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Geology of the northern Flinders Ranges

The geology of the Neoproterozoic Adelaide Geosyncline (also termed the Adelaide Rift Complex) is reviewed by Preiss (1987, 1993, 2000), with Coats and Blissett (1971) focusing on the Mount Painter area and its surrounds. The Paleozoic, Mesozoic and Cenozoic successions of the region are reviewed by Drexel and Preiss (1995). These works remain unsurpassed in providing a framework to understanding the geology of the region.

Arkaroola is located in the northern Flinders Ranges (Figure 1), where rocks of the Mount Painter Inlier form a basement nucleus over which a younger Neoproterozoic succession was deposited. The Mount Painter Inlier comprises Mesoproterozoic metasediments and metavolcanics (including the Radium Creek Metamorphics) intruded by granites, pegmatites and minor amphibolite dykes. The highly radiogenic nature of the Mesoproterozoic granites has resulted in a long-lasting history of hydrothermal activity that has continued to the present.

The Neoproterozoic succession includes numerous horizons of stromatolitic carbonates, evidence for two Cryogenian glaciations, and an Ediacaran impact ejecta horizon derived from the Acraman impact structure in the adjacent Gawler Ranges. The main phase of deformation was the Ordovician Delamerian Orogeny at 514–490 Ma (Drexel and Preiss, 1995; Foden et al., 2006). Ordovician granites and pegmatites form a younger granite suite which intrudes the Proterozoic basement (Hore et al., 2005).

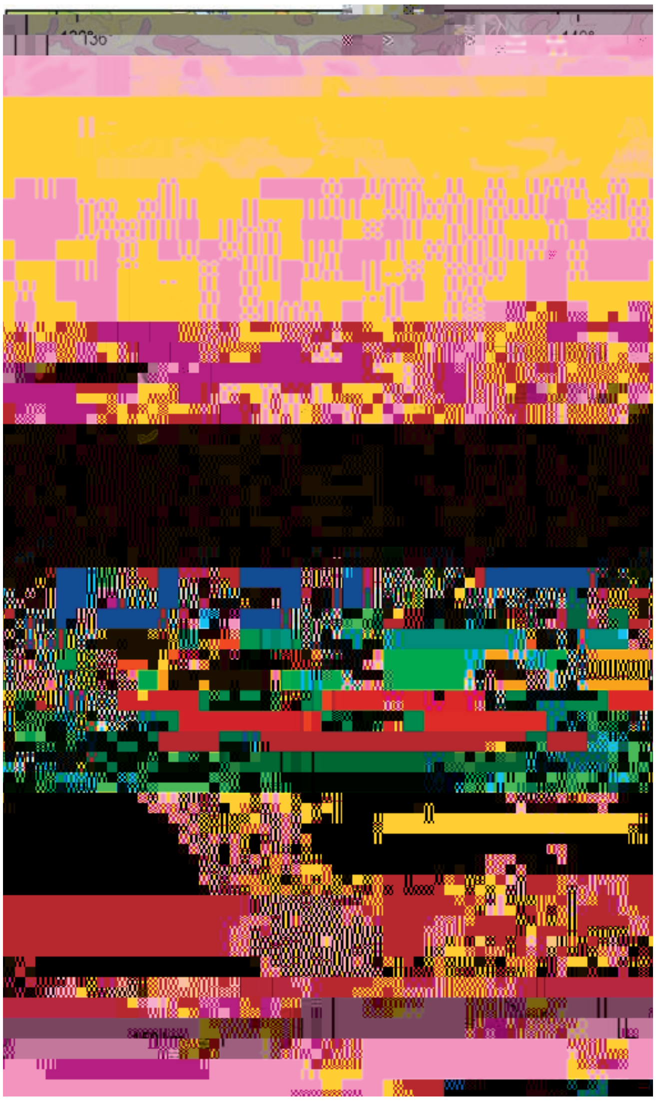

***Figure 1** Regional geological context of the study area.*

Mesozoic and early Cenozoic sediments unconformably overlie the Proterozoic and Paleozoic rocks. This cover has been almost completely removed by later Cenozoic reactivation and uplift of the folded strata to form the Flinders Ranges. The youngest Cenozoic sediments form piedmont alluvial aprons derived from the ranges.

