Flinders Ranges: A proposed nomination for World Heritage

Preliminary statement of values

Final technical report – March 2017

SOUTH AUSTRALIA

Government of South Australia

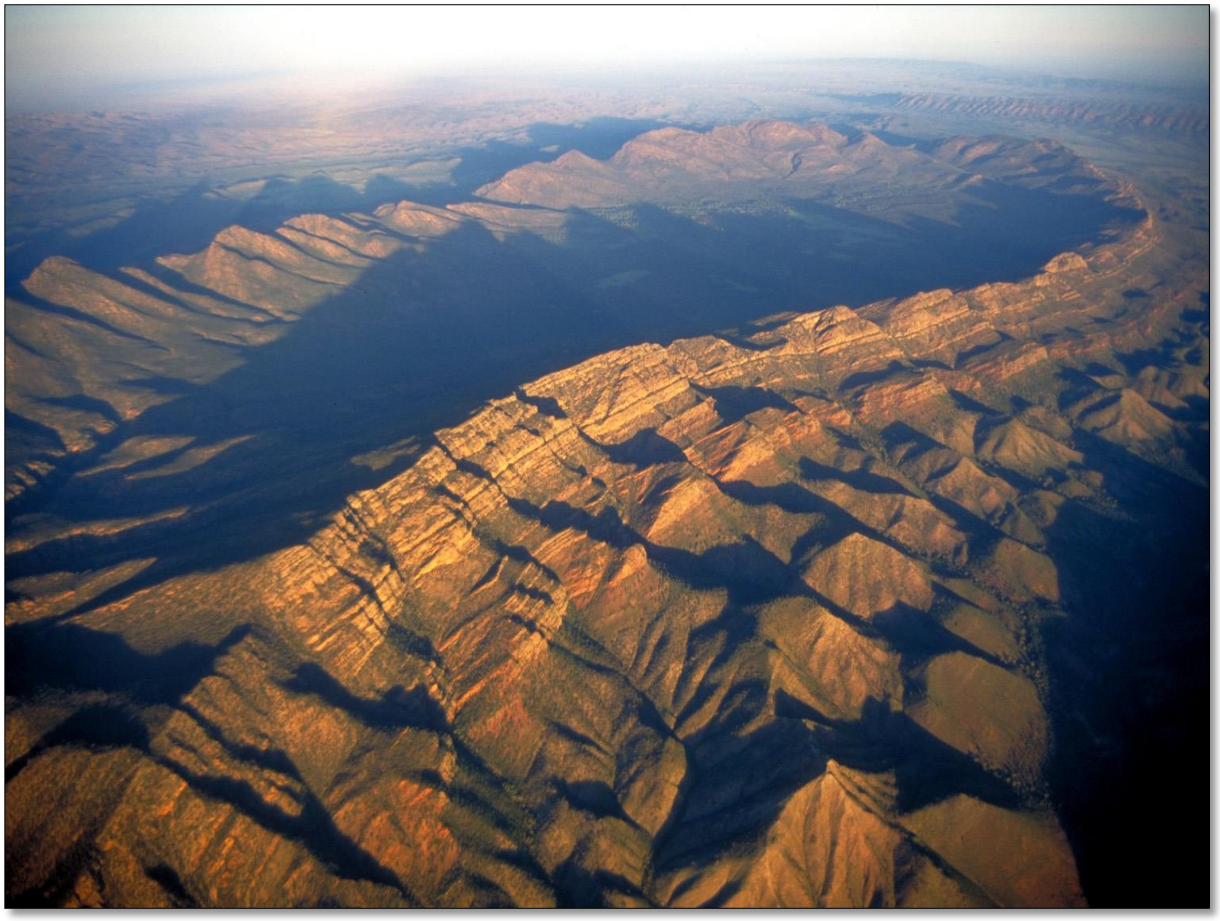

Photo 1 Dramatic scenery of 'Ikara' or Wilpena Pound, Flinders Ranges, South Australia (Source: Jim Gehling)

Status and purpose of this report

This 'Preliminary statement of values' report is a technical report of the South Australian Government. It has been contributed to by leading Australian-based geologists and palaeontologists at an Expert Workshop held in Adelaide on 1–2 August 2016, and subsequently peer reviewed by these specialists. The report confirms that the exceptional, unique geological features of the Flinders Ranges are worthy phenomena for being considered for World Heritage inscription.

This report is intended to be used to inform the development of a World Heritage nomination for the Flinders Ranges, and to assist in communicating to a range of audiences their outstanding geological and palaeontological values. It has been written using non-technical language. A Glossary is provided at the end of the report to explain some of the technical terms that have been used and to identify alternatives to some terminology.

This report represents a very preliminary stage in the development of a World Heritage nomination for the Flinders Ranges. To that end, the terminology used and details included in this report are subject to change in a future nomination document.

Acknowledgements

Appreciation is extended to the geologists and palaeontologists who provided expert input to this report, particularly Mr Stephen Hore, Dr Wolfgang Preiss, Mr Wayne Cowley, Professor Jim Gehling, Professor Mary Droser, Professor John Paterson, Associate Professor Glenn Brock, Dr Diego García-Bellido, Professor Malcolm Walter, Associate Professor Malcolm William Wallace and Dr Peter Kruse. Many thanks are also extended to all those who contributed to the report during and subsequent to the Expert Workshop in Adelaide.

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1 INTRODUCTION

A proposed nomination for World Heritage

The Flinders Ranges, South Australia, contains exceptional and unique geological heritage, as demonstrated by exemplar sites across the region. These outstanding geological values in the Flinders Ranges have been proposed for recognition as a UNESCO World Heritage Serial Property under criterion (viii).

This Preliminary Statement of Values technical report provides a brief description of these outstanding geological values. It has been prepared following a meeting of geological experts convened at an Expert Workshop in Adelaide on 1–2 August 2016 that reviewed the special values of the Flinders Ranges from the perspective of World Heritage.

