their observations confirm the presence of near-equatorial ice during this time, but also provide unequivocal evidence for open water movement during the Marinoan. The authors note the need for more precise dating, which could only be constrained to between 640 and 580 Ma.

**Figure 9. Glacial tillite in the upper Elatina Formation, Brachina Creek.** Photo 415209

The upper Elatina is strongly tidally influenced (Williams et al. 2008; Le Heron et al. 2011a, b). Cyclic, mm- to cm-scale bundling of laminae (Fig. 10) within the formation has been the focus of several studies, and was initially thought to be the product of solar activity cycles (Williams and Sonnett 1985; Sonnett and Williams 1987). Later interpretations moved to a model requiring solar-tidal interaction (Zahnle and Walker 1987; Sonnett et al. 1988), and finally to a purely tidal origin for the rhythmic sequence (Williams 1988; 1990; 1997) Although the tidal origin is currently generally accepted, some recent authors (e.g. Raub 2010) have returned to the accepting the plausibility of the solar hypothesis.

Le Heron et al. (2011b) compared both the Sturtian and the later Marinoan intervals and found several differences in the glacial facies sequences and in the style of deglaciation, but noted that six distinct facies associations could be applied to both sequences. Diamictites (poorly sorted sediments) in both intervals are typified by a wide range of clast lithologies and are closely associated with cross-stratification, implying subaqueous deposition in conditions free of complete sea-ice cover. Other facies (hummocky cross-stratification beds, sheet sandstones deposited in outwash plains, and tidally influenced flaser bedding) also provide evidence that glacial periods were at least intermittent. However, the older Sturtian sequence is significantly thicker than the upper Elatina (maximum thicknesses of 4.5 km vs. 1 km), and is generally deposited in deeper, more marine conditions. Tillites in both the Sturtian and Marinoan sequences can be tentatively correlated to glaciogenic deposits in other basins in central and western Australia (Coats and Preiss 1980), implying that glaciation was widespread throughout Australia at the time.

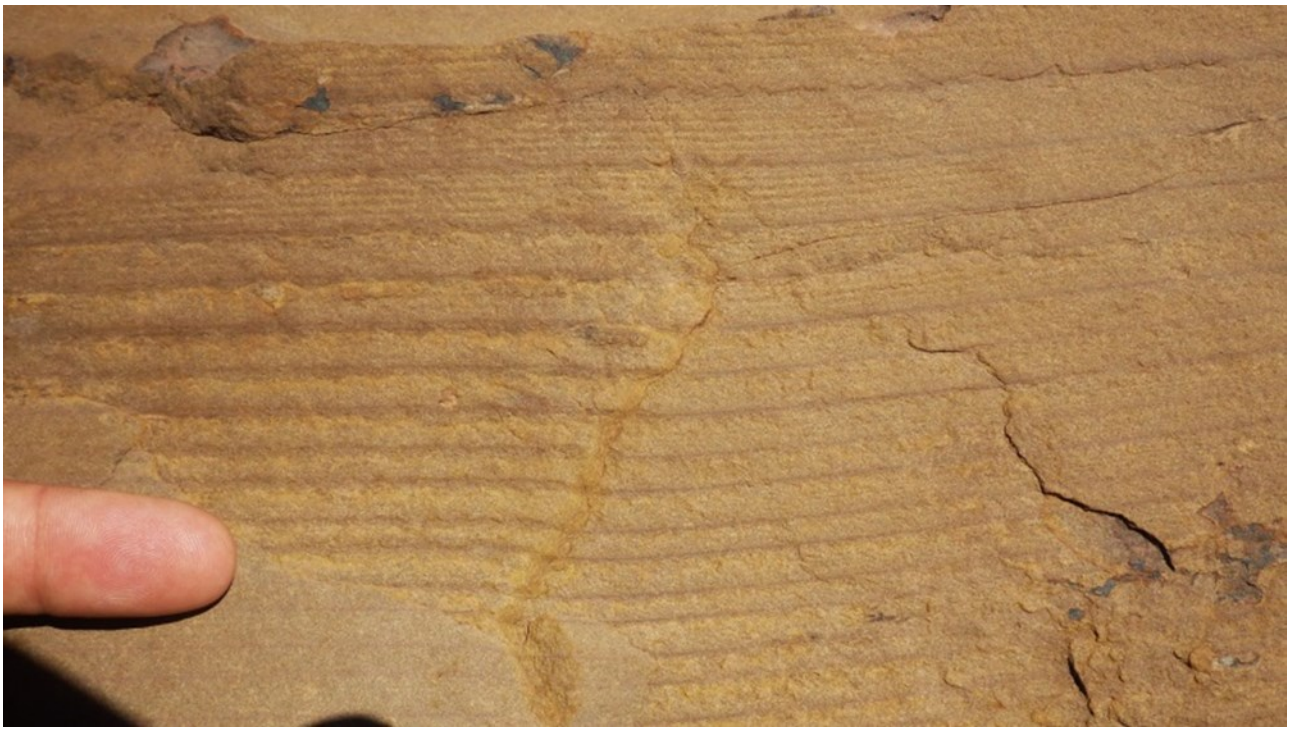

**Figure 10. Tidal rhythmites in the Elatina Formation near Pichi Richi.** Photo 415210

## WILPENA GROUP

The Wilpena Group comprises the latest Precambrian strata in the basin, and is made up of two large, coarsening and shallowing-upward sequences (sequence-sets Marinoan 3 and 4 of Preiss, 2000) separated by a regional unconformity. The Elatina Formation (and thus the Umberatana Group) is capped by the lowermost formation in the Wilpena Group: the laterally persistent, dolomitic Nuccaleena Formation. The base of the Nuccaleena is also the Global Stratotype Section and Point (GSSP) that defines the base of the Ediacaran System worldwide (Fig. 11; Knoll et al. 2006), which is now established to be around 635 Ma based on zircon dates from Namibia (Hoffman et al., 2004). Nuccaleena-type ‘cap carbonates’ often overlie glacial deposits in Neoproterozoic successions worldwide (Kennedy et al. 2001), leading to the hypothesis of a genetic link between the termination of glacial conditions and the deposition of these units. Cap carbonates often share a host of features that give clues to their formation; these include tepee structures, early cementation and brecciation, gas hydrate escape structures, and features indicating microbial binding (Kennedy et al. 2001). The formation of large tepee structures (Fig. 12) topped by small growth faults was interpreted by Gammon et al. (2005) to be the product of early subsurface diagenesis and expansive crystallisation. Other authors, however, have alternative interpretations for these unusual structures. Allen and Hoffman (2005) believed them to be synsedimentary giant wave ripples, and Kennedy (1996) suggested they are related to gas escape structures (cold seeps). More significant is the global persistence of these lithologies and the underlying mechanism behind their deposition. Rose and Maloof (2010) examined several proposed models for cap carbonate deposition after glaciation. Three mechanisms have been proposed:

1. A synchronous model wherein carbonates were deposited at the same time globally due to methane clathrate seeps.
2. A semi-diachronous model where meltwater from receding glaciers led to a stratified ocean and carbonate was precipitated by microbes in a low-salinity ocean. Carbonate deposition would initially track receding glaciers but would then be isochronous once high-latitude glaciers had melted and meltwater was evenly distributed.
3. A diachronous model that relies on 'super-greenhouse' conditions during deglaciation, which led to acidic meteoric waters, rapid weathering, and subsequent alkaline oceans and cap carbonate deposition. In this scenario, carbonate deposition would be dependent on paleoelevation and would track rising sea level.


**Figure 11. The basal Ediacaran GSSP ('Golden Spike') in Brachina Creek.** Photo 415211

**Figure 12. A large tepee structure in the Nuccaleena dolomite.** Photo 415212

After a thorough review of sedimentology and isotope stratigraphy of the Nuccaleena in the Flinders Ranges, Rose and Maloof could not rule out any of the three models. Retallack (2011) proposes that the Nuccaleena is a terrestrial loess deposit, a view that has generally not taken hold.

Above the Nuccaleena, the Brachina Formation is a thick clastic unit that is widespread across the Adelaide Rift Complex, predominantly composed of shale and siltstone with sandstone interbeds in several stratigraphic members. The Brachina is generally regarded as a shallowing upward sequence, but specific interpretations of depositional environments have varied. Interpretations of the lower members of the Brachina range from subtidal mudflat to deeper water turbidites, and the Moorillah and Bayley Range Siltstones in the middle and upper Brachina have been interpreted as tidal flats (Plummer 1978). In parts of the Flinders, the upper Brachina intertongues with the overlying ABC Range Quartzite that may represent a series of prograding delta complexes (Preiss 1987).

The ABC Range Quartzite was named by Mawson in 1939 after a series of prominent ridges in the Flinders Ranges where it is exposed. It is composed of relatively clean quartz sand and can be up to two kilometres thick due to synsedimentary faulting. If the progradational delta model is correct, the upper ABC Range may be time-equivalent to parts of the Brachina and record a shallow-marine to offshore transition. Von der Borch et al. (1988) interpret the top of the ABC Range Quartzite to be the top of a sequence that encompasses the lowermost Wilpena Group and the nearshore sediments of the ABC Range Sandstone. The Nuccaleena to ABC range sequence set (Marinoan 3) forms a large-scale post-glacial transgression that spans approximately 30 million years.

The overlying Bunyeroo Formation is lacking in detailed environmental studies and is primarily made of alternating bands of red, green, and grey shales. The fine-grained, laminated lithologies suggest a deepwater environment, it therefore represents a substantial transgression following the ABC Range (Preiss1987; Von der Borch et al. 1988). The formation also contains a thin layer of coarser volcanic clasts believed to be deposited by the Acraman meteorite impact event several hundred kilometres to the west (Fig. 13; Gostin et al. 1986; Gostin and Zbik 1999; Williams and Gostin 2005). This ejecta blanket can be traced across South Australia and provides an unambiguous correlation horizon across hundreds of kilometres.

The Wonoka Formation has been the subject of much discussion in the literature, owing partially to the occurrence of kilometre-deep canyons that begin within the mid-Wonoka and cut deeply into the Bunyeroo and Brachina Formations. The Wonoka is well-exposed and widespread throughout the Flinders Ranges, and has also been studied with regard to its sedimentology, paleontology, sequence stratigraphic context, and geochemistry. Urlwin (1992) used Strontium isotopes to give an age of 560–590 Ma for the Wonoka Formation. Haines (1987) completed a thorough study of the Wonoka Formation for his thesis at the University of Adelaide, parts of which were later published as several research articles. He divided the Wonoka (outside the canyon fill) into eleven stratigraphic units based on the section at Bunyeroo Gorge. The majority of the Wonoka was interpreted to be an outer to middle shelf deposit, generally shallowing upward towards the Bonney Sandstone, with the uppermost units (8–11) marking a significant change to tidally influenced, shallow marine environments. In the revision of the Parachilna map sheet by Reid and Preiss (1999), these units were moved into the lower Bonney Sandstone and termed the Patsy Hill Member. Wonoka units 5–7 contain abundant, cyclic hummocky cross-stratification, and were the focus of a specific study (Haines 1988). These unit designations provide the basis for much of the subsequent discussion of the Wonoka Formation. Haines (2000) also described body fossils of probable algal origin found in the upper part of the section. In the northern Flinders, evidence exists for numerous emergent diapirs that formed topographic highs or islands during late Wonoka time.


**Figure 13. The Acraman ejecta layer in the Bunyeroo Formation, Bunyeroo Gorge.** Photo 415213

Dixon (1999) measured four detailed sections of Haines' units 1–5 within the Wonoka just north of Hawker, away from any canyon incision. Within unit 2, he described event beds and turbidites separated by siltstones. 'Event beds' in his study area were fine- to medium-grained sandstones with scoured bases and trough cross-bedding. These were overlain by turbidites with incomplete Bouma sequences of varying thickness; turbidite beds were also described as containing slumping and hummocky cross-straification. This was interpreted to be a deepening-upward sequence. Facies in upper unit 2 and lower unit 3 suggest a subsequent shallowing upward sequence to a generally shallow marine environment encompassing the interval wherein canyons originate to the north. An erosional surface is noted in this interval, but no evidence for subaerial exposure was seen. Strongly negative $\delta^{13}C$ isotopes are interpreted as evidence for a stratified water body and possibly a restricted basin.