Regolith and landscapes of the northern Flinders Ranges and surrounds

Regolith and associated paleolandscapes within the Mesozoic Eromanga Basin include a paleodrainage deposition (fluvial and minor glacial) in a landscape of moderate topographic relief and bedrock exposure (Davey and Hill, 2007; Hill and Hore, 2009). Cretaceous marine transgressions across low-lying parts of the landscape deposited chemically reduced clays and silts. The Mesozoic sediments have since been partially oxidised and tectonically disrupted, particularly during the Neogene (Davey and Hill, 2007). Early Cenozoic regolith and landscape evolution is associated with the development of the Lake Eyre Basin region and Paleogene fluvial deposits. Ephemeral fluvial, lacustrine, colluvial and aeolian deposition, as well as tectonism and pedogenesis, have been spatially and temporally variable in the more recent geological evolution (Hill, 2008).

The youngest Cenozoic landscapes of the plains to the east and north of the Arkaroola region record a complex evolution under changing climatic conditions (Twidale and Bourne, 1996; Twidale and Wopfner, 1996; Hill, 2008). Major alluvial fan systems occur along the range front and drain into the adjacent salt lakes (Frome, Grace, Blanche and Callabonna) or into the dune fields on the margin of the Strzelecki Desert. The fans are variably duricrusted and dissected and record a Quaternary history of fan deposition and incision related to both climate change and tectonics. Examples of these Cenozoic deposits flank the Flinders Ranges at the Paralana Hot Springs (see below). The various surfaces, duricrusts and sediments provide an analogue for the complex landforms to be expected on Mars. Some of these deposits, such as the mobile barchanoid sand dunes at Gurra Gurra Waterhole, have previously been studied as Mars analogues (Bishop, 1999).

Astrobiology in the Flinders Ranges

Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe. This multidisciplinary field encompasses the search for habitable environments... the search for evidence of prebiotic chemistry and life on Mars and other bodies in our Solar System, laboratory and field research into the origins and early evolution of life on Earth, and studies of the potential for life to adapt to challenges on Earth and in space. From: "About Astrobiology". (*NASA Astrobiology Institute*, 2008).

Neoproterozoic stromatolites at Arkaroola

There are numerous Neoproterozoic stromatolitic carbonates and associated chert formations within the Adelaide Geosyncline, which may contain microfossils. These include the oldest carbonates of the Callanna Group and the Skillogalee Dolomite of the Burra Group, (both pre-Cryogenian), the Cryogenian interglacial carbonates of the Balcanoona, Etina and Trenzona formations, the Ediacaran Wonoka Formation, and numerous horizons in the Cambrian (Coats, 1972; Preiss, 1987, 1993, and references therein). They attest to a flourishing photosynthetic bacterial microbiota that was widespread in marine (and probably also lacustrine) environments ranging from peritidal to the base of the photic zone (c.100–150 m depth) during favourable conditions throughout the region. In the Arkaroola area, the best preserved stromatolites are found in the Balcanoona Formation as large reefs up to 1.1 km thick, with associated enigmatic structures that may be sponges (Giddings et al., 2009). Fore-reef, reef-margin and back-reef facies are all well represented.

The astrobiological significance of stromatolites lies in their ubiquity, as they are the oldest known macroscopic evidence of life on Earth and are found in diverse environments including saline and freshwater lakes, intertidal flats, springs, hydrothermal vents, and both shallow and deep marine. While not all stromatolite-like structures are biogenic, not all biogenic stromatolites preserve microfossils or biomarkers (Brasier et al., 2002; Schopf, 2006), and both microfossils and biomarkers can be found in non-stromatolitic lithologies (Marshall, 2007). Recognition of stromatolite-like features on Mars would be a major discovery and would provide a focus for subsequent investigations. Therefore various researchers have suggested that recognition for stromatolitic morphologies be included in the search for life on Mars (e.g., Walter and Des Marais, 1993; McKay and Stoker, 1989), as well as drawing parallels between terrestrial stromatolites and what might be found on Mars (e.g., Allwood et al., 2007; Van Kranendonk, 2006).