Two major themes were recognised at the workshop and are presented here as 'The Dawn of Animal Life' and 'Natural Radioactive Heat Phenomena' as well as text prepared on 'Criterion (viii) Considerations'. This report does not deal with the 'Integrity' or 'Protection and Management' aspects of World Heritage Outstanding Universal Value.

The setting

The Flinders Ranges is a topographically and environmentally varied geographic region of South Australia that includes outstanding scenic, environmental, cultural, historical and, above all, scientific values. The Flinders Ranges, approximately 500 kilometres north of South Australia's capital city, Adelaide, have been described as 'one great big outdoor museum' by Antarctic explorer Sir Douglas Mawson, one of Australia's most distinguished geologists.

The outstanding geological values in the Flinders Ranges share a common origin in a single, depositional system that existed for more than 300 million years – this system is described in this report as the 'Adelaide Rift Complex'. These sedimentary rocks are the repository of a record of Earth and life history from the Neoproterozoic to the Cambrian (approximately 830–500 million years ago) that includes major changes in the Earth's physical environment and key evolutionary events in the emergence of animal life. There is no other place on Earth where such an extensive record, and especially the emergence of animal life, is so well preserved in a near-continuous succession and in such compact, easily-accessible and well-presented settings.

The geo-historical record does not end with the last Cambrian sedimentary rocks, for the Adelaide Rift Complex was then subject to a mountain-building event, the Delamerian Orogeny, in the middle to late part of the Cambrian period, producing the pattern of folded strata of the Flinders Ranges so clearly visible on satellite imagery. In the north-eastern part of the Flinders Ranges (Arkaroola), there is an additional record of both older (Mesoproterozoic, approximately 1,590–1,550 million years old) basement rocks that form the floor of the Adelaide Rift Complex deposits, and younger (Ordovician to Devonian, approximately 440–360 million years old) tectonic, igneous, hydrothermal and mineralising events. Many of these events resulted from the heating effects of natural radioactivity of the buried granitic basement rocks and produced geological phenomena not found anywhere else on Earth. These heating effects persist to the present day as exemplified by the Paralana Hot Springs of Arkaroola.

The geology in the Flinders Ranges provides a record of the rotation of planet Earth and lunar cycles during the Precambrian, the Earth's changing ancient ocean water chemistries, atmospheric composition and conditions, and varying sedimentary environments and depositionary conditions, including extreme glacial conditions possibly of near-global extent (sometimes referred to as 'Snowball Earth'). The Flinders Ranges also contains the Global Stratotype Section and Point (GSSP) for the Ediacaran System/Period, the period during which the first large soft-bodied animals evolved, leaving fossil impressions on sandstone beds of the Pound Subgroup of the Flinders Ranges. This is the only GSSP in the southern hemisphere.

The outstanding geology in the Flinders Ranges includes evidence of oscillating extreme Precambrian (cold and non-cold) climates at Earth's equator; the presence of single-cell life forms; the emergence of pre-Ediacaran enigmatic first animal life forms at Arkaroola Reef; and an Ediacaran 'explosion of life' demonstrated by an exceptional fossil site at Nilpena. It also demonstrates the emergence, at the onset of the Cambrian period, of Cambrian animals and predatory behaviour; and rich evidence of the Cambrian 'explosion of life', including outstanding archaeocyatha reef systems and the oldest known corals within restructured marine ecosystems.

For much of the Flinders Ranges, the strata of the Adelaide Rift Complex have been only mildly folded, with gentle to moderate dips. Subsequent erosion of the fold structures has revealed near-continuous sections through these strata, such that they can be studied in succession, like the pages in a book. This accessibility to 330 million years of Earth's recorded history, along with the arid inland location and its minimal vegetation cover and exposed rock surfaces, has provided geologists and others with exceptional opportunities to research Earth's ancient past. No other site on Earth can match this exemplary location.

Figure 1 shows some of the sites in the Flinders Ranges that contain these outstanding geological features of potential World Heritage value.