The origin of canyon structures in the Wonoka Formation (e.g. those in Fig. 14) has been the subject of much debate. Two questions generally frame the discussion: 1) Whether canyons were incised in a submarine or a subaerial environment, and 2) what mechanisms allow for such deep incision? These questions have been actively studied for several decades. Features that would eventually be recognised as canyons were first noted by Coats (1964) and were further described by Coats and Blissett (1971), among others. Detailed work on the canyons and their origin began in the 1980s with studies by Von der Borch et al. (1982; 1985). These initial studies tentatively favoured a submarine origin, with incision being the result of turbidity currents. Lack of classical turbidite deposits, however, led to the questioning of this hypothesis. Eickhoff et al. (1988) looked at both hypotheses and favoured a subaerial interpretation, based on sedimentary facies within the canyon fill. A subaerial interpretation was also favoured by Christie–Blick et al. (1990), based on canyon fill sedimentology as well as channel sinuosity, which tend to meander in subaerial settings but are straighter in submarine canyons. Higgins (1997) supported a subaerial, fluvial-incision model for the Pamatta Pass canyon, based on isotope signature of the carbonate wall plaster and the inference of a pre-Delamerian deformation event. He also noted evidence for a multi-phase process of incision, with one event incising just after the Wearing Dolomite, and another during deposition of unit 3. Canyon fill is interpreted to be shallow marine due to rising sea level. More recently, Giddings et al. (2010) have returned to the original submarine hypothesis. They re-interpret canyon fill as lacking any definitive shallow-water indicators, and believe that wall-lining carbonates are deep marine rather than the terrestrial interpretation of previous workers. They also note the presence of phosphatised clasts and mass flow deposits, and note that canyons originate from deep-water facies within the Wonoka. The favoured hypothesis of canyon formation has thus ranged from a submarine model, to subaerial exposure, and back again to the submarine hypothesis. Retallack (2014) returns again to a subaerial interpretation, based on a variety of geochemical proxies and sedimentological evidence.

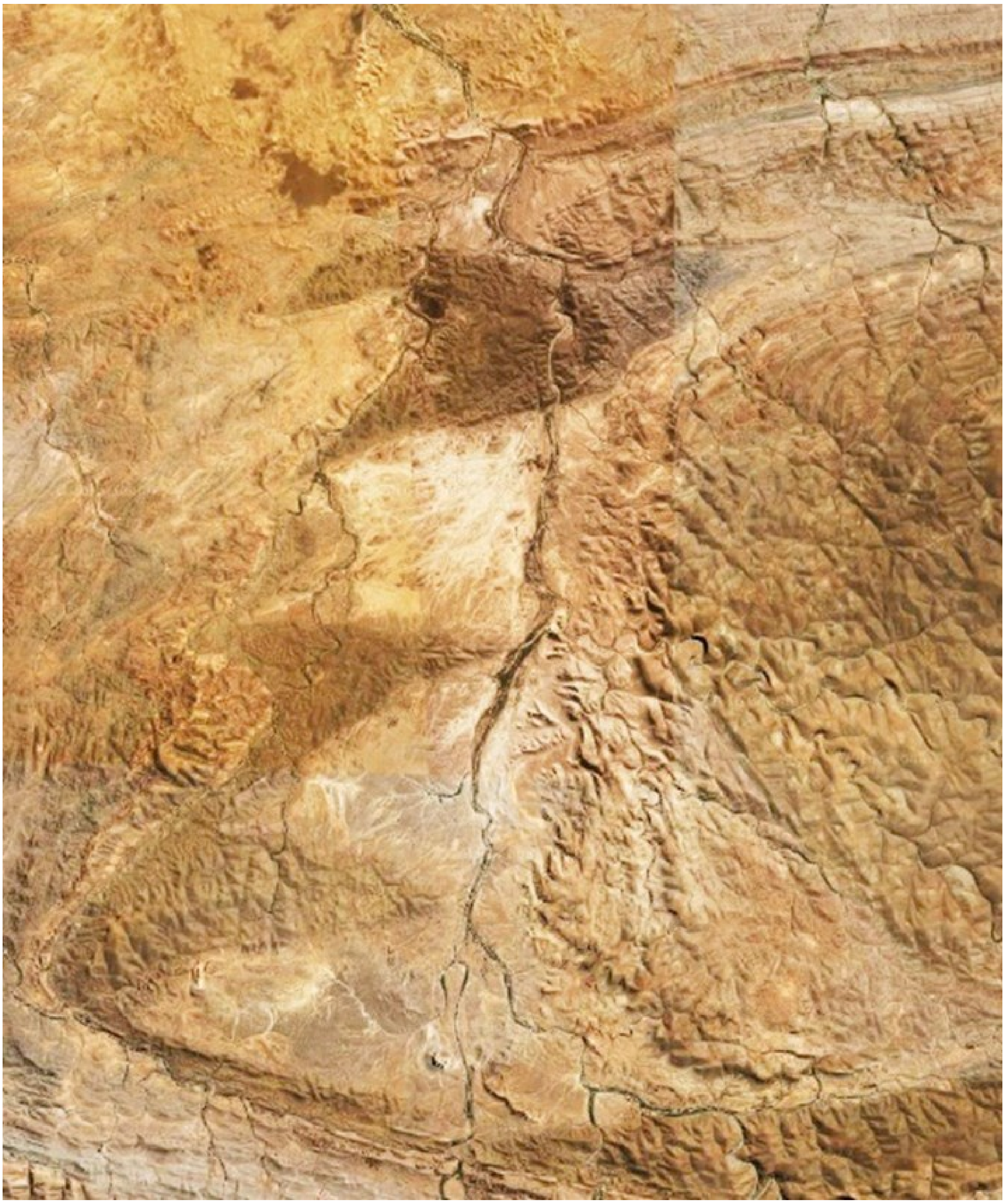

**Figure 14. Google Earth view of the Fortress Hill canyon complex in the Wonoka Formation on Umberatana Station.**

Hypotheses for the mechanism of canyon formation in these studies have generally fallen into four categories: 1) kilometre-scale eustatic fall (generally considered unlikely due to the scale of sea-level change required and lack of evidence for such a large fall elsewhere) 2) Regional uplift due to a large mantle plume (described in Williams and Gostin 2000), 3) incision related to Messinian-style drawdown of a restricted basin, or 4) submarine formation wherein no extreme hypotheses are needed, as recent studies have shown that canyon formation can happen in deepwater settings (e.g. Pratson and Coakley 1996; Bertoni and Cartwright 2005). Jansyn (1990) noted a fault-bounded trough-like structure in the Wonoka near Wilpena Pound, believed to be coincident with the canyons to the north. In this trough, extensional faults occurred over zones of weakness, which were later further eroded by submarine currents. This may shed light on canyon formation, as deeper canyons may have been initiated in a similar manner. Jansyn (1990) interprets units 2 and 3 to be deeper, shelf- slope deposits, units 4–9 to be prograding shelf sediments, and unit 10 in the Wonoka to represent a transgression. Calver (2000) agreed with the Messinian drawdown hypothesis, on the basis of $\delta^{13}C$ evidence.

The Wonoka Formation also contains a globally correlative $\delta^{13}C$ excursion that is likely the most strongly negative $\delta^{13}C$ value in Earth history. The $\delta^{13}C$ value (i.e. the ratio of $^{13}C$ to $^{12}C$ compared to a standard) preserved in carbonate sediments can be used as a proxy to determine the ratio of buried organic to inorganic carbon at a given point in time. As organisms preferentially uptake lighter $^{12}C$, negative values typically occur when biomass is oxidised. The extremely negative values of the Wonoka/Shuram excursion (named for its simultaneous occurrence in Oman) suggested initially that this signal was diagenetic in origin. Further analysis of evidence, however, suggests that it represents a primary marine signature (Fike et al. 2006), although this is not universally accepted and Grotzinger et al. (2011) still suggest the possibility of an unprecedented global diagenetic event. Others (e.g. Derry 2010; Swart and Kennedy 2012) also do not rule out a diagenetic origin. The excursion also spans a significant time frame (likely tens of millions of years), which would indicate a continuous period of substantially altered ocean chemistry and perturbation of the global carbon cycle (Le Guerroue 2010). If the event is indeed primary, it may be a product of the sustained oxidation of a large amount of lighter organic carbon. Such an event is not known from any other time in earth history, and ultimately, the nature and causes of this isotope excursion remain enigmatic. Elsewhere in the formation, Urlwin (1992) studied the $\delta^{13}C$ isotope signature of the Wonoka and found that it could be divided into two intervals: the lower Wonoka, which has a consistent negative signal of -8 to -7%, and the upper Wonoka, with a more positive -5 to -6% signature. He interpreted the upper signature to be representative of shallow, partially restricted deposition in a lagoon, and the lower, more negative signal to be basinal in origin.

Above the Wonoka Formation, the Bonney Sandstone and the Rawnsley Quartzite constitute the Pound Subgroup. In the central Flinders Ranges, the Bonney Sandstone is composed of multiple coarsening-upward parasequences deposited in a proximal deltaic environment (Counts et al. 2016). Elsewhere, the Bonney may have been subaerially exposed in a more fluvially dominated setting, and shows evidence of interaction with emergent salt diapirs. Bonney sediments were likely sourced from the northwest, as evidenced by abundant zircons likely originating from the central Australian Musgrave Province (Counts 2016). In the northern Flinders Ranges, the Bonney Sandstone and/or upper Wonoka Formation are replaced by the Billy Springs Formation, a monotonous package of mudstones and siltstones deposited in deeper water and influenced by salt movement (Counts and Amos 2016).

The overlying Rawnsley Quartzite (Fig. 15) has received significantly more attention, and has been studied from a sedimentological perspective primarily by Gehling (1982; 2000) as it hosts a well-preserved soft-bodied Ediacaran metazoan assemblage (Fig. 16). These animals represent some of the first multicellular life-forms in earth history, and thus the depositional setting of the formation has significant implications for the evolution and development of complex life. The Rawnsley Quartzite is divided into three members, and the fossil assemblage is found only in the middle Ediacara Member. The lower Chace Member is predominantly composed of sands, sometimes with very coarse sand or granule stringers, and containing ʌ-shaped 'tepee' structures that have been interpreted as resulting from expansive crystallisation on an evaporitic, intertidal tidal flat (Gehling 1982). Elsewhere, the Chace Member contains evidence of channelisation and fluvial influence. The Ediacara Member contains a variety of lithofacies, including shelf, prodelta, delta front, delta top environments (Gehling 2000), and has an erosive base that occasionally cuts down into the Bonney Sandstone. Fossils are found within and on the shoulders of incised valleys that are filled by shallow marine sediments. Jenkins et al. (1983) interpreted the Ediacara Member as having been deposited in shelf, tidally influenced lagoon, and barrier bar environments during a transgressive interval. Retallack's (2012) view of Ediacaran fauna as terrestrial lichens has been refuted by substantial sedimentologic and geochemical evidence from South Australia and elsewhere (Callow et al. 2013). The upper, unnamed member of the Rawnsley is several hundred metres thick, and returns to the intertidal sand flat environment similar to that in the Chace Member (Gehling 1982).

**Figure 15. Fine-grained shales and rapidly deposited sands with load structures in the Ediacara Member in Brachina Gorge.** Photo 415214

**Figure 16. Dickinsonia, an Ediacaran organism, on display in Parachilna.** Field of view is approximately 5 cm. Photo 415215

## HAWKER AND LAKE FROME GROUPS

The transition to the Phanerozoic is abrupt at the top of the Rawnsley Quartzite, where it is marked by the first occurrence of vertical burrowing (the ichnofossil *Treptichnus pedum*) in the lowermost Cambrian units, the Uratanna and Parachilna Formations (Fig. 17; Droser and Gehling 1999). These formations form part of the Hawker Group, an interval dominated by deposition on a broad carbonate ramp. Major carbonate units in the Hawker Group include the Wirrapowie and

Wilkawillina limestones and the Mernmerna Formation, which are all primarily composed of micritic limestone with archaeocyathid and Renalcis microbial buildups (James and Gravestock 1990). These formations are generally shelfal ('lagoonal' in the terminology of Youngs 1977), but also include some higher-energy, shallow water facies such as ooid shoals, especially in the northern and eastern Flinders Ranges. Small platforms associated with structural features occur in the Wilkawillina Limestone in places (Clarke 1990). The Hawker Group consists of three sequences, with lowstand surfaces occurring at the top of the unit, above the Mernmerna Formation, and within the Wilkawillina Limestone (Gravestock, 1995). Throughout the basin, shallower-water facies are seen south and east of the Wirrealpa Hill Hinge, a line that transects the basin diagonally and was likely a shelf break in the early Cambrian. These Cambrian units are considered to have been deposited across the region in the Arrowie Basin, which overlies and overlaps with the Adelaide Rift Complex but has a different centre of deposition. Higher in the Hawker Group, formations become more clastic, with Bunkers Sandstone and Oraparinna Shale still recording marine deposition. A series of volcanic arcs, in what is now the Murray Basin, developed off the coast during the early Cambrian, and their tuffs are preserved within Arrowie Basin sediments to the north (Gravestock, 1995).

**Figure 17. Vertical burrows in the Parachilna Formation, Parachilna Gorge.** Photo 415216

Above the Hawker Group, a series of around 1000 metres of red and green, trilobite-bearing silts, shales, and sands make up the Billy Creek Formation, likely having been deposited in tidally influenced, nearshore marine, intertidal, and fluvial conditions (Moore, 1979; Gravestock, 1995). The overlying Wirrealpa Limestone contains Archaeocyathid and microbial buildups as well as higher energy facies (ooid shoals, present in the northern and eastern part of the basin) and lagoonal micrites (Youngs, 1978). These units are not placed within formal stratigraphic groups.