A possible Neoproterozoic deep hot biosphere

The Arkaroola region is also notable for the serendipitous discovery of possible evidence for a deep hot biosphere that inhabited Neoproterozoic sedimentary successions during peak burial and metamorphism. While examples of such organisms are known from deep wells today (Fyfe, 1996) and have been postulated to have lived as long as 3.8 billion years ago (Pinti et al., 2001), fossil examples are poorly known. Structural investigations by Bons and Montenari (2005) examined fibrous anataxial calcite veins in the Tindelpina Shale Member of the Tapley Hill Formation. These formed at c. 585 Ma at an estimated 3–6 km depth. Scanning electron microscope observations revealed about 1-micron-sized structures within the veins. Further studies showed that these structures were composed of calcite but contained higher sulfur than the surrounding material. Fluid inclusions in the calcite indicate a temperature of formation of c. 60–80°C, and not exceeding 100°C. While a nonbiogenic origin of the objects is possible, it was considered unlikely (Bons et al., 2007). The weight of evidence from morphology, chemistry and size distribution indicates that the objects are fossilised microbes that lived in the veins at the time and depth of vein formation. Further work is needed on the structures to test their biogenicity. If these features are indeed biogenic they are a potential analogue for a possible martian habitat (Hoffmann and Farmer, 2000).

Mount Painter/Mount Gee

The Mount Painter area contains a complex collection of breccias, which are characterised by large dyke-like bodies of siliceous hematitic breccia and are interpreted to represent hydrothermal systems (Hore and Hill, 2009). This hydrothermal activity is most evident in the area centred on Mount Painter and Mount Gee (Sprigg, 1945; Drexel and Major, 1987) with lesser expressions to the east at Livelys Find Au prospect (Collier, 2000) and to the northeast at the Hodgkinson U prospect (Smith, 1992). Many of these breccias contain U and minor sulfide mineralisation. The breccias occur as irregular bodies within the basement complex, adjacent to a zone of extensive faulting, which also contains Ordovician granites and pegmatites (Lambert et al., 1982). The Mount Gee system includes a range of features including crustiform and colloform textures, bladed and replacement carbonate, fluorite, zeolites and siliceous fluids resulting in cavity-fill crystallisation and jasperoidal formations as seen in Figure 2 (Hore, 2008). The jasperoidal unit at Mount Gee could have been deposited as a gel (e.g., Eugster and Jones, 1967), and many textures in the Mount Painter and Mount Gee silica deposits are similar to the botryoidal silica surfaces observed at the Sleeper Au deposit in Nevada (Saunders, 1994) and the recrystallised silica gels from Yellowstone National Park (Fournier et al., 1991). While the preservation of microfossils would appear likely in the Mount Painter hydrothermal deposits, preliminary attempts to find them have been unsuccessful (Carlton, 2002).

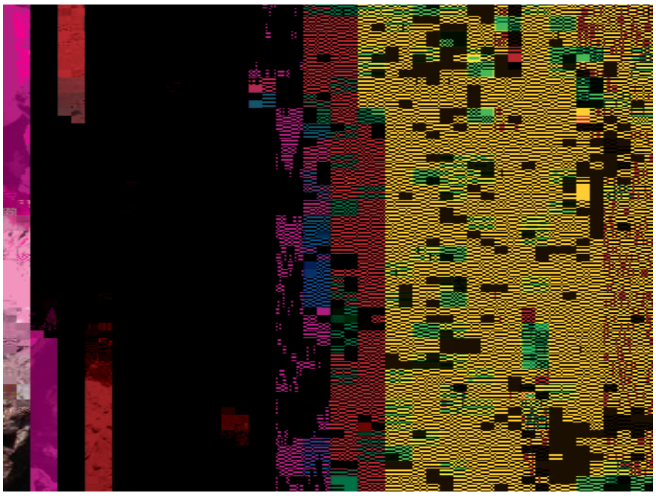

Figure 2 Mount Gee epithermal quartz.