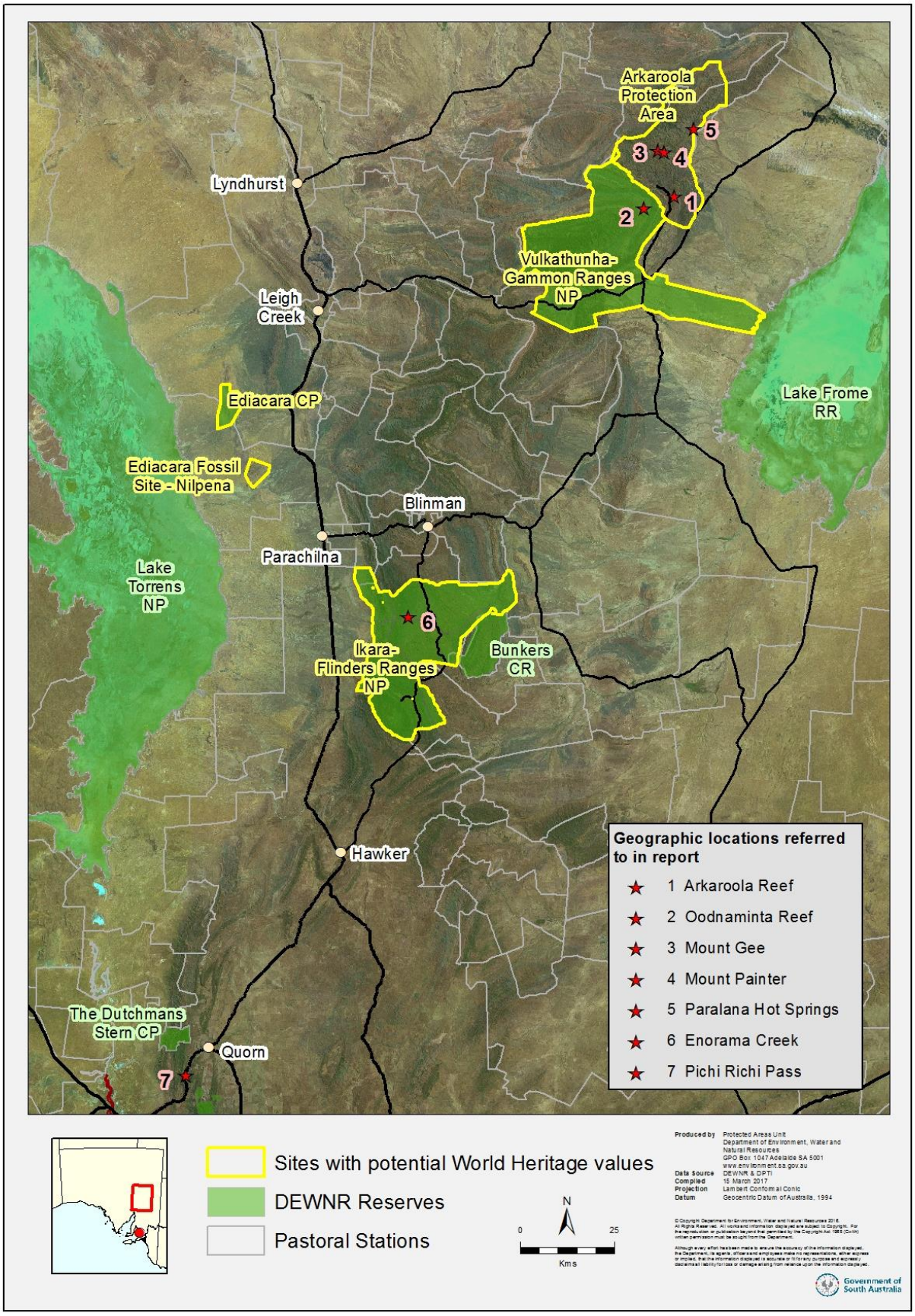

Figure 1 Sites in the Flinders Ranges with potential World Heritage values (subject to further investigation)

2 THE DAWN OF ANIMAL LIFE

Four evolutionary events

The Flinders Ranges' near-continuous rock successions span the 'Dawn of Animal Life on Earth' in ancient marine environments and record, in one depositional setting, four evolutionary events of global significance:

1. Examples of some of the earliest evidence of macroscopic life forms on Earth, which are found as reef-building organisms of uncertain affinities in a carbonate formation of about 650–640 million years old at Arkaroola and Oodnaminta Reefs.
2. The world's finest example of the Ediacaran 'explosion of life' during the Ediacaran period (635–541 million years ago) at the National Heritage Listed Ediacara Fossil Site at Nilpena, where more than 80 morphologically different life forms representing fossils from the four major Ediacaran fossil assemblages known worldwide have been identified.
3. Records of the emergence of key animal life forms, many with the first mineralised skeletal elements and external tubes, which transformed sea floor habitats and the survivorship of other species at multiple sites where early Cambrian sediments were deposited, unconformably upon Ediacaran strata following a short period of erosion.
4. Evidence in early Cambrian strata of the Cambrian 'explosion of life' (between about 530 and 510 million years ago), including archaeocyatha framework reefs on various scales; and the earliest corals (coralomorphs) on Earth.

These four evolutionary events in the 'Dawn of Animal Life on Earth' are illustrated graphically in Figure 2. (The significant features and events depicted in Figure 2, as well as other significant features and events mentioned through Sections 2 and 3 of this report, are presented in a simplified stratigraphic table for the Flinders Ranges – see Appendix 1.)

Single-celled life forms

Life in the form of single-celled organisms has existed on Earth for at least 3.7 billion years and has survived through dramatic changes of the Earth's oceans and atmosphere. This is evidenced by the widespread occurrence of Precambrian stromatolites, which are usually neatly laminated, domed or columnar organo-sedimentary structures produced by the life activities of single-celled organisms such as cyanobacteria, and by rarer occurrences of microfossils preserved in resistant rocks such as chert. These life forms are present throughout the Flinders Ranges, and include a record of diverse stromatolites, both before and after the onset of glaciation (Figure 2), and microfossils preserved in black cherts. Outstanding (exemplar) stromatolite bioherms (mound-like groupings of stromatolites) were developed in the Flinders Ranges in pre-glacial and interglacial warm periods (about 800–700 and 650–640 million years ago respectively) in environments that preceded the evolution of complex animal life. The stromatolites were, however, influenced by animal life once these complex life forms evolved. The Flinders Ranges sedimentary successions show this change dramatically. A 'short walk' up-section across the Precambrian-Cambrian boundary demonstrates the influence of burrowing and scavenging by animals in the Cambrian. Where there had been no disturbance in the Precambrian, the bioturbation of sedimentary layers by Cambrian animals changed the nature of the stromatolite organo-sedimentary structures that included the development of large columnar structures known as 'thrombolites' that show regular disturbance by animals as the stromatolites developed.

Arkaroola and Oodnaminta Reefs

Some of the best preserved and (now) best documented Neoproterozoic barrier reefs (650–640 million years old) found on Earth were formed in the Adelaide Rift Complex with the warming of the oceans, and are particularly well-represented within the Balcanoona Formation at the Arkaroola and Oodnaminta Reefs in the northern Flinders Ranges (Figure 1). This was immediately after the Sturtian glaciation – perhaps one of the most severe glaciations in Earth's history (Figure 2). These reefs are an outstanding feature of the region's geological values, as are the associated ancient fossils they preserve.

On the fore-reef, deep below the influence of waves, macroscopic life forms (some of the oldest on Earth) were associated with the reef framework. These enigmatic sponge-like fossils may also be the earliest animal life known on Earth and pre-date the well-known Ediacara biota by almost 100 million years. "*Whatever their affinity, we suggest these structures record a significant evolutionary event on the path to organic complexity*" (Professor Malcolm William Wallace and colleagues, 2014). The reef structure reflects inorganic precipitation of carbonate as well as the presence of stromatolites, especially in the shallow lagoon/shore-side area of the reef structure.