The uppermost deposits in the basin (Lake Frome Group; sequence Cambrian 3) are likely Middle Cambrian based on biostratigraphy (Jago et al. 2006), although their exact age is unknown (Jago et al. 2010). These formations are generally clastic, and are likely at least partially continental or terrestrial in origin (Moore 1990; Jago et al. 2013). The Balcoracana and Moodlatana Formations are paralic and cyclical, containing trilobites and their traces (Preiss 1999). The Pantapinna Sandstone contains cross-stratification and turbidite sands, and has been interpreted as fluvial to shallow marine, with occasional open-marine influence. In the Dawson Hill Member of the Grindstone Range Sandstone (the uppermost unit in the basin), sandstones are seen containing large cobble-sized clasts of unclear origin (Jago and Gatehouse 2014).

# SALT-SEDIMENT INTERACTION IN THE ADELAIDE RIFT COMPLEX

The general rate of subsidence and accommodation in the basin is influenced by several large scale 'rift and sag' episodes; however, numerous sub-basins were continuously formed during this time. These minibasins are generally 10–30 km wide and have a circular to elliptical shape, and are the product of withdrawal and diapirism of underlying Callanna Group evaporites, where mobile salt forms piercement structures that penetrate through the upper basin fill (Dalgarno and Johnson 1968). Similar features are present in salt-influenced settings throughout the world, and are often important components of petroleum reserves (e.g. those seen in Fig. 18). This section briefly discusses some key issues in the formation of these structures, and examines some potential analogues for minibasins found in the Flinders Ranges.

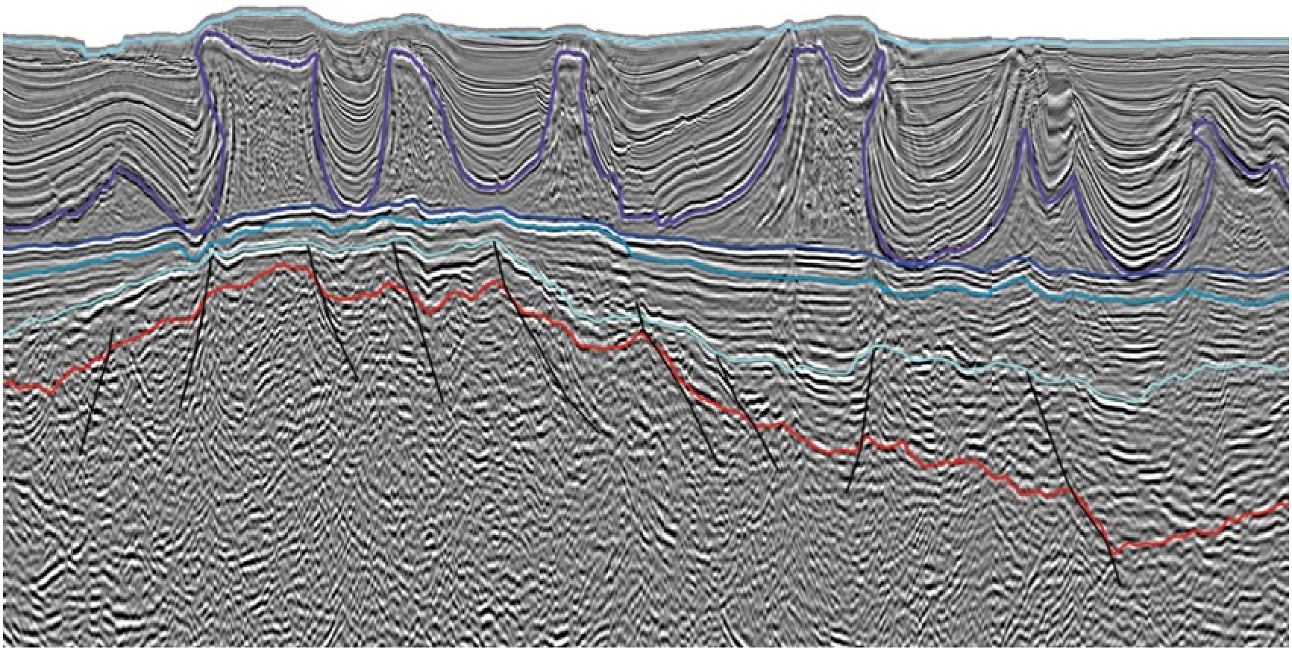

**Figure 18. Minibasins seen in seismic section, Kwanza Basin, offshore East Africa.** From TGS 2015.

## MINIBASIN FORMATION AND STRATAL ARCHITECTURE

Traditionally, salt-withdrawal mini-basins are thought to be the product of denser clastic sediment loading and sinking into an underlying less-dense, relatively thick layer of salt (Jackson and Talbot 1986). However, Hudec et al. (2009) note that mini-basin development often begins before sediments are compact enough to have a density greater than the salt that they displace. They propose a number of other mechanisms by which mini-basin formation could be initiated. These include 1) diapir shortening, where diapirs surrounding a mini-basin are inflated due to downslope salt movement, leaving the basin as a relative topographic low, 2) extensional diapir fall, where regional extension preferentially leads to subsidence and mini-basin formation atop existing diapirs, 3) decay of salt topography, where a salt bulge expressed on the seafloor decays by gravitational spreading once the salt flow stops, 4) differential sediment loading atop a diapir as sediments prograde seaward or are deposited around a localised depocentre, and 5) subsalt deformation, where either normal faulting or compression can initiate bathymetric lows that can evolve into mini-basins. Goteti et al. (2012) further investigated mechanism (4) through computer modelling, and found it to be a valid mechanism of basin formation, but unlikely to be the one by which most minibasins form.

Collie and Giles (2011), Giles and Lawton (2002), and Giles and Rowan (2012) examined the relationship between synsedimentary diapir activity and larger-scale stratigraphic patterns in adjacent sediments (Fig. 19). The influence of diapirs on stratigraphic architecture is dependent on several factors: 1) the rate of salt rise, 2) the rate of sediment accumulation, 3) the vertical velocity of the salt mass, 4) the rate of salt dissolution, and 5) the rate of subsidence. These processes create different stratal geometries of the surrounding sedimentary deposits, resulting in halokinetic sequences. Unlike depositional sequences that occur on a much larger-scale, halokinetic sequences are present only in the area immediately surrounding active diapirs. Sediments onlapping a diapiric high have two end member geometries, referred to as ‘wedge’ and ‘hook’. Wedge geometries have a broad, <30° slope away from the diapir, with drape folding 300–1000 m away from the diapir edge and gradational facies changes with increasing distance from the structure. Hook-type geometries dip away from the diapir much more rapidly, at 30–90° angles and with more abrupt facies changes. These geometries are dependent on the relative rates of sedimentation and diapir movement; hook-type geometries generally represent a relatively greater diapir rise to sedimentation rate ratio compared to wedge geometries. When stacked, hook and wedge sequence geometries can be classified into tabular and tapered composite halokinetic sequences (CHS), respectively (Giles and Rowan 2012; Fig. 17). Such geometries are important when considering the reservoir properties of minibasins.

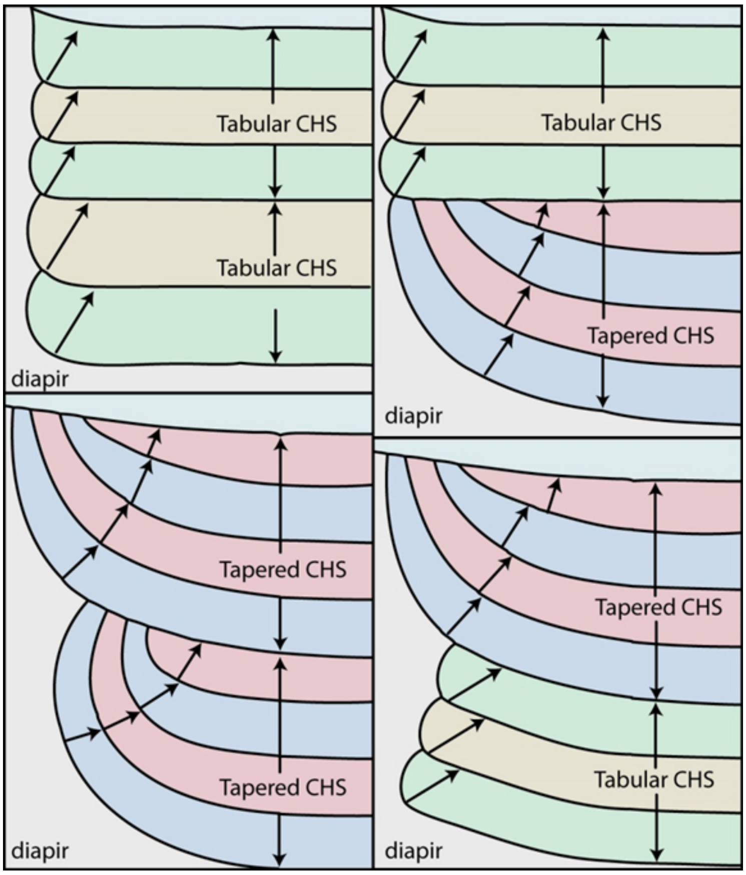


**Figure 19. Various stacking patterns of halokinetic sequences.** Modified from Giles and Rowan (2012).

## MINIBASINS IN THE ADELAIDE RIFT COMPLEX

Salt withdrawal minibasins are present throughout the Adelaide Rift Complex. Due to their size, shape, and known proximity to diapiric activity, many of the synclines in the central and northern Flinders most likely had some component of their subsidence related to salt withdrawal. In most portions of the Flinders, this original basin topography and architecture has been substantially overprinted by the Cambro-Ordovician Delamerian Orogeny. Many synclinal structures initially thought to have been structural or compressional in origin are likely to have initiated syndepositionally (Rowan and Vendeville 2006). Diapirs were not recognised as such until 1960 (Webb 1960), with most earlier authors hypothesising that the dolomitic breccias found throughout the basin were the product of tectonic processes (see discussion in Mount 1975).

A lack of high-quality seismic data prevents the exact nature of subsurface basin architecture from being fully deciphered, but Backe et al. (2010) were able to make some inferences from gravity and magnetic data. They note that the locations of salt diapirs are often controlled by deep basement extensional faults, as opposed to a flat basement with a decollement surface on top. Faults were inverted during the Delamerian Orogeny, with later Neoproterozoic and Cambrian strata formed anticlinal folds centered around diapirs and basement faults. This process of post-diapir and post-extensional compression and fault reversal is important to consider when considering appropriate analogues. In addition, the involvement of deep basement faulting in determining diapir locations may make the morphology of Flinders-area minibasins somewhat different from some other salt-tectonised provinces around the world, although the later and more localised interaction between salt and sediments remains similar. Seismic data has been acquired in the Officer Basin, where diapirs similar to those in the Flinders Ranges are clearly visible in the subsurface (Koupriantchik et al., 2005).

Today, diapir bodies in the Adelaide Rift Complex are preserved as breccias with a microcrystalline dolomitic matrix and large clasts of varying lithologies. Original evaporites have not been found, even in drillholes (Cooper, 1991), but evidence for their former presence exists in the form of crystal pseudomorphs (Dalgarno and Johnson, 1968).The syndepositional nature of diapirs and is established by the onlap, depositional thinning, facies change, and halokinetic sequences in sedimentary units adjacent to diapir bodies (Counts, 2016, and references therein).Several individual minibasins and diapirs in the Adelaide Rift Complex have been documented in some amount of detail. Dalgarno and Johnson (1968) summarised much of the existing knowledge at the time, which has since been built upon through studies of individual minibasins and increasing knowledge of similar features elsewhere. In a University of Adelaide PhD thesis, Mount (1975) studied the Arkaba diapir in detail, detailing the surrounding strata and the highly variable composition of large clasts found within the diapir body. Lemon (1985) conducted sandbox experiments to show that the Oratunga diapir shared many features with plasticly behaving salt diapirs. Dyson (1996) showed how upward diapir growth can lead to the formation of large grabens, using the Oraparinna diapir as an example; Dyson (1999; 2004; 2004a; 2004b) later studied diapirs at Beltana, Wirrealpa, Pinda, and in the Willouran Ranges, providing summaries of their modes of formation and associated sedimentary features. Collie and Giles (2011) looked at the Wirrealpa diapir and the surrounding Donkey Bore and Woodendinna synclines and found different halokinetic sequences and stratal geometries on either side of the diapir, suggesting unequal rates of subsidence or deposition in response to diapir rise. Lemon (2000) observed carbonate facies change in response to proximity of the Enorama diapir, demonstrating a significant influence of the diapir on the grain size and charater of the surrounding Enorama Shale. More recently, Hearon et al. (2013) completed studies reconstructing halokinetic sequences surrounding diapirs in the Willouran Ranges to the northwest of the main basin axis. Despite these studies, many of the minibasins and diapirs in the basin have still not been examined in any amount of detail, and much work remains to be done.

# HYDROCARBON-BEARING ANALOGUES FOR THE ADELAIDE RIFT COMPLEX

Several factors are important to consider when interpreting reservoir analogues, including the size and shape of the basin, the depositional setting and nature of the sediment supply (e.g. subaerial vs. subaqueous, clastic vs. carbonate, sand vs. shale, etc.), relative rates of diapir rise and sediment subsidence, which influence the style and stacking pattern of halokinetic sequences surrounding the diapir, and the post-depositional structural history of the basin. These issues directly influence the requirements that are necessary for a petroleum reservoir — the source, reservoir, and seal potential of the rocks.