Ancient hot-spring deposits and associated hydrothermal alteration exemplify key environments in the exploration and study of earliest life on Earth (e.g., Bock and Goode, 1996). These systems could have similar significance in the search for extraterrestrial life, and particularly on our nearest neighbour, Mars, where hydrothermal activity is likely to have occurred in the past and may even continue somewhere underground today (e.g., Walter and Des Marais, 1993; Catling and Moore, 2003). Martian hematite-precipitating spring deposits are high-value targets for martian astrobiology missions, in particular sample return missions (Catling and Moore, 2003; Allen et al., 2001, 2004). The hematite-rich shallow hydrothermal systems of the Mount Painter Inlier are therefore of considerable astrobiological interest as Mars analogues (Thomas and Walter, 2002, 2004; Brugger et al., 2011) because of the high preservation potential for both microfossils and organic matter in the silica-hematite precipitates. The high radiation environment of these systems, of which Paralana Hot Springs (see below) is the current example, provides another similarity to the surface of Mars, while the association of hydrothermal

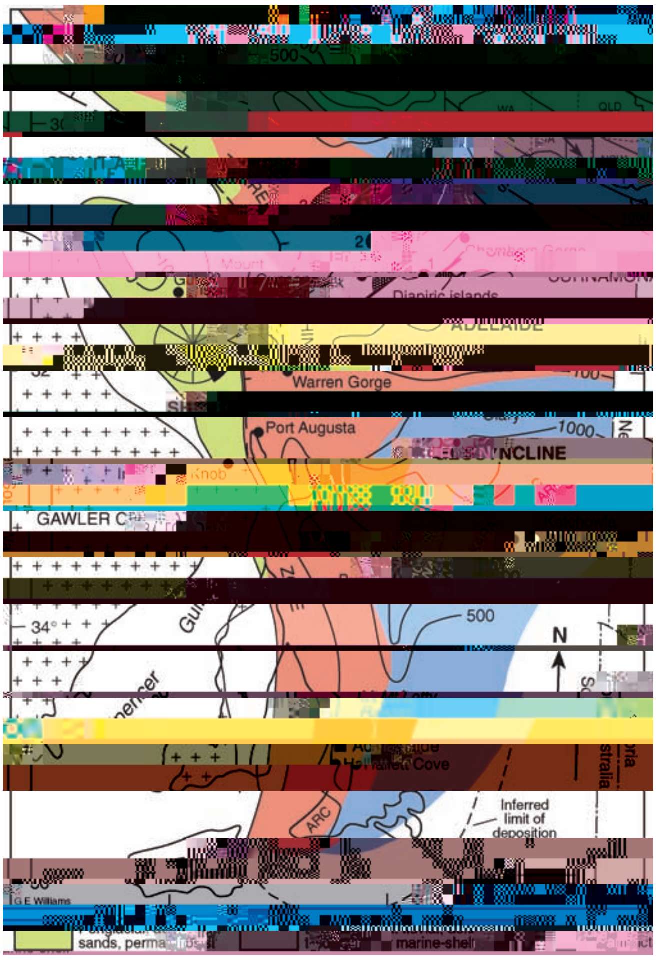

Figure 4 Facies of the late Cryogenian Elatina glaciation. Isopachs

Schmidt and Williams, 1995; Sohl et al., 1999). However, the indicated paleogeography, with extensive and long-lived open seas, unglaciated continental regions and an active hydrological cycle, conflicts with the "snowball Earth" hypothesis of Hoffman and Schrag (2002).

The older, Sturt glaciation is equally well represented by diverse facies throughout the Flinders Ranges (Preiss, 1987, 1993; Young and Gostin, 1989). At Stubbs Waterhole, 5 km from Arkaroola, spectacular thick-bedded sandy boulder and pebble conglomerates with diverse lithologies were deposited from vigorous glacial meltwater streams. It is believed that during the middle Cryogenian an elevated large ice cap covered the whole area between the Mount Painter Inlier and Broken Hill (250 km to the southeast). Major thickness variations of the c. 500 m thick Bolla Bollana Formation reflect rapid subsidence in rifted basins.