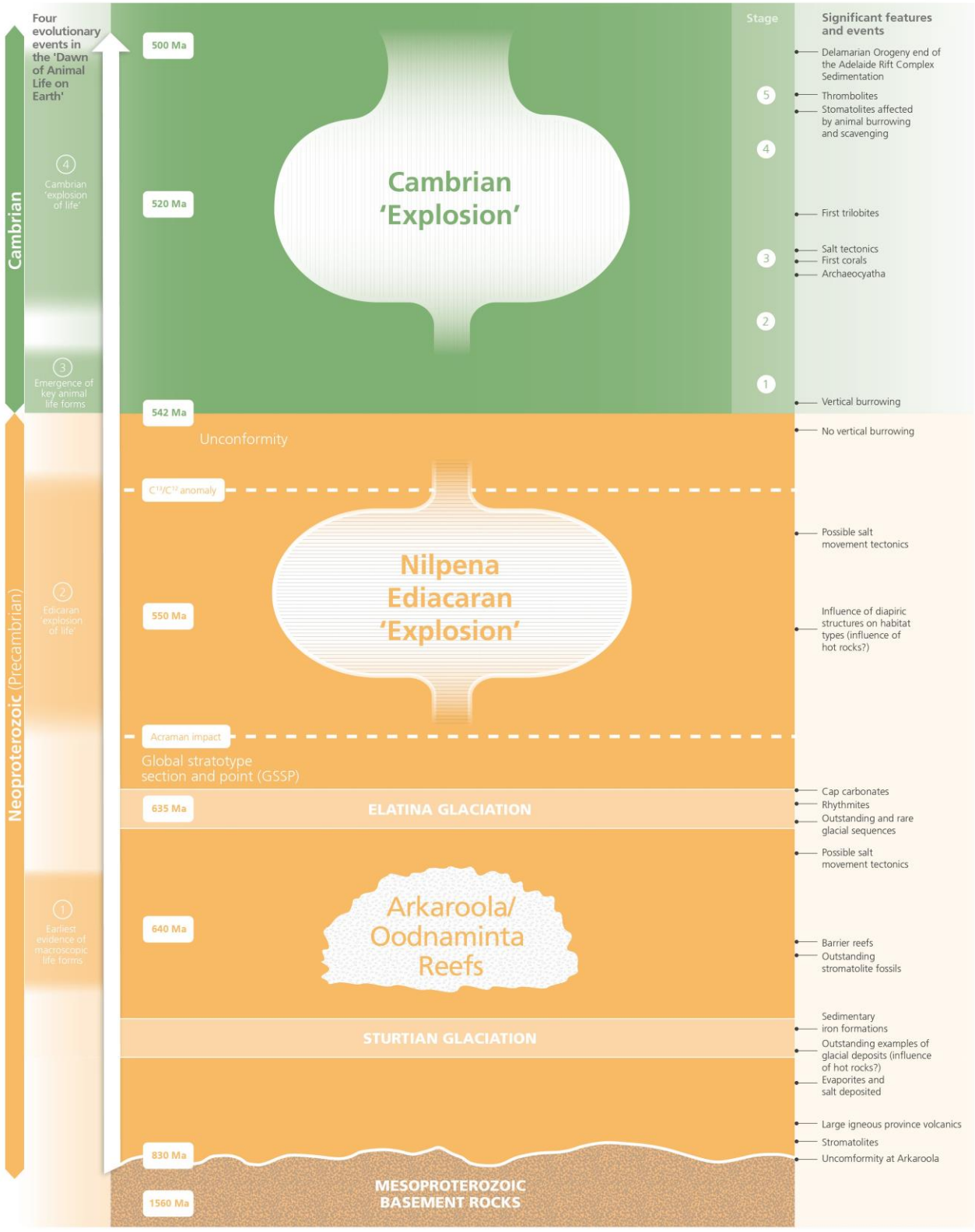

Figure 2 Visual representation of the Flinders Ranges depositional succession spanning 330 million years

Elatina glaciation

After 'the warming' that followed the Sturtian glaciation, the Adelaide Rift Complex succession records further environmental changes with the first South Australian appearance of widespread oxidised, red-coloured sediments (redbeds); a second severe glaciation event (the Elatina glaciation about 635 million years ago) and the disappearance from the fossil record of the enigmatic reef life forms (Figure 2).

The Elatina Formation varies in composition within the Flinders Ranges. Although it is mostly reddish sandstone, in some locations it contains a glacial diamictite (rock that includes poorly sorted particles) that includes rock clasts of diverse size and composition. In other sites, the contained rock fragments were likely to be derived locally. This rock unit also preserves evidence (in the form of tidal rhythmites) of a protracted record of tidal sedimentation within the Adelaide Rift Complex and evidence (in the form of frost wedges and brecciation) of a seasonal freeze-thaw cycle in its shoreline that extends west of the Flinders Ranges.

The wide extent of the Elatina Formation across the Adelaide Rift Complex rules out local land-based glaciers. Rather, as with the Sturtian glaciation, the Elatina event represents melting of sea ice close to the equator. The palaeomagnetic record (an analysis of the orientation of deposited particles during sedimentation) demonstrates that ice was melting within 15 degrees of the equator.

The Elatina glaciation evidence of the Flinders Ranges provides arguably the best documented evidence of protracted sedimentation of an ice age within low latitudes anywhere on Earth.