Basins containing evaporite sediments within their fill are found throughout the world, but are exposed only rarely. Many outcropping salt-influenced provinces share at least some similarities with the sediments in focus here. Several salt-tectonised provinces that are actively producing hydrocarbons may also be considered analogues; some of these are well-known, and an examination of the diapirs and minibasins in these areas may shed light onto the important factors to consider when describing and interpreting salt-sediment interaction. This section discusses some aspects of salt tectonics in the Gulf of Mexico, offshore Brazil, and in the onshore Paradox Basin, which contain well-known, currently productive hydrocarbon reservoirs that are significantly influenced by salt withdrawal and diapirism. These areas have been extensively researched, with hundreds of published studies; it is therefore not possible to review the entire body of literature for each. Here, they are examined only briefly in order to provide a point of comparison for the Adelaide Rift Complex.

## GULF OF MEXICO

Salt tectonics and sedimentation in the Gulf of Mexico are complex and span a wide range of time, from the Mesozoic to the recent. In the Cenozoic, depositional environments varied greatly through time and across the basin (Galloway et al. 2000). The source of evaporite diapirs is the Jurassic Louann Salt, which is generally present between the Mississippi Canyon province and the outer Sigsbee Escarpment (Bryant et al. 1990). These boundaries form an offshore area of salt-related primary and secondary minibasins that are the focus of most of the petroleum exploration in the area (Fig. 20). Within this area, dozens of minibasins are present, each with a scale of tens of kilometres (Bouma and Bryant 1995). Sedimentation and progradation of the shelf has taken place over tens of millions of years, from the Jurassic to the recent. Pilcher et al. (2011) recognise three provinces that are defined by the nature of salt structures. To the east, the disconnected salt-stock-canopy province contains relatively isolated diapirs separated by primary basins formed on in situ salt. Importantly, secondary minibasins formed on the salt canopy are separated from source rocks and are thin and generally not productive. In this area, most production is centred around traps at the base of overhanging salt layers. In the amalgamated salt-stock-canopy province, salt supply was higher, and salt has detached and formed a canopy onto which secondary mini-basins have formed. Production in this province comes from both subsalt primary basins and secondary minibasins, which are often well-developed enough that the salt canopy is extruded and the base of the minibasin is welded to the underlying older sediment. Both of these provinces have seen considerable post-depositional compression. In the bucket-weld province, primary basins are more discontinuous, overlain by a thick salt canopy and welded to deep, young secondary minibasins. This province is likely the result of continued evolution of an amalgamated salt-stock-canopy province precursor; few vertical feeders to the salt canopy remain.

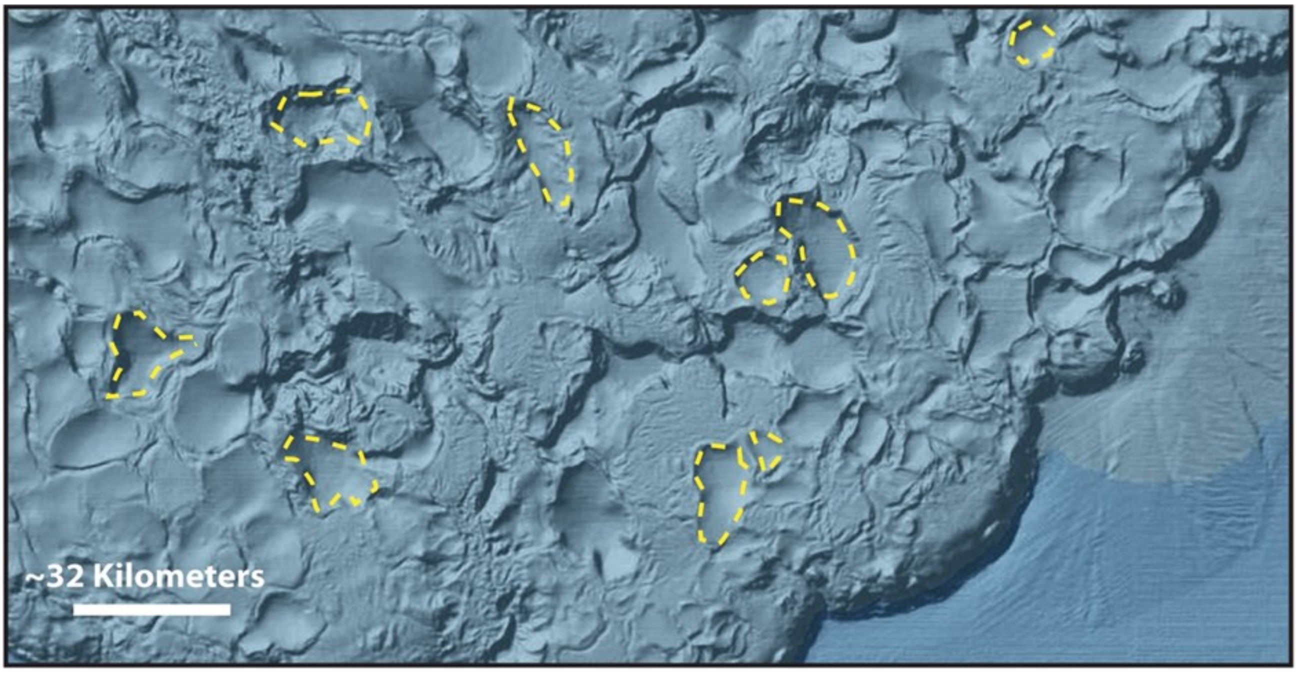


**Figure 20. Seafloor topography in the Gulf of Mexico, showing salt-withdrawal minibasins in the Bucket-weld and Amalgamated salt-stock-canopy provinces of Pilcher et al. (2011).** Some minibasins outlined to highlight boundaries, others not outlined to better show topographic relief. Image courtesy National Oceanic and Atmospheric Administration Bathymetric Data Viewer.

The primary difference between these provinces is the overall supply of salt, with the disconnected salt-stock-canopy province having the least, and the bucket-weld province having the most. Although charge and trapping mechanisms are locally variable, several consistent play types are present in each of these provinces. Minibasins form atop allochthonous salt layers as well as atop the primary bedded salt formation, forming a variety of welds and petroleum traps (Fig. 21). In the Adelaide Rift Complex, it is unknown whether an extensive, regional salt canopy was formed. In this way, the Flinders may be more similar to the disconnected salt-stock-canopy province in the Gulf of Mexico. Although some Adelaide Rift Complex minibasins are completely surrounded by salt, it is not always clear whether the diapiric structure was still connected to the primary evaporite layer.

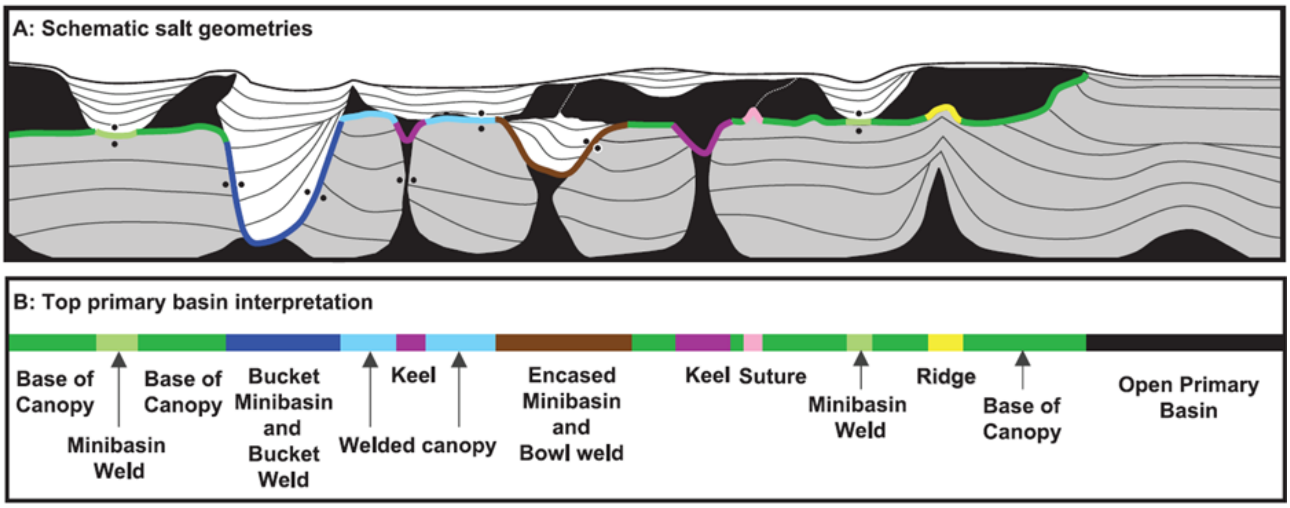


**Figure 21. Schematic salt geometries in the Gulf of Mexico.** From Pilcher et al., 2011.

The character of minibasin fill in the Gulf of Mexico is known from core, wireline logs, and seismic data. Some minibasins contain thousands of metres of sediments, often with ponded sheet and channel sands that thicken into minibasin centre and erode underlying deposits, creating a series of unconformities. These sands are contained within background muds, and their distribution within and around minibasins is controlled by the length and gradient of the slope, the location of the sediment source, and the topography of the bounding salt ridges (Booth et al. 2003). In other minibasins, fill is composed of both mud- and sand-dominated turbidites, hemipelagic muds, and intrabasinal heterolithic mass transport complexes. Mass transport complexes (slumps) make up around 45% of the fill of the Fuji minibasin, for example, and are triggered by passive salt movement (Madof et al. 2009). Mallarino et al. (2006) also found that minibasin fill was composed of a series of dark- and light-grey muds, black clay, and well-sorted quartz sands, reflecting the balance between fine-grained background sedimentation and the deposition of sands during lowstand or regressive intervals. Piston core from some of these mass transport complexes show occasional larger clasts similar to those seen in some minibasins in the Adelaide Rift Complex (Olson and Damuth 2009).

Rowan and Vendeville (2006) compared salt withdrawal basins in the Flinders with similar basins in the Gulf of Mexico. Based on experimental models, they examined the similarities in both areas, with the goal of determining if their deformation styles were the result of similar timing with regard to diapir formation and later compression. Using silicone ‘salt’, they created mature salt diapir structures through sediment loading adjacent to incipient diapirs, which were then subjected to compressive shortening. The results of these experiments matched both the Flinders Ranges and the Gulf of Mexico examples. The later compression was shown to be an important factor in the overall 3-D structure of the fold belt, and it explains both the remnant diapir morphology and shows the influence of diapirs on later patterns of folding. Diapirs were shown to occur at the terminations of strain-perpendicular folds that were cored by salt welds, and their spatial distribution formed a polygonal pattern that can be seen in both the Flinders and the Gulf of Mexico. In addition, the authors noted several other possible examples where similar structural deformation may have taken place—these include the Atlas Mountains in North Africa, the Zagros Mountains of Iran, the La Popa Basin in Mexico, and the Carpathian Mountains in Romania.

## OFFSHORE BRAZIL

Like the Gulf of Mexico, the southeastern offshore continental margin of Brazil contains a thick section of Mesozoic salt that has penetrated and deformed the upper Cenozoic sediments. Three basins in offshore Brazil, the Espirito Santo, Campos, and Santos, are known or potential petroleum producers. The Campos and Santos basins (Fig. 22), like the Gulf of Mexico, can be divided into provinces based on salt-tectonic regime, with a proximal extensional province and a larger, more distal contractional domain (Demercian et al. 1993; Meisling et al. 2001).