Tidal rhythmites and Earth's paleorotation, Pichi Richi Pass

The Elatina Formation near the margins of the Adelaide Geosyncline includes tidal rhythmites of siltstone and fine-grained sandstone deposited on a series of ebb-tidal deltas and estuarine tidal flats that formed during a high stand of sea level during temporary glacial retreat (Williams, 1991, 2000; Williams et al., 2008). The fine-grained sediment load of ebb tidal currents is related directly to tidal range (or maximum tidal height), and deposition offshore from ebb-tidal jets and plumes forms neap–spring cycles comprising semidiurnal and diurnal (lunar day) graded laminae mostly of fine sand and silt, with mud bands deposited during slack water at neaps (Figure 5). The rhythmite unit is 18 m thick at Warren Gorge (Williams, 1996) and somewhat thinner at a more distal setting in Pichi Richi Pass (Figure 4) where exposure is limited.

Detailed study of cores from three vertical holes drilled through the rhythmite unit in Pichi Richi Pass have provided an internally-consistent paleotidal data-set comprising numerous tidal cycles ranging from semidiurnal to the lunar nodal cycle (9.4 m log of 1580 successive fortnightly neap–spring cycles recording 60 years of continuous deposition; Williams, 1991). The neap–spring cycles contain 8–16 diurnal laminae, with many cycles abbreviated at neaps (Figure 5b); semidiurnal increments occur locally, and are conspicuous in thicker neap–spring cycles from tidal rhythmites in the correlative Reynella Siltstone Member near Hallett Cove, 300 km to the south (Figures 5a and 6). Paleotidal cycles resulting from variation in the thickness of successive neap–spring cycles compare closely with modern tidal patterns for Townsville, Queensland (Figure 7): features common to both data sets include first-order peaks marking the solar year and the annual oscillation of sea level, second-order peaks marking the semiannual tidal cycle, and a sawtooth pattern reflecting alternate high and low spring tides due to the eccentric lunar orbit. The duration of Elatina rhythmite deposition matches the c.70 year

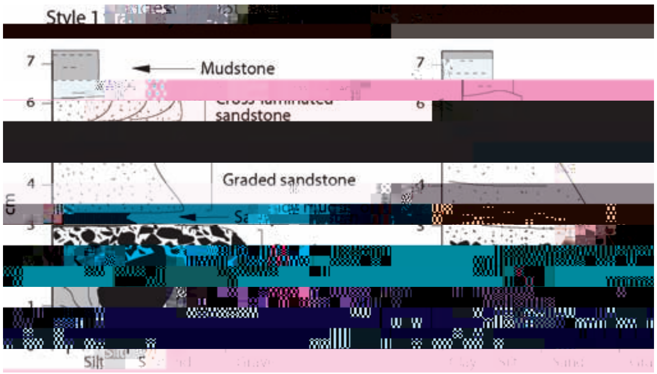

Figure 8 Stratigraphic column for Ediacaran strata in the central Adelaide Geosyncline. AIEH = Acraman impact ejecta horizon. The famous metazoan fossil assemblage (Ediacara biota) occurs near

metamorphism and the horizon is anomalous in cosmogenic siderophile elements, including Ir (Gostin et al., 1989). U-Pb zircon dating, paleomagnetic data and the regional distribution of the ejecta confirm derivation of the volcanic fragments from the Acraman impact structure in the 1592 Ma Yardea Dacite on the Gawler Craton (Compston et al., 1987; Schmidt and Williams, 1996; Williams and Wallace, 2003; Williams and Gostin 2005). Typical sections of the ejecta are shown in Figure 9 and ejecta regional distribution in Figure 10.

The magnitude, age and potential environmental effects of the Acraman impact and the nature of the AIEH were reviewed by Williams and Wallace (2003) and Williams and Gostin (2005). The Acraman impact structure is complex, with a transient cavity 40 km in diameter and a final structural rim (90 km diameter) that is eroded ≥2.5 km below the original crater floor. The AIEH in the Adelaide Geosyncline occurs at radial unfolded distances of up to 400 km from the centre of the Acraman structure. The impact occurred at a low (c. 12.5°) paleolatitude and probably perturbed the atmosphere in both the northern and southern hemispheres. The dimensions of Acraman

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