Ediacaran Global Stratotype Section and Point (GSSP)

The end of the Elatina glaciation marks the end of the Cryogenian geological period and the beginning of the Ediacaran geological period. The location of the Ediacaran Global Stratotype Section and Point (GSSP) was selected, after 14 years of work, by the International Commission on Stratigraphy Working Group on the Terminal Proterozoic Period ('Terminal Proterozoic' was the provisional name for the Ediacaran period). The GSSP site is located at Enorama Creek in the heart of the Ikara-Flinders Ranges National Park. The Ediacaran GSSP was ratified in 2004 by the International Union of Geological Sciences and was the first new global System and Period to be defined in more than a century, the first in the southern hemisphere and one of fewer than 70 in the world. The GSSP site at Enorama Creek is of global significance. It contains assemblages of Ediacaran fossils (580–542 million years old) that are characteristic of this time period, which are also found at the Ediacara Conservation Park, the National Heritage Listed Ediacara Fossil Site at Nilpena and other outstanding Flinders Ranges localities. Ediacaran geological sequences are found worldwide, including locations at the Mistaken Point World Heritage Property (Canada), the White Sea (Russia), Charnwood Forest (United Kingdom) and Namibia.

Ediacaran 'explosion of life'

In 1946, Australian geologist Reginald Sprigg AO discovered ancient fossils near the Ediacara Hills while investigating the Ediacara Mineral Field for the Geological Survey of South Australia. He (along with palaeontologist Martin Glaessner) recognised the stratigraphic importance of the fossils. Sprigg's historically important discovery site is now protected by the Ediacara Conservation Park.

At the nearby National Heritage Listed Ediacara Fossil Site at Nilpena, a large-scale excavation and field laboratory has been established. Nilpena presents the world's finest evidence of the extraordinary Ediacaran 'explosion of life' forms at about 550 million years ago. The exceptional preservation, diversity of life forms, palaeoecological complexity and range of ancient environments underpin the global status of this exemplar site. There is no other equivalent site on Earth. *"It's Earth's oldest animal ecosystem and Australia has the best record"* (Professor Mary Droser, ABC TV interview, *Landline*, August 2013).

The Ediacaran depositional environments can be categorised into five 'facies' (Figure 3):

1. Shoreface Sands
2. Wave-base Sands
3. Delta-front Sands
4. Sheet-flow Sands in deeper water
5. Mass-flow Sands in submarine canyons.

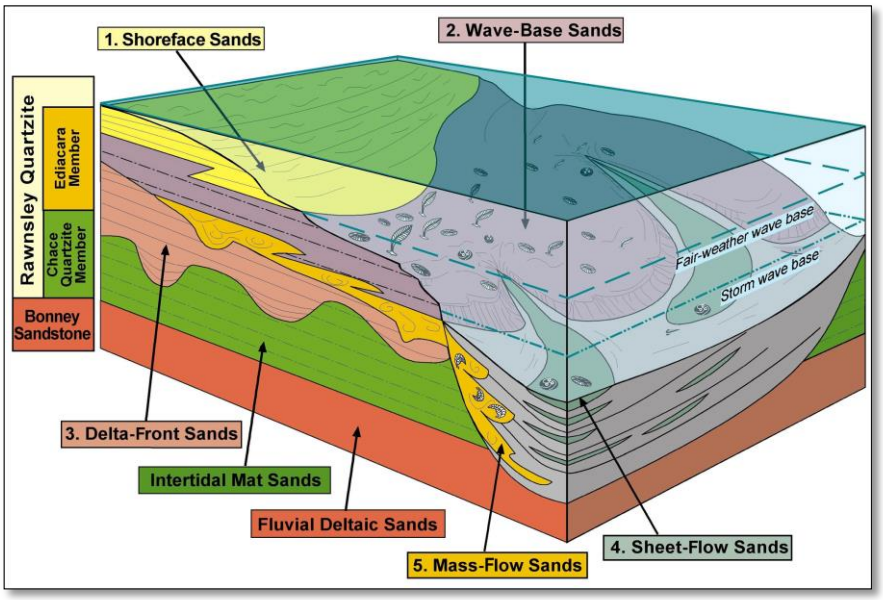

Figure 3 Late Ediacaran depositional environments (Source: Jim Gehling)

At Nilpena, researchers have recorded more than 80 distinctive life forms (within 15 taxa) in four of these depositional environments (Figure 4). (Being within the active wave zone, the Shoreface Sands depositional environment would have been too high energy to preserve the life forms present within it, hence none have been identified within that 'facies'.)

TAXA / FACIES	*Dickinsonia*	*Charniodiscus*	*Parvancorina*	*Tribrachidium*	*Rugoconites*	*Spriggina*	*Kimberella*	*Helminthoid ichnites*	*Charnia*	Plumose Rangiomorphs	*Rangea*	*Archaeichnium*	*Pteridinium*	*Nasepia*	*Palaeopasc-ichnus*
Fair-weather to Storm Wavebase	■	■	■	■	■	■	■	■							■
Delta Front	■	■	■	■	■	■	■	■	■	■	■	■			
Sheet Sands	■	■	■	■	■			■	■						
Canyon Fill	■	■								■		■	■	■	

Figure 4 Ediacara fossil assemblages at Nilpena (Source: Jim Gehling)

[Note: The facies listed here correspond to depositional environments 2, 3, 4 and 5 listed in the text above and shown in Figure 3.]

The Ediacaran fossils at Nilpena are recognised as an exemplar record of one of the greatest bursts in the evolution of life on Earth. While many of these organisms, which occupied late Ediacaran seafloors, do not appear in the Cambrian fossil record, 10 million years later, their success is measured by the fact that many species are known from other Ediacaran sites in Namibia, north-west Russia, south China, north-west Canada and Newfoundland, which at this time were fragments of continents spanning both hemispheres. By any measure, the Ediacara biota were an evolutionary success. While almost all the large-sized taxa are missing from the Cambrian record, the diminutive forms, such as *Spriggina*, and the tiny cryptic trace makers living in Ediacaran mat-grounds likely spawned Cambrian descendants.