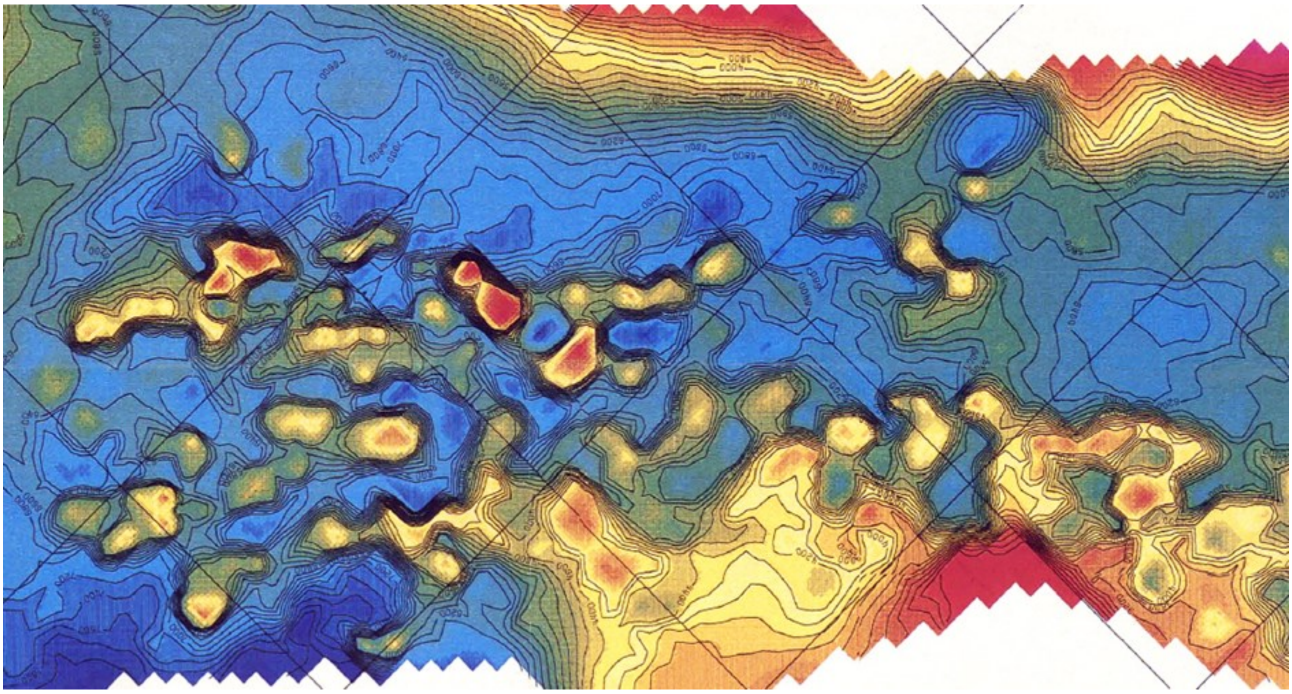

**Figure 22. Subsurface structure map of top of evaporite sequence, Campos-Santos region, offshore Brazil.** Highs in red/yellow are salt-related features; shoreline is toward top of picture. Modified from Demercian et al. (1993).

The Campos basin contains a significant proportion of Brazil's oil reserves, much of which is contained within salt-withdrawal mini-basins. Source rocks in the Campos Basin are pre-salt lacustrine carbonates (Meisling et al. 2001); many mini-basins are welded to the underlying section, forming an important pathway for hydrocarbon migration (Roberts et al. 2004). The Santos Basin is less-studied than the Campos, and is not yet known to contain as significant amount of a hydrocarbon accumulation. Only in the southern part of the Santos basin are true, well-developed minibasins present; these are formed on autochthonous salt that is separated by regularly spaced, high-amplitude diapirs and ridges (Modica and Brush 2004). Minibasins in the Santos basin are 20 km in diameter, and are filled with Cretaceous to recent hemipelagic mudstones (Jackson 2012). Mass-transport complexes consisting of slide blocks and muddy debris flows are also found in the minibasin fill, where they detached from the topographically higher margin and were redeposited closer to the basin centre. In the Espirito Santo basin, minibasins are formed in Cretaceous-Cainozoic carbonates and sandstones. Salt structures show a basinward transformation from salt rollers, to various types of diapir piercements, to allochthonous canopies. Like the Gulf of Mexico, these structural styles are dependent on the original depositional salt thickness, and more distal salt structures have been laterally compressed and extruded (Fiduk et al. 2004). Salt structures influence the locations of faults, which in turn influence the distribution of submarine canyons and reservoirs (Alves et al. 2009). Collapse features atop diapirs are common features in the Santos Basin (Guerra and Underhill 2012).

Brazilian salt basins share many similarities to those seen in the Adelaide Rift Complex, although the kind of basin-scale extensional-compressional regimes documented in Brazil have not been interpreted here. Most Brazilian minibasins are lacking in detailed sedimentologic and stratigraphic analysis; the depositional controls and internal architecture of these features in the area are not well-understood and could greatly benefit from insights gained from outcrop analogues.

## PARADOX BASIN

The Paradox Basin outcrops in the southwestern U.S. and differs from salt-tectonised provinces in Brazil and the Gulf of Mexico in that minibasin formation generally occurred in a continental environment (Fig. 23). It is therefore a better analogue for certain formations in the Adelaide Rift Complex, some of which may also be continental in origin, and more is known about its sedimentology and stratigraphic architecture due to outcrop accessibility. Oil and gas are produced from subsurface structures in a number of formations from the Devonian to the Cretaceous, including those that interact with diapirs (Stevenson and Wray 2009). Thus, accurate facies models for salt-sediment interaction are essential for the prediction of the locations of hydrocarbon reserves in this type of environment.

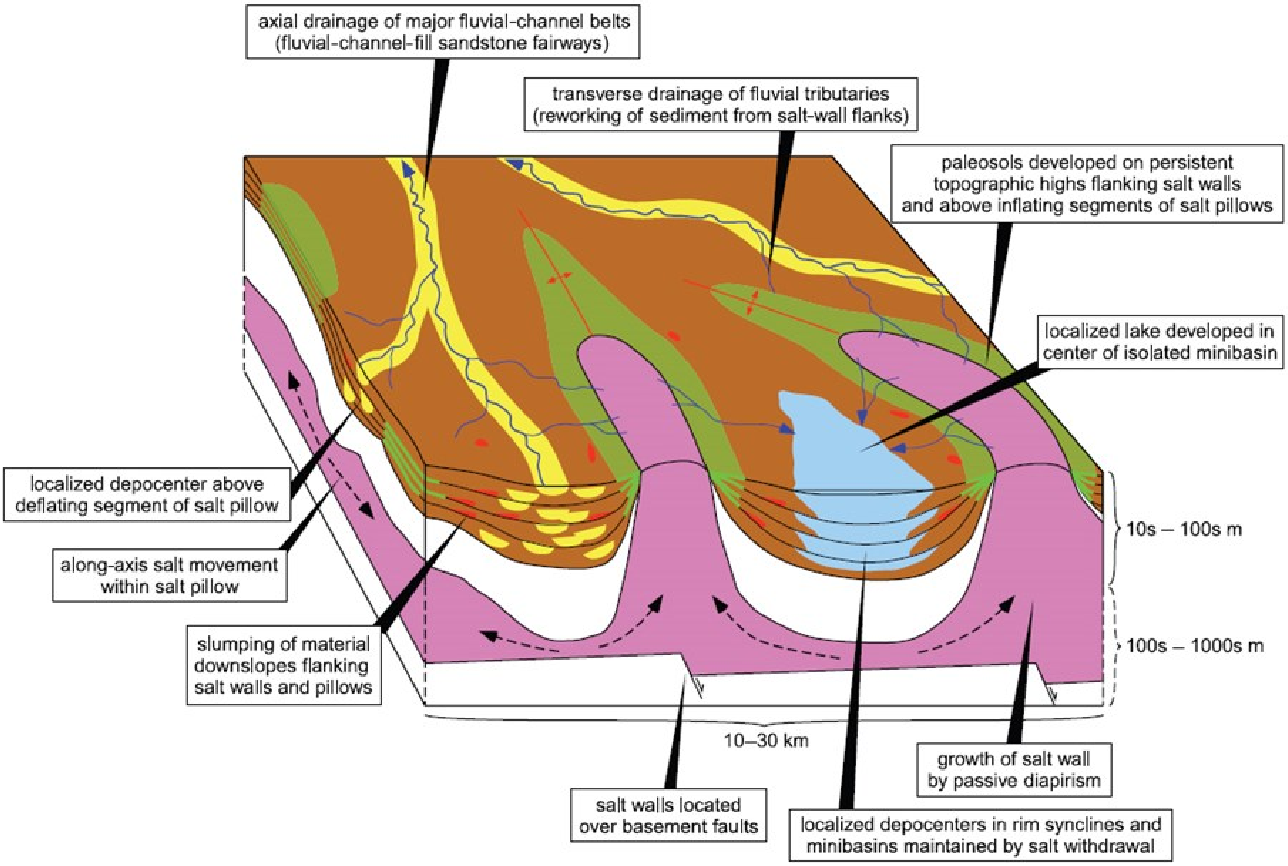


**Figure 23. Deposition model of salt diapirs and minibasinsin the Paradox Basin.** From Matthews et al. 2007.

The Paradox Basin formed during Pennsylvanian extension atop a pre-existing Precambrian fracture system. Restriction of the basin resulted in very thick evaporite deposits, which mobilised shortly thereafter to affect subsequent sedimentation. Most basin deposits consist of fluvial sediments, aeolian dunes, playa lakes, and paleosols (Bromley 1991), in isolated depocentres which shifted and evolved over time. In the Pennsylvanian, Permian, and Jurassic, the rise of salt ridges influenced the course of rivers in a fluvially dominated terrestrial environment, although primary drainage axes may differ between individual minibasins. Rivers either ran axially down elongate minibasin valleys, paralleling salt ridges, or transversely from salt-cored topographic highs (Matthews et al. 2007; Banham and Mountney 2013). Sediments thin and onlap onto diapir margins, and passive salt rise is a major control of facies distribution in the basin. Paleosols form on minibasin margins, with minibasin centres being either mud- or sand dominated, depending on the relative rates of subsidence and sedimentation. Gravels are more prone to occur as parts of fluvial deposits within minibasins, although the provenance of clasts and whether they are derived from diapirs has not been determined. Banham and Mountney (2013) showed that fluvially dominated minibasins followed a predictable evolution over time as minbasins are filled and flow is diverted from depocentres; a process that affects the development of reservoir facies. Many of these features may be compared to those seen in and around several of the minibasins in the Adelaide Rift Complex, especially those intersecting continentally derived formations.

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# REFERENCES

ALLEN, P.A. and HOFFMAN, P.F., 2005, Extreme winds and waves in the aftermath of a Neoproterozoic glaciation. *Nature*, 433, 123-127.

ALVES, T. M., CARTWRIGHT, J. and DAVIES, R. J., 2009, Faulting of salt-withdrawal basins during early halokinesis: effects on the Paleogene Rio Doce Canyon system (Espírito Santo Basin, Brazil). *AAPG Bulletin*, 93, 617-652.

BACKÉ, G., BAINES, G., GILES, D., PREISS, W. and ALESCI, A., 2010, Basin geometry and salt diapirs in the Flinders Ranges, South Australia: Insights gained from geologically-constrained modelling of potential field data. *Marine and Petroleum Geology*, 27, 650-665.

BANHAM, S. G. and MOUNTNEY, N. P., 2013, Evolution of fluvial systems in salt-walled mini-basins: a review and new insights. *Sedimentary Geology*, 296, 142-166.

BERTONI, C. and CARTWRIGHT, J., 2005, 3D seismic analysis of slope-confined canyons from the Plio–Pleistocene of the Ebro Continental Margin (Western Mediterranean). *Basin Research*, 17, 43-62.

BOGDANOVA, S.V., PISAREVSKY, S.A. and LI, Z.X., 2009, Assembly and Breakup of Rodinia (Some results of IGCP project 440). *Stratigraphy and Geological Correlation*, 17, 259-274.

BOOTH, J. R., DEAN, M. C., DUVERNAY, A. E. and STYZEN, M. J., 2003, Paleo-bathymetric controls on the stratigraphic architecture and reservoir development of confined fans in the Auger Basin: central Gulf of Mexico slope. *Marine and Petroleum Geology*, 20, 563-586.

BOUMA, A. H. and BRYANT, W. R., 1994, Physiographic features on the northern Gulf of Mexico continental slope. *Geo-Marine Letters*, 14, 252-263.

BROMLEY, M. H., 1991, Architectural features of the Kayenta Formation (Lower Jurassic), Colorado Plateau, USA: relationship to salt tectonics in the Paradox Basin. *Sedimentary Geology*, 73, 77-99.

BROOKFIELD, M.E., 1993. Neoproterozoic Laurentia-Australia fit. *Geology*, 21, 683–686.

BRYANT, W. R., BRYANT, J. R., FEELEY, M. H. and SIMMONS, G. R., 1990, Physiographic and bathymetric characteristics of the continental slope, northwest Gulf of Mexico. *Geo-Marine Letters*, 10, 182-199.

BUSFIELD, M.E., and LE HERON, D.P., 2014, Sequencing the Sturtian icehouse: dynamic ice behaviour in South Australia. *Journal of the Geological Society*, 171, 443-456.

CALLOW, R. H., BRASIER, M. D. and MCILROY, D., 2013, Discussion: “Were the Ediacaran siliciclastics of South Australia coastal or deep marine?” by Retallack et al., *Sedimentology*, 59, 1208–1236. *Sedimentology*, 60, 624-627.

CALVER, C.R., 2000, Isotope stratigraphy of the Ediacarian (Neoproterozoic III) of the Adelaide Rift Complex, Australia, and the overprint of water column stratification. *Precambrian Research*, 100, 121-150.

CÉLÉRIER, J., SANDIFORD, M., HANSEN, D. L. and QUIGLEY, M., 2005, Modes of active intraplate deformation, Flinders Ranges, Australia. *Tectonics*, 24, 1-17.

CHRISTIE-BLICK, N., VON DER BORCH, C.C. and DIBONA, P.A., 1990, Working hypothesis for the origin of the Wonoka Canyons (Neoproterozoic), South Australia. *American Journal of Science*, 290, 295-332.

CLARKE J.D.A., 1988, Geology of the Hawker Group (Early Cambrian), Wilkawillina Gorge, South Australia. Flinders University of South Australia, PhD thesis.

CLARKE, J. D. A., 1990, An Early Cambrian carbonate platform near Wilkawillina Gorge, South Australia', *Australian Journal of Earth Sciences*, 37, 471-483.

COATS, R.P., 1964, Large scale Precambrian slump structures, Flinders Ranges. *Quarterly Geological Notes, Geological Survey of South Australia*, 11, 1-2.

COATS R. P., 1973, Copley map sheet. Geological Survey of South Australia Geological Atlas 1:250 000 Series, sheet H54-9.

COATS, R. P. and BLISSETT, A. H., 1971, Regional and economic geology of the Mt. Painter Province. *Bulletin of the Geological Survey of South Australia*, 43, 426 p.

COATS, R. P. and W. V. PREISS, 1980, Stratigraphic and geochronological reinterpretation of late Proterozoic glaciogenic sequences in the Kimberley region, Western Australia. *Precambrian Research*, 13, 181-208.

COLLIE, A.J. and GILES, K., 2011, Comparison of Lower Cambrian Carbonate Facies and Halokinetic Sequences in Minibasins Developed on Opposite Sides of Wirrealpa Diapir, Central Flinders Ranges, South Australia. *AAPG Search and Discovery Article* 50442.

COLLINS, W. J. and SHAW, R. D., 1995, Geochronological constraints on orogenic events in the Arunta Inlier: a review. *Precambrian Research*, 71, 315-346.

COOPER, A.M., 1991, Late Proterozoic hydrocarbon potential and its associated with diapirism in Blinman #2, central Flinders Ranges, South Australia. University of Adelaide Honours thesis, unpublished.

COUNTS, J.W., 2016, Sedimentology, Provenance, and Salt-Sediment Interaction in the Ediacaran Pound Subgroup, Flinders Ranges, South Australia. University of Adelaide PhD Dissertation.

COUNTS, J. W. and AMOS, K. J., 2016, Sedimentology, depositional environments and significance of an Ediacaran salt-withdrawal minibasin, Billy Springs Formation, Flinders Ranges, South Australia. *Sedimentology*, 63, 1084-1123.

COUNTS, J. W., RARITY, F., AINSWORTH, R.B., AMOS, K.J., LANE, T., MORON, S. TRAINOR, J., VALENTI, C. and NANSON, R., 2016, Sedimentological interpretation of an Ediacaran delta: Bonney Sandstone, South Australia. *Australian Journal of Earth Sciences*, 63, 257-273.

DALGARNO, C. R. and JOHNSON, J. E., 1966, Parachilna: Geological Atlas Series Sheet H 54-13, scale 1:250,000. Geological Survey of South Australia, Adelaide.

DALGARNO, C. R. and JOHNSON, J. E., 1968, Diapiric structures and late Precambrian-early Cambrian sedimentation in Flinders Ranges, South Australia. In: Braunstein, J., and O'Brien, G.D. (eds.) *AAPG Memoir*, 8, 301-314.

DEMERCIAN, S., SZATMARI, P. and COBBOLD, P. R., 1993, Style and pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil. *Tectonophysics*, 228, 393-433.

DERRY, L. A., 2010, A burial diagenesis origin for the Ediacaran Shuram–Wonoka carbon isotope anomaly. *Earth and Planetary Science Letters*, 294, 152-162.

DEVRIES, S. T., PRYER, L. L. and FRY, N., 2008, Evolution of Neoarchaean and Proterozoic basins of Australia. *Precambrian Research*, 166, 39-53.

DIXON, J., 1999, Forcing factors influencing deposition of the Wonoka Formation, Flinders Ranges, South Australia, and triggers for canyon development. University of Adelaide BSc Honors Thesis, unpublished.

DROSER, M. L., GEHLING, J. G. and JENSEN, S., 1999, When the worm turned: Concordance of Early Cambrian ichnofabric and trace-fossil record in siliciclastic rocks of South Australia. *Geology*, 27, 625-628.

DYKSTERHUIS, S. and MÜLLER, R. D., 2008, Cause and evolution of intraplate orogeny in Australia. *Geology*, 36, 495-498.

DYSON, I.A., 1996, A new model for diapirism in the Adelaide Geosyncline. *MESA Journal*, 3, 41-48.

DYSON, I. A., 1999, The Beltana Diapir: a salt withdrawal mini-basin in the northern Flinders Ranges: *Mines and Energy of South Australia Journal*, 15, 40-46.

DYSON, I. A., 2004, Geology of the eastern Willouran Ranges–evidence for earliest onset of salt tectonics in the Adelaide Geosyncline. *MESA Journal*, 35, 48-56.

DYSON, I.A., 2004a, Christmas Tree Diapirs and Development of Hydrocarbon Reservoirs: A Model from the Adelaide Geosyncline, South Australia. In: Salt-sediment interactions and hydrocarbon prospectivity: Concepts, Applications, and Case Studies for the 21st Century (Eds P.J. Post, D.L. Olson, K.T. Lyons, S.L. Palmes, P.F. Harrison and N.C. Rosen) 24th GCSSEPM Bob F. Perkins Research Conference, 133-165.

DYSON, I. A., 2004b, Geology of the eastern Willouran Ranges—evidence for earliest onset of salt tectonics in the Adelaide Geosyncline. *MESA Journal*, 35, 48-56.

EICKHOFF, K.H., VON DER BORCH, C.C. and GRADY, A.E., 1988, Proterozoic canyons of the Flinders Ranges (South Australia): submarine canyons or drowned river valleys? *Sedimentary Geology*, 58, 217-235.

EYLES, N. and JANUSCZAK, N., 2004, 'Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma. *Earth-Science Reviews*, 65, 1-73.

EYLES, C.H., EYLES, N. and GREY, K., 2007, Palaeoclimate implications from deep drilling of Neoproterozoic strata in the Officer Basin and Adelaide Rift Complex of Australia; a marine record of wet-based glaciers. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 248, 291-312.

FANNING, C.M, LUDWIG, K.R., FORBES, B.G. and PREISS, W.V., 1986, Single and multiple grain zircon analyses for the early Adelaidean Rook Tuff, Willouran Ranges, South Australia. In: Abstracts, 8th Australian Geological Convention. Geological Society of Australia, 71-72.

FANNING, C.M., and LINK, P.K., 2008, Age constraints for the Sturtian glaciation: data from the Adelaide geosyncline, South Australia and Pocatello Formation, Idaho, USA. *Selwyn Symposium,* 91, 57-62.

FIDUK, J.C., BRUSH, E.R., ANDERSON, L.E., GIBBS, P.B. and ROWAN, M.G., 2004, Salt deformation, magmatism, and hydrocarbon prospectivity in the Espirito Santo Basin, offshore Brazil. In: *Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century: Houston, Gulf Coast Section Society of Economic Paleontologists and Mineralogists, 24th Annual Research Conference*, 370-392.

FIKE, D. A., GROTZINGER, J. P., PRATT, L. M. and SUMMONS, R. E., 2006, Oxidation of the Ediacaran ocean. *Nature*, 444, 744-747.

FRANK, T.D. and FIELDING, C.R., 2003, Marine Origin for Precambrian, carbonate-hosted magnesite? *Geology*, 31, 1101-1104.

GALLOWAY, W. E., GANEY-CURRY, P. E., LI, X. and BUFFLER, R. T., 2000, Cenozoic depositional history of the Gulf of Mexico basin. *AAPG Bulletin*, 84, 1743-1774.

GAMMON, P.R., MCKIRDY, D.M. and SMITH, H.D., 2005, The timing and environment of tepee formation in a Marinoan cap carbonate. *Sedimentary Geology*, 177, 195-208.

GEHLING, J.G., 1982, Sedimentology and Stratigraphy of the Late Precambrian Pound Subgroup, Central Flinders Ranges, S.A. University of Adelaide MSc thesis.

GEHLING, J. G., 2000, Environmental interpretation and a sequence stratigraphic framework for the terminal Proterozoic Ediacara Member within the Rawnsley Quartzite, South Australia. *Precambrian Research*, 100, 65-95.

GIDDINGS, J. A. and WALLACE, M.W., 2009, Sedimentology and C-isotope geochemistry of the 'Sturtian'cap carbonate, South Australia. *Sedimentary Geology*, 216, 1-14.

GIDDINGS, J.A., WALLACE, M.W., HAINES, P.W. and MORNANE, K., 2010, Submarine origin for the Neoproterozoic Wonoka canyons, south Australia. *Sedimentary Geology*, 223, 35-50.

GILES, K.A. and LAWTON, T.F., 2002, Halokinetic sequence stratigraphy adjacent to the El Papalote diapir, northeastern Mexico. *AAPG Bulletin*, 86, 823-840.

GILES, K. A. and ROWAN, M. G., 2012, Concepts in halokinetic-sequence deformation and stratigraphy. *Geological Society, London, Special Publications*, 363, 7-31.

GILES, K. A., LAWTON, T. F. and ROWAN, M. G., 2004, Summary of halokinetic sequence characteristics from outcrop studies of La Popa salt basin, northeastern Mexico. In: *Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century: 24th Annual Gulf Coast Section*. SEPM. Bob F. Perkins Research Conference Program and Abstracts, 16 p.

GOSTIN, V. A. and ZBIK, M., 1999, Petrology and microstructure of distal impact ejecta from the Flinders Ranges, Australia. *Meteoritics and Planetary Science*, 34, 587-592.

GOSTIN, V.A., HAINES, P.W., JENKINS, R.J.F., COMPSTON, W. and WILLIAMS, I.S., 1986, Impact Ejecta within Late Precambrian Shales, Adelaide Geosyncline, South Australia. *Science*, 233, 198-200.

GOTETI, R., INGS, S.J. and BEAUMONT, C., 2012, Development of salt minibasins initiated by sedimentary topographic relief. *Earth and Planetary Science Letters*, 339, 103-116.

GRAVESTOCK, D.I., 1995, Chapter 7: Early and Middle Palaeozoic. In: Drexel, J.F., and Preiss, W.V. (eds.) The Geology of South Australia. Vol. 2, The Phanerozoic. *South Australia Geological Survey Bulletin* 54, 3-62.

GREY, K. and CALVER, C.R., 2007, Correlating the Ediacaran of Australia. *Geological Society, London, Special Publications*, 286, 115-135.

GROTZINGER, J. P., FIKE, D. A. and FISCHER, W. W., 2011, Enigmatic origin of the largest-known carbon isotope excursion in Earth's history. *Nature Geoscience*, 4, 285-292.

GUERRA, M. C. and UNDERHILL, J. R., 2012, Role of halokinesis in controlling structural styles and sediment dispersal in the Santos Basin, offshore Brazil. *Geological Society, London, Special Publications*, 363, 175-206.

GURNIS, M., 1988, Large-scale mantle convection and the aggregation and dispersal of supercontinents. *Nature*, 332, 695-699.

HAINES, P.W., 1987, Carbonate shelf and basin sedimentation, late Proterozoic Wonoka Formation, South Australia . University of Adelaide Unpublished PhD Dissertation.

HAINES, P.W., 1988, Storm-dominated mixed carbonate/siliciclastic shelf sequence displaying cycles of hummocky cross-stratification, late Proterozoic Wonoka Formation, South Australia. *Sedimentary Geology*, 58, 237-254.

HAINES, P. W., 2000, Problematic fossils in the late Neoproterozoic Wonoka Formation, South Australia. *Precambrian Research*, 100, 97-108.

HEARON IV, T. E., ROWAN, M. G., GILES, K. A., KERNEN, R. A., GANNAWAY, C. E., LAWTON, T. F. and FIDUK, J. C., 2013, Allochthonous salt initiation and advance in the Flinders and eastern Willouran Ranges, South Australia: using outcrops to test subsurface-based models from the northern Gulf of Mexico. *AAPG Bulletin*, 99, 293-331.

HEITHERSAY, P.S., 1979, Sedimentology of the Burra group in the East Rooks area, Northeastern Willouran Ranges, South Australia. University of Adelaide BSc Honors Thesis, unpublished.

HIGGINS, J., 1997, Pamatta Pass Canyon Complex: Neoproterozoic Wonoka Formation, Flinders Ranges, South Australia. University of Adelaide BSc Honors Thesis, unpublished.

HIGGINS, J., FISCHER,W., SCHRAG, D., 2009. Oxygenation of the ocean and sediments: consequences for the seafloor carbonate factory. *Earth and Planetary Science Letters*, 284, 25–33.

HILL, A.C. and WALTER, M.R., 2000, Mid-Neoproterozoic (~830-750 Ma) isotope stratigraphy of Australia and global correlation. *Precambrian Research*, 100, 181-211.

HOFFMAN, P. F., KAUFMAN, A. J., HALVERSON, G. P. and SCHRAG, D. P. (1998). A Neoproterozoic snowball earth. *Science*, 281, 1342-1346.

HOFFMAN, P. F., 1999, The break-up of Rodinia, birth of Gondwana, true polar wander and the snowball Earth. *Journal of African Earth Sciences*, 28, 17-33.

HOFFMANN, K.H., CONDON, D.J., BOWRING, S.A., CROWLEY, J.L., 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation. *Geology*, 32, 817–820.