In recent times, the reinvestigation of the discovery sites in the Ediacara Conservation Park, 30 kilometres north of the National Heritage Listed Ediacara Fossil Site at Nilpena, has demonstrated the presence of fossil beds preserving small-

scale Ediacaran species in exquisite detail. Through techniques previously unavailable, researchers have been able to prepare excavated fossil beds and reveal organisms at millimetric scale preserved in life positions on the sandstone moulds of seafloor communities.

A reassessment of Ediacaran fossil sites throughout the Flinders Ranges in 2016 is demonstrating a wealth of new material that preserves in situ seafloor assemblages. The sites represent the preservation of a complexity of recognisable body fossils at scales from 2 millimetres to more than 200 millimetres. The fossils are preserved in association with microbial mat textured surfaces. These fossil beds were preserved, once smothered, by very rapid silicification.

The extraordinary preservation of the Ediacaran sequences at Nilpena (550 million years old) provides evidence of life forms from a range of palaeoenvironments (Figure 3), as well as important palaeoenvironmental and palaeoecological information. This rich Ediacaran fossil assemblage complements (not duplicates) other important global Ediacaran sites. Nilpena includes (in greater diversity) Ediacaran life forms known from the older and deeper-water settings of the World Heritage Listed Mistaken Point assemblage in Canada (565 million years old). The Nilpena sequences also include the life forms found in younger Namibian sequences (545 million years old) and their rich 550 million year old assemblages that have made the site famous. Similar-aged White Sea assemblages in Russia are known but are less accessible and not as well preserved. The suite of Ediacaran fossils found at Nilpena are the most globally diverse known, representing elements from all four recognised Ediacaran fossil assemblages in the terminal Ediacaran. (Types of Ediacaran life forms identified for Nilpena and other key locations around the world have been presented – see Appendix 1.)

Newly-discovered bilaterian Ediacara fauna at Nilpena may also provide one answer to 'Darwin's dilemma' – the apparent too-rapid emergence of life forms in the Cambrian.

Photo 2 Sir David Attenborough and Dr Jim Gehling at Nilpena, BBC "First Life" production (Source: Jim Gehling collection)

Figure 5 Artist's impression of Dickinsonia*, one of the first mobile animals (Source: Atlantic Productions)*

Cambrian 'explosion of life'

The highly accessible and well-presented Flinders Ranges strata permit researchers and visitors to move through the history of the Precambrian geological sequences into the Cambrian sequences with ease. Such a complete sedimentary- and fossil-rich succession in one geological setting is not found anywhere else on Earth. In some locations in the Flinders Ranges, the boundary between these important time intervals may easily be straddled with a single step. Australian geologist and Antarctic explorer Sir Douglas Mawson was one who mapped these Neoproterozoic and Cambrian rocks, and some of his cross-sections were reproduced on an (historic) Australian $100 bank note (Figure 6).

Figure 6 Flinders Ranges geological cross-sections famously depicted on an (historic) Australian $100 bank note (Source: Web Commons).

[Featuring geologist and Antarctic explorer Sir Douglas Mawson.]

The Flinders Ranges Cambrian successions record important changes, including the emergence of burrowing animals, at the (unconformable) Precambrian-Cambrian boundary (Figure 7). During the early Cambrian, some of the earliest archaeocyatha reefs and the first record of early corals on Earth emerged in the Adelaide Rift Complex. This Cambrian 'explosion of life' is well represented in the Flinders Ranges successions.

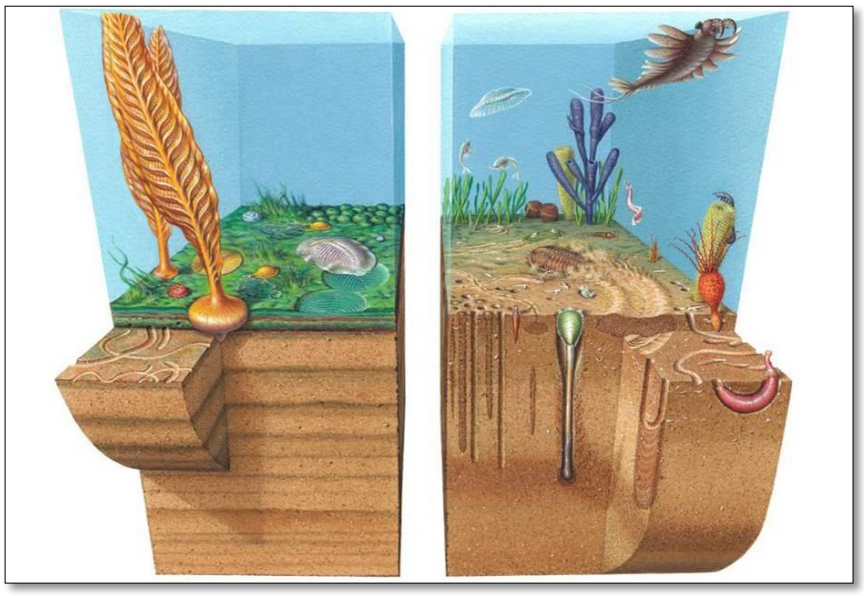

Figure 7 Ediacaran (550 million year old) microbial mat community (Left); Cambrian (approximately 520 million year old) animal community (Right) (Source: Peter Trusler)

[Note: This evolutionary transition of marine life can be readily seen in the Flinders Ranges geological successions.]

The Flinders Ranges Cambrian fauna complement (that is, they do not duplicate) the younger Cambrian life forms of the Canadian Burgess Shale World Heritage Property (508 million years old) and the older fossils of the Chinese Chengjiang World Heritage Property. The Flinders Ranges archaeocyatha reefs, early tabulate corals and some shelly fossils were preserved in shallower waters and, when aggregated, this rich suite of animals provides a remarkable record of the Cambrian 'explosion of life' from a variety of marine settings. The Flinders Ranges fossils are older than the Burgess Shale fossils (which were preserved in deeper, oxygen-poor sediments some distance from shore (and that include exceptional preservation of flattened fossils in shale)) and they complement the fossils found in China's slightly older Chengjiang deep-water deposits.