HOFFMAN, P. F. and LI, Z. X., 2009, A palaeogeographic context for Neoproterozoic glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 277, 158-172.

HOFFMAN, P. F. and SCHRAG, D. P., 2002, The snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, 14, 129-155.

HOWCHIN, W., 1900, Preliminary Report on glacial beds of Cambrian age in South Australia. *Royal Society of South Australia Transactions*, 25, 10.

HUDEC, M.R., JACKSON, M.P. and SCHULTZ-ELA, D.D., 2009, The paradox of minibasin subsidence into salt: Clues to the evolution of crustal basins. *Geological Society of America Bulletin*, 121, 201-221.

HURTGEN, M.T., ARTHUR, M.A., SUITS, N.S. and KAUFMAN, A.J., 2002, The sulfur isotopic composition of Neoproterozoic seawater sulfate: Implications for a snowball Earth?. *Earth and Planetary Science Letters*, 203, 413–429.

JACKSON, M.T. and TALBOT, C.J., 1986, External shapes, strain rates, and dynamics of salt structures. *Geological Society of America Bulletin*, 97, 305-323

JACKSON, C. A. L., 2012, The initiation of submarine slope failure and the emplacement of mass transport complexes in salt-related minibasins: A three-dimensional seismic-reflection case study from the Santos Basin, offshore Brazil. *Geological Society of America Bulletin*, 124, 746-761.

JAGO, J. B. and GATEHOUSE, C. G., 2014, A small trace fossil assemblage from the middle Cambrian Pantapinna Sandstone, Flinders Ranges, South Australia and its paleoenvironmental significance. *Australian Journal of Earth Sciences*, 61, 837-841.

JAGO, J. B., ZANG, W. L., SUN, X., BROCK, G. A., PATERSON, J. R. and SKOVSTED, C. B., 2006, A review of the Cambrian biostratigraphy of South Australia. *Palaeoworld*, 15, 406-423.

JAGO, J. B., GATEHOUSE, C. G., POWELL, C. M., CASEY, T. and ALEXANDER, E. M., 2010, The Dawson Hill Member of the Grindstone Range Sandstone in the Flinders Ranges, South Australia. *Transactions of the Royal Society of South Australia*, 134, 115-124.

JAGO, J. B., GATEHOUSE, C. G. and CASEY, T., 2013, Response to GJ Retallack's 'Discussion'of Jago et al.(2013). *Australian Journal of Earth Sciences*, 60, 543-545.

JAMES, N. P. and GRAVESTOCK, D. I., 1990, Lower Cambrian shelf and shelf margin buildups, Flinders Ranges, South Australia. *Sedimentology*, 37, 455-480.

JANSYN, J., 1990, Strato-tectonic evolution of a large subsidence structure associated with the late Proterozoic Wonoka Formation at Wilpena Pound, central Flinders Ranges, South Australia. University of Adelaide unpublished BSc Honors Thesis.

JENKINS, R. J. F., FORD, C. H. and GEHLING, J. G., 1983, The Ediacara member of the Rawnsley quartzite: The context of the Ediacara assemblage (late Precambrian, Flinders Ranges). *Journal of the Geological Society of Australia*, 30, 101-119.

JOB, A., 2011, Evolution of the basal Adelaidean in the northern Flinders Ranges: deposition, provenance and deformation of the Callanna and lower Burra Groups. University of Adelaide BSc Honours Thesis, unpublished.

KAH, L. C., LYONS, T. W. and CHESLEY, J. T., 2001, Geochemistry of a 1.2 Ga carbonate-evaporite succession, northern Baffin and Bylot Islands: implications for Mesoproterozoic marine evolution. *Precambrian Research*, 111, 203-234.

KARLSTROM, K.E., HARLAN, S.S., WILLIAMS, M.L., MCLELLAND, J. and GEISSMAN, J.W., 1999, Refining Rodinia: geologic evidence for the Australia–Western U.S. connection in the Proterozoic. *GSA Today*, 9, 1–7.

KENNEDY, M. J., 1996, Stratigraphy, sedimentology, and isotopic geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, $\delta^{13}C$ excursions, and carbonate precipitation. *Journal of Sedimentary Research*, 66, 1050-1064.

KENNEDY, M. J., CHRISTIE-BLICK, N. and SOHL, L. E., 2001, Are Proterozoic cap carbonates and isotopic excursions a record of gas hydrate destabilization following Earth's coldest intervals?. *Geology*, 29, 443-446.

KNOLL, A., WALTER, M., NARBONNE, G. and CHRISTIE-BLICK, N., 2006, The Ediacaran Period: a new addition to the geologic time scale. *Lethaia*, 39, 13-30.

KOUPRIANTCHIK, D., HUNT, S., BOULT, P., and MEYERS, A., 2005, Geomechanical modeling of salt diapirs: Generic shapes and a 3D salt structure from the Officer Basin, South Australia. In: Barla, G., and Barla, M., (eds.) *Proceedings of the 11th International Conference on Computer Methods and Advances in Geomechanics* Patron Editore, 27-34.

LE GUERROUÉ, E., 2010, Duration and synchroneity of the largest negative carbon isotope excursion on Earth: the Shuram/Wonoka anomaly. *Comptes Rendus Geoscience*, 342, 204-214.

LE HERON, D.P., 2012, The Cryogenian record of glaciation and deglaciation in South Australia. *Sedimentary Geology*, 243, 57-69.

LE HERON, D.P., COX, G., TRUNDLEY, A. and COLLINS, A.S., 2011(a), Two Cryogenian glacial successions compared: Aspects of the Sturt and Elatina sediment records of South Australia. *Precambrian Research*, 186, 147-168.

LE HERON, D.P., COX, G., TRUNDLEY, A. and COLLINS, A.S., 2011(b), Sea ice-free conditions during the Sturtian glaciation (early Cryogenian), South Australia. *Geology*, 39, 31-34.

LEMON, N.M., 1985, Physical modelling of sedimentation adjacent to diapirs and comparison with late Precambrian Oratunga breccia body in central Flinders Ranges, South Australia. *AAPG Bulletin*, 69, 1327-1338.

LEMON, N.M., 2000, A Neoproterozoic fringing stromatolite reef complex, Flinders Ranges, South Australia. *Precambrian Research*, 100, 109-120.

LEMON, N.M. and GOSTIN, V.A., 1990, Glacigenic sediments of the late Proterozoic Elatina Formation and equivalents, Adelaide Geosyncline of South Australia. In: Jago, J.B., and Moore, P.S., (eds.) *The Evolution of a Late Precambrian-Early Paleozoic rift complex: the Adelaide Geosyncline*. Geological Society of South Australia, Special Publication, 16, 149-163.

LI, Z.X., BOGDANOVA, S.V., COLLINS, A.S., DAVIDSON, A., DE WAELE, B., ERNST, R.E., FITZSIMMONS, I.C.W., FUCK, R.A., GLADKOCHUB, D.P., JACOBS, J, KARLSTROM, K.E., LU, S.,

NATAPOV, L.M., PEASE, V., PISAREVSKY, S.A., THRANE, K. and VERNIKOVSKY, V., 2008, Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Research*, 160, 179-210.

LI, Z.X., BOGDANOVA, S.V., COLLINS, A.S., DAVIDSON, A., DE WAELE, B., ERNST, R.E., EVANS, D.A.D., FITZSIMONS, I.C.W., FUCK, R.A., GLADKOCHUB, D.P. and JACOBS, J., 2009, How not to build a supercontinent: a reply to JDA Piper. *Precambrian Research*, 174, 208-214.

LINDSAY, J. F., KORSCH, R. J. and WILFORD, J. R., 1987, Timing the breakup of a Proterozoic supercontinent: evidence from Australian intracratonic basins. *Geology*, 15, 1061-1064.

LINDSAY, J.F. and LEVIN, J.H., 1996, Evolution of a Neoproterozoic to Palaeozoic intracratonic setting, Officer Basin, South Australia. *Basin Research*, 8, 403-424.

LINK, P. K. and GOSTIN, V.A., 1981, Facies and paleogeography of Sturtian glacial strata (late Precambrian), South Australia. *American Journal of Science*, 281, 353-374.

MACKAY, W. G., 2011, Structure and sedimentology of the Curdimurka Subgroup, northern Adelaide Fold Belt, South Australia. Unpublished PhD thesis, University of Tasmania.

MADOF, A. S., CHRISTIE-BLICK, N. and ANDERS, M. H., 2009, Stratigraphic controls on a salt-withdrawal intraslope minibasin, north-central Green Canyon, Gulf of Mexico: Implications for misinterpreting sea level change. *AAPG Bulletin*, 93, 535-561.

MAIDMENT, D.W., WILLIAMS, I.S. and HAND, M., 2007, Testing long-term patterns of basin sedimentation by detrital zircon geochronology, Centralian Superbasin, Australia. *Basin Research*, 19, 335-360.

MALLARINO, G., BEAUBOUEF, R. T., DROXLER, A. W., ABREU, V. and LABEYRIE, L., 2006, Sea level influence on the nature and timing of a minibasin sedimentary fill (northwestern slope of the Gulf of Mexico). *AAPG Bulletin*, 90, 1089-1119.

MATTHEWS, W. J., HAMPSON, G. J., TRUDGILL, B. D. and UNDERHILL, J. R., 2007, Controls on fluviolacustrine reservoir distribution and architecture in passive salt-diapir provinces: Insights from outcrop analogs. *AAPG Bulletin*, 91, 1367-1403.

MAWSON, D., 1939, The Late Proterozoic Sediments of South Australia. Report of the Australian and New Zealand Association for the Advancement of Science, 24, 79-88.

MAWSON, D., 1941, The Wilpena Pound formation and underlying Proterozoic sediments. *Transactions of the Royal Society of South Australia*, 65, p. 295-300.

MACMENAMIN, M.A. and MACMENAMIN, D.L.S., 1990, The emergence of animals: the Cambrian breakthrough. Columbia University Press, New York.

MEERT, J.G., 2012, What's in a name? The Columbia (Paleopangaea/Nuna) supercontinent. Unpublished manuscript.

MEERT, J. G. and TORSVIK, T. H., 2004, Paleomagnetic Constraints on Neoproterozoic 'Snowball Earth' Continental Reconstructions. In: Jenkins, G.S., McMenamin, M., McKay, C.P., and Sohl, L. *The Extreme Proterozoic: Geology, Geochemistry, and Climate*. American Geophysical Union, p. 5-11.

MEERT, J.G. and VAN DER VOO, R., 1994, The Neoproterozoic (1000-540 Ma) glacial intervals: No more snowball earth? *Earth and Planetary Science Letters*, 123, 1-13.

MEISLING, K. E., COBBOLD, P. R. and MOUNT, V. S., 2001, Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. *AAPG Bulletin*, 85, 1903-1924.

MINCHAM, H., 1977, *The Story of the Flinders Ranges*. Rigby, Adelaide, 305 p.

MODICA, C.J. and BRUSH, E.R., 2004, Postrift sequence stratigraphy, paleogeography, and fill history of the deep-water Santos Basin, offshore southeast Brazil. *AAPG Bulletin*, 88, 923-945.

MOORE, P. S., 1979, Deltaic Sedimentation--Cambrian of South Australia. *Journal of Sedimentary Research*, 49, 1229-1244.

MOORE, P. S., 1990, Origin of redbeds and variegated sediments, Cambrian, Adelaide Geosyncline, South Australia. *Geological Society of Australia Special Publication*, 16, 334-350.

MOUNT, T. J., 1975, Diapirs and diapirism in the Adelaide 'Geosyncline' South Australia. University of Adelaide unpublished PhD thesis.

MURRELL, B., 1977. Stratigraphy and tectonics across the Torrens Hinge Zone between Andamooka and Marree, South Australia..University of Adelaide. Ph.D. thesis, unpublished.

O'HALLORAN, G., 1992, Sedimentology and Nd isotopic ~~geochemistry~~ of some early Adelaidean rocks from the northern Flinders Ranges, S.A. University of Adelaide BSc Honors Thesis, unpublished.

OLSON, H. C. and DAMUTH, J. E., 2010, Character, Distribution and Timing of Latest Quaternary Mass-Transport Deposits in Texas—Louisiana Intraslope Basins Based on High-Resolution (3.5 kHz) Seismic Facies and Piston Cores. In: *Submarine Mass Movements and Their Consequences*, Springer, Netherlands, 607-617.

PILCHER, R.S., KILSDONK, B. and TRUDE, J., 2011, Primary basins and their boundaries in the deep-water northern Gulf of Mexico: Origin, trap types, and petroleum system implications. *AAPG Bulletin*, 95, 219-240.

PIPER, J.D., 2000, The Neoproterozoic Supercontinent: Rodinia or Palaeopangaea? *Earth and Planetary Science Letters*, 176, 131-146.

PIPER, J.D., 2007, The Neoproterozoic supercontinent Palaeopangaea. *Gondwana Research*, 12, 202-227.

PIPER, J.D., 2009, Comment on "Assembly, configuration, and break-up history of Rodinia: A synthesis" by Li et al.[Precambrian Res., 160 (2008) 179–210]. *Precambrian Research*, 174, 200-207.

PISAREVSKY, S.A., WINGATE, M.T.D., STEVENS, M.K. and HAINES, P.W., 2007, Palaeomagnetic results from the Lancer 1 stratigraphic drillhole, Officer Basin, Western Australia, and implications for Rodinia reconstructions. *Australian Journal of Earth Sciences*, 54, 561-572.

PLUMMER, P. S., 1978, Stratigraphy of the lower Wilpena Group (late Precambrian), Flinders Ranges, South Australia. *Transactions of the Royal Society of South Australia*, 102, 25-38.

PRATSON, L.F. and COAKLEY, B.J., 1996, A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. *Geological Society of America Bulletin*, 108, 225-234.

PREISS, W.V. (Compiler), 1987, The Adelaide Geosyncline—late Proterozoic stratigraphy, sedimentation, paleontology and tectonics. *Bulletin of the Geological Survey of South Australia*, 53, 438 p.

PREISS, W.V., BELPERIO, A.P., COWLEY, W.M. and RANKIN, L.R., 1993, Neoproterozoic. Chapter 6 in: Drexel, J.F., Preiss, W.V. and Parker, A.J. (Eds), *The Geology of South Australia. Vol. 1, The Precambrian*. South Australia Geological Survey Bulletin, 54, 171-203.

PREISS, W.V. and COWLEY, W.M., 1999, Genetic Stratigraphy and revised lithostratigraphic classification of the Burra Group in the Adelaide Geosyncline. *MESA Journal*, 14, 30-40.

PREISS, W.V., DYSON, I.A., REID, P.W., and COWLEY, W.M., 1998, Revision of lithostratigraphic classification of the Umberatana Group. *MESA Journal*, 9, 36-42.

PREISS, W.V. and FORBES, B.G., 1981, Stratigraphy, correlation and sedimentary history of Adelaidean (Late Proterozoic) basins in Australia. *Precambrian Research*, 15, 255-304.

PREISS, W. V., GOSTIN, V.A., MCKIRDY, D.M., ASHLEY, P.M., WILLIAMS, G.E. and SCHMIDT, P.W., 2011, The glacial succession of Sturtian age in South Australia: the Yudnamutana Subgroup. *Geological Society, London, Memoirs*, 36, 701-712.

PREISS, W. V., KORSCH, R. J., BLEWETT, R. S., FOMIN, T., COWLEY, W. M., NEUMANN, N. L. and MEIXNER, A. J., 2010, Geological interpretation of deep seismic reflection line 09GA-CG1: the Curnamona Province–Gawler Craton Link Line, South Australia. *Geoscience Australia*, Record, 10, 66-76.

PREISS, W.V., 1999, PARACHILNA, South Australia, sheet SH54-13 (second edition). South Australia. Geological Survey. 1:250 000 Series – Explanatory Notes.

PREISS, W.V., 2000, The Adelaide Geosyncline of South Australia and it's significance in Neoproterozoic continental reconstruction. *Precambrian Research*, 100, 21-63.-

RAUB, T.D., 2010, Stratigraphic context revitalizes solar interpretation for the Neoproterozoic deglacial Elatina rhythmites. *Geological Society of America Abstracts with Programs*, 42, 402.

REID, P. and PREISS, W.V., 1999, Parachilna Sheet SH54-13. 1:250 000 scale Geological Map and Explanatory Notes, Primary Industries and Resources South Australia. Second edition. 52p.

RETALLACK, G.J., 2011, Neoproterozoic loess and limits to snowball Earth. *Journal of the Geological Society, London*, 168, 289-307.

RETALLACK, G. J., 2012, Were Ediacaran siliciclastics of South Australia coastal or deep marine?. *Sedimentology*, 59, 1208-1236.

RETALLACK, G. J., MARCONATO, A., OSTERHOUT, J. T., WATTS, K. E. and BINDEMAN, I. N., 2014, Revised Wonoka isotopic anomaly in South Australia and Late Ediacaran mass extinction. *Journal of the Geological Society*, 171, 709-722.

ROBERTS, M.J., METZGAR, C.R., LIU, J. and LIM, S.J., 2004, Regional assessment of salt weld timing, Campos Basin, Brazil. In Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century. 24th Annual Gulf Coast Section SEPM Foundation, Bob F. Perkins Research Conference.

ROSE, C.V. and MALOOF, A.C., 2010, Testing models for post-glacial ‘cap dolostone’deposition: Nuccaleena Formation, South Australia. *Earth and Planetary Science Letters*, 296, 165-180.

ROWAN, M.G. and VENDEVILLE, B.C., 2006, Foldbelts with early salt withdrawal and diapirism: Physical model and examples from the northern Gulf of Mexico and the Flinders Ranges, Australia. *Marine and Petroleum Geology*, 23, 871-891.

SONNETT, C.P., FINNEY, S.A. and WILLIAMS, C.R., 1988, The lunar orbit in the late Precambrian and the Elatina sandstone laminae. *Nature*, 335, 806-808.

SONNETT, C.P. and WILLIAMS, G.E., 1987, Frequency modulation and stochastic variability of the Elatina varve record: a proxy for solar cyclicity? *Solar Physics*, 110, 397-410.

STEVENSON, G. M. and WRAY, L. L., 2009, History of petroleum exploration of Paleozoic targets in the Paradox Basin. in Houston et al., The Paradox Basin Revisited – New Developments in Petroleum Systems and Basin Analysis: *RMAG Special Publication*, 1-23.

SWART, P. K. and M. J. KENNEDY. 2012, Does the global stratigraphic reproducibility of $\delta^{13}C$ in Neoproterozoic carbonates require a marine origin? A Pliocene–Pleistocene comparison. *Geology*, 40, 87-90.

TGS 2015. Deepwater Kwanza Basin. A prospective Pre-Salt Province? GEOExPro, viewed June 2017, <http://www.geoexpro.com/articles/2015/11/deepwater-kwanza-basin>.

THOMSON, B. P., 1966, The lower boundary of the Adelaide system and older basement relationships in south Australia. *Journal of the Geological Society of Australia*, 13, 203-228.

THOMSON, B.P., COATS, R.P., MIRAMS, R.C., FORBES, B.G., DALGARNO, C.R. and JOHNSON, J.E., 1964, Precambrian rock groups in the Adelaide Geosyncline: a new subdivision. *Quarterly Geological Notes*, Geological Survey of South Australia, 9, 1-19.

TURNER, G. R., 1976, Stratigraphy, structural geology and metamorphism of the Callanna beds and base of the Burra Group in the Arkaroola Village area, South Australia. Unpublished University of Adelaide BSc Honors Thesis.

UPPILL, R. K., 1979, Sedimentology of the Late Precambrian Mundallio Subgroup: A clastic-carbonate (Dolomite, Magnesite) sequence in the Mt. Lofty and Flinders Ranges, South Australia. Unpublished University of Adelaide PhD Dissertation.

URLWIN, B., 1992, Carbon isotope stratigraphy of the late Proterozoic Wonoka formation of the Adelaide fold belt: diagenetic assessment and interpretation of isotopic signature and correlations with previously measured isotopic curves. Unpublished University of Adelaide BSc Honors Thesis.

VON DER BORCH, C. C., 1980, Evolution of late proterozoic to early paleozoic Adelaide foldbelt, Australia: Comparisons with postpermian rifts and passive margins. *Tectonophysics*, 70, 115-134.

VON DER BORCH, C.C. and LOCK, D., 1979, Geological Significance of Coorong Dolomites. *Sedimentology*, 26, 813-824.

VON DER BORCH, C. C., GRADY, A. E., ALDAM, R., MILLER, D., NEUMANN, R., ROVIRA, A. and EICKHOFF, K., 1985, A large-scale meandering submarine canyon: outcrop example from the late Proterozoic Adelaide Geosyncline, South Australia. *Sedimentology*, 32, 507-518.

VON DER BORCH, C. C., SMIT, R. and GRADY, A.E., 1982, Late Proterozoic submarine canyons of Adelaide Geosyncline, South Australia, *AAPG Bulletin*, 66, 332-347.

VON DER BORCH, C.C., CHRISTIE-BLICK, N. and GRADY, A. E., 1988, Depositional sequence analysis applied to Late Proterozoic Wilpena Group, Adelaide Geosyncline, South Australia. *Australian Journal of Earth Sciences*, 35, 59-72.

WALLACE, M.W., v.S HOOD, A., WOON, E.M., GIDDINGS, J.A., and FROMHOLD, T.A., 2015, The Cryogenian Balcanoona reef complexes of the Northern Flinders Ranges: implications for Neoproterozoic ocean chemistry. Palaeogeography, Palaeoclimatology, Palaeoecology, 417, 320-336.

WALTER, M.R., VEEVERS, J.J., CALVER, C.R. and GREY, K., 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia. *Precambrian Research*, 73, 173-195.

WEBB, B.P., 1960, Diapiric structures in the Flinders Ranges. *Australian Journal of Science*, 22, 390-391.

WILLIAMS, G.E., 1988, Cyclicity in the late Precambrian Elatina Formation, South Australia: solar or tidal signature? *Climatic Change*, 13, 117-128.

WILLIAMS, G.E., 1990, Tidal rhythmites: key to the history of the Earth's rotation and lunar orbit. *Journal of Physics of the Earth*, 38, 475-491.

WILLIAMS, G.E., 1997, Precambrian length of day and the validity of tidal rhythmite paleotidal values. *Geophysical Research Letters*, 24, 421-424.

WILLIAMS, G.E. and GOSTIN, V.A., 2000, Mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia. *Journal of the Geological Society*, 157, 759-768.

WILLIAMS, G.E. and GOSTIN, V.A., 2005, Acraman-Bunyeroo impact event (Ediacaran), South Australia, and environmental consequences: twenty-five years on. *Australian Journal of Earth Sciences*, 52, 607-620.

WILLIAMS, G.E. and SONNETT, C.P., 1985, Solar signature in sedimentary cycles from the late Precambrian Elatina Formation, Australia. *Nature*, 318, 523-527.

WILLIAMS, G.E., GOSTIN, V.A., MCKIRDY, D.M. and PREISS, W.V., 2008, The Elatina glaciation, late Cryogenian (Marinoan Epoch), South Australia: Sedimentary facies and palaeoenvironments. *Precambrian Research*, 163, 307-331.

WILLIAMS, G. E., GOSTIN, V. A., MCKIRDY, D. M., PREISS, W. V. and SCHMIDT, P. W., 2011, The Elatina glaciation (late Cryogenian), South Australia. *Geological Society, London, Memoirs*, 36, 713-721.

WINGATE, M. T., CAMPBELL, I. H., COMPSTON, W. and GIBSON, G. M., 1998, Ion microprobe U–Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia. *Precambrian Research*, 87, 135-159.

WINGATE, M.T., PISAREVSKY, S.A. and EVANS, D.A., 2002, Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? *Terra Nova*, 14, 121-128.

WYSOCZANSKI, R. J. and ALLIBONE, A. H., 2004, Age, correlation, and provenance of the Neoproterozoic Skelton Group, Antarctica: Grenville age detritus on the margin of East Antarctica. *The Journal of Geology*, 112, 401-416.

YOUNG, G. M. and GOSTIN, V.A., 1988, Stratigraphy and sedimentology of Sturtian glacigenic deposits in the western part of the North Flinders Basin, South Australia. *Precambrian Research*, 39, 151-170.

YOUNG, G.M. and GOSTIN, V.A., 1989, An exceptionally thick upper Proterozoic (Sturtian) glacial succession in the Mount Painter area, South Australia. *Geological Society of America Bulletin*, 101, 834-845.

YOUNG, G.M. and GOSTIN, V.A., 1990, Sturtian glacial deposition in the vicinity of the Yankaninna Anticline, north Flinders Basin, South Australia. *Australian Journal of Earth Sciences*, 37, 447-458.

YOUNG, G.M. and GOSTIN, V.A., 1991, Late Proterozoic (Sturtian) succession of the North Flinders Basin, South Australia: an example of temperate glaciation in an active rift setting. In Anderson, J.B., and Ashley, G.M., *Glacial Marine Sedimentation: Paleoclimatic Significance. GSA Special Publication*, 261, 207-222.

YOUNGS, B.C., 1977, The sedimentology of the Cambrian Wirrealpa and Aroona Creek Limestones: *Geological Survey of South Australia Bulletin* 47, 73 p.

YOUNGS, B.C., 1978, The petrology and depositional environments of the Middle Cambrian Wirrealpa and Aroona Creek limestones (South Australia). *Journal of Sedimentary Research*, 48, 63-74.

ZAHNLE, K.J. and WALKER, J.C.G., 1987, Climatic oscillations during the Precambrian Era. *Climatic Change*, 10, 269-284.

ZHAO, J.X., MCCULLOCH, M.T. and KORSCH, R.J., 1994, Characterisation of a plume-related ~ 800 Ma magmatic event and its implications for basin formation in central-southern Australia. *Earth and Planetary Science Letters*, 121, 349-367.

ZHAO, G., SUN, M., WILDE, S.A., LI, S. and ZHANG, J., 2006, Some key issues in reconstructions of Proterozoic supercontinents. *Journal of Asian Earth Sciences*, 28, 3-19.