3 NATURAL RADIOACTIVE HEAT PHENOMENA

Flinders Ranges Mesoproterozoic basement rocks

In addition to the record of the emergence of animal life, the Adelaide Rift Complex succession of the Flinders Ranges records many extraordinary physical and chemical geological processes of global significance. At Arkaroola in the north-east of the Flinders Ranges (Figure 1), the basement core of a regional anticline has been exposed by erosion. This is not seen anywhere else in the Flinders Ranges. Here, the oldest known formations comprise metamorphosed sedimentary rocks known as the Radium Creek Group. These ancient rocks are not seen anywhere else in the Flinders Ranges. Molten magmas intruded them between 1,580 and 1,550 million years ago, cooling to form bodies of granite. Many of the granites, such as the Mount Neill Granite, were naturally rich in minerals containing radioactive potassium, uranium and thorium. These radioactive elements decayed over long periods of time, forming new daughter elements and generating radioactive heat and radon gas in the process. When layers of strata of the Adelaide Rift Complex were deposited successively upon these basement rocks in the Neoproterozoic and Cambrian (830–500 million years ago), they acted as an insulating blanket and trapped heat to form a 'super-heated rock' or 'hot rock' environment.

There were multiple consequences and phenomena generated that are not known anywhere else on Earth, including:

- the only known melting of sedimentary rocks (Radium Creek Group) thought by most geologists to be caused by radiogenic heat [some other geologists have suggested a magmatic origin as well for the heat source] to form a new granite body, The British Empire Granite (approximately 440 million years ago);
- a rare, large, naturally-occurring subterranean fracturing ('explosion') that brecciated the Mesoproterozoic granites and sediments over an area of 10 square kilometres;
- potentially the longest-lived intra-continental epithermal system known on Earth with its associated fossil geyser and hot pool deposits and an underlying epithermal plumbing system [Subject to further specific research, this system may have commenced during the mid-Palaeozoic with one of its latest phases being the Permian or younger, thus identifying it may be the longest-lived epithermal system known. There is no doubt that the radiogenically-heated meteoric waters have contributed to the system for a time span that far exceeds the 'norm' for a magmatic/volcanically-driven system.];
- the 'crystal mountain', Mount Gee (Figure 1) – the only known naturally-exposed three-dimensional surface expression of a radiogenically-heated epithermal plumbing system on Earth [Note: Relatively recently, exploratory work concluded that phases of the Mount Gee Sinter contained anomalous amounts of the elements indicative of "significant magmatic component". If this work is confirmed then consideration of the system being both a magmatic and radiogenically heat driven system will be encompassed.]; and
- the Paralana Hot Springs (Figure 1) (which are active at the present time) resulting from continued radiogenic heating of groundwater and its escape within the Paralana Fault Zone.

Geologists from all around the world visit Arkaroola to study these unique 'hot rock' phenomena.

Melting of rocks – the British Empire Granite

At about 830 million years ago, tectonic activity caused the Earth's crust to pull apart to form a series of rift basins (the Adelaide Rift Complex) with uncommon radioactive decay-heated rocks as basement rocks. As layers of strata were placed on top of these basement rocks, they acted as an insulating blanket and trapped heat to form a 'hot' environment. Metamorphism occurred to the order of 500°C but deeper in the crust, temperatures were even higher and rocks were heated to 750°C. Researchers advise that this resulted in the melting of the Mesoproterozoic sediments to form a new granite body, the S-type British Empire Granite and an I-type granite (granodiorite), approximately 440 million years ago. This is the only recorded occurrence on Earth where radiogenic heat has melted surrounding rocks to form a new granite body (Figure 8). [Note: Some geologists consider that there may have been a magmatic heat source in addition to the radiogenic heat.]

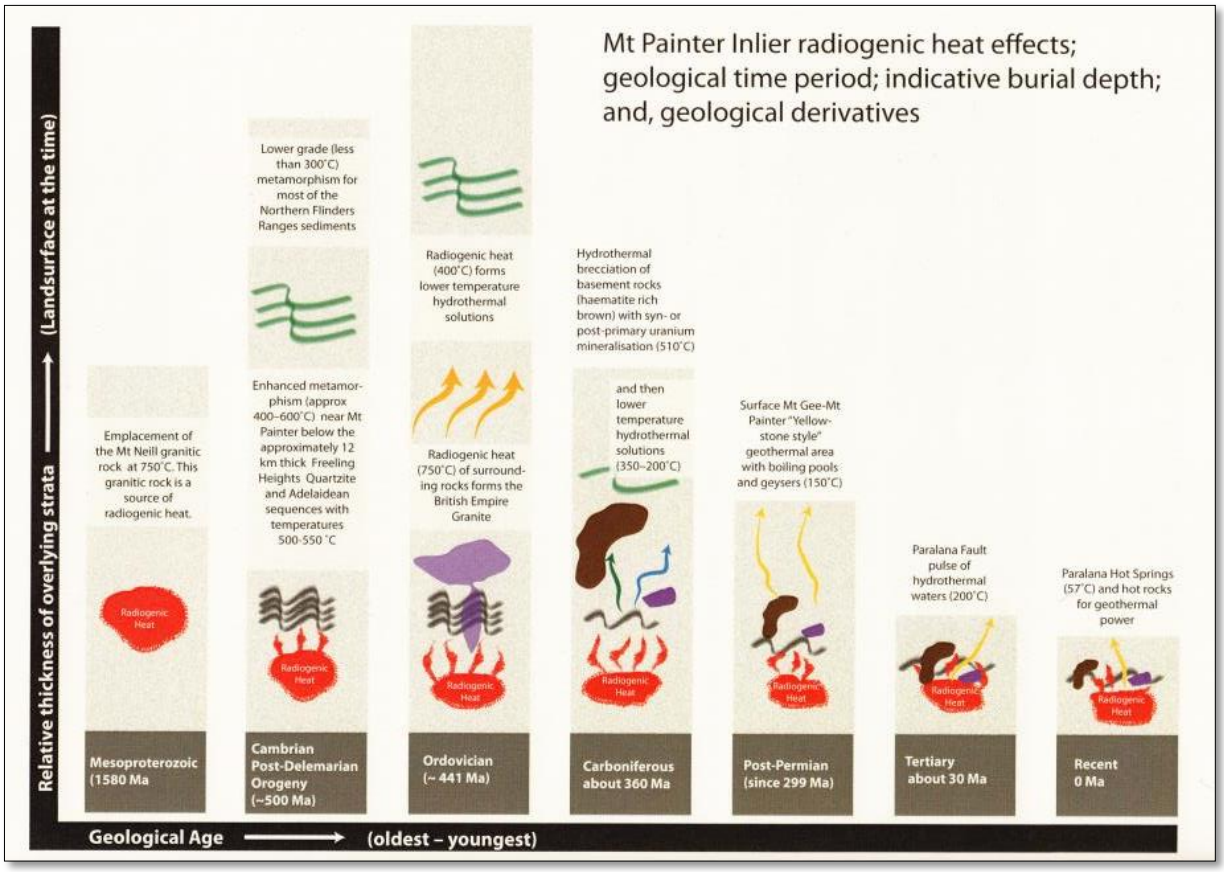

Figure 8 Radiogenic heat-generated geological phenomena, Arkaroola, northern Flinders Ranges

Subterranean 'explosion' and uranium mineralisation

This radiogenically-sourced deep-seated heat was to have further effects with time (Figure 9). During the mid to late Palaeozoic, ongoing processes of folding, rifting, uplift and erosion allowed water to ingress deep into the extremely hot basement underlying the Adelaide Rift Complex. One spectacular result was a massive fracturing ('explosion'), which possibly occurred around 440 million years ago but prior to around 360 million years ago; it generated a breccia from the Mesoproterozoic sediments and granitic bodies that extends 1 kilometre by 10 kilometres in area across localities within Arkaroola from Radium Ridge and Mount Gee north-easterly to Paralana Hot Springs. This near-surface expression of a deep-seated natural subterranean explosion is studied by geologists from around the world, for such a phenomenon is very rare and usually only known from drill cores. Radiogenically-heated rocks and water penetrating deep into and below the Rift Complex and its basement interacted for a very long time in the Flinders Ranges. One result was hot-fluid uranium mineralisation of the brecciated material around 360 million years ago (Figure 8).

Geysers, hot pools and hot springs

Superheated ground waters generated geysers and hot pools over a prolonged period when this water came to the surface from time to time, driven by continuing radiogenic heat emitted by the basement rocks. It has generated a fossil geothermal site at Arkaroola with epithermal deposits formed from geysers, boiling mud pools and a dynamic surface depositional environment (Figure 9). Preliminary estimates identify that this geothermal/epithermal feature may have existed for 260 million years, but further research work is being undertaken. Paralana Hot Springs, at Arkaroola, still bubbles radon gas and hot water (57°C) to the surface and provides evidence for the continuation of this activity. This may represent an active example of the longest duration (260 million year) geothermal area known on Earth.

One of the 'epithermal features' is the remarkable and unique 'crystal mountain' of Arkaroola, Mount Gee. It is the only known naturally-exposed three-dimensional surface expression of an epithermal plumbing system on Earth (Photo 3).

The Paralana Hot Springs are the only remaining active hot springs and are found within the Paralana Fault Zone near the eastern boundary of Arkaroola. The hot springs discharge water at 16 litres per second and at 57°C. The springs have been studied as an analogue for early life and microbial adaptation to extreme temperatures and radioactivity levels.

Figure 9 Artist's impression of geysers at Mount Painter, Arkaroola, during the late Permian (Source: Andrew Plant)

[Note: Australia was in southern latitudes near the South Pole.]

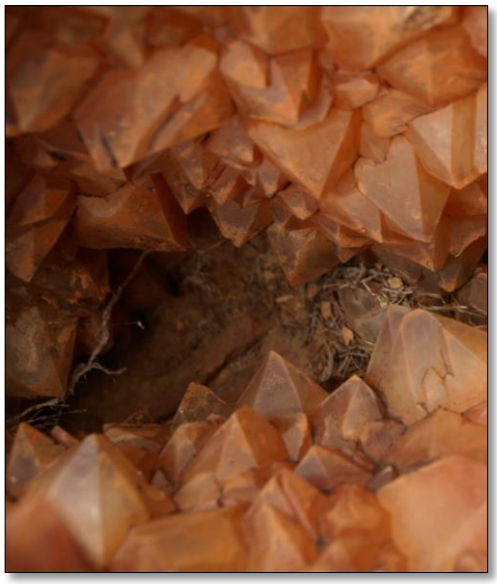

Photo 3 Quartz crystal-lined cavity, Mount Gee, part of this mountain's fossil epithermal cavernous and interconnected plumbing system that transported hot fluids to the surface (Source: Graeme L. Worboys)

4 OTHER ADELAIDE RIFT COMPLEX CONSIDERATIONS

The Flinders Ranges (Adelaide Rift Complex) provides tantalising insights into a range of geological phenomena. The possible connection between individual phenomena and recorded events foreshadows potential for ongoing research in the Flinders Ranges. Some considerations are described here.

Rift volcanics – possible influence on glaciation

Initiation of the Adelaide Rift Complex at 830 million years ago included stretching of the Earth's crust and decompression melting in the upper mantle, with the resulting basalt magmas being poured out over a wide area of eastern South Australia (including Arkaroola) and western New South Wales. The weathering of basalt, where exposed at the Earth's surface, consumes carbon dioxide from the atmosphere and this has been suggested to be one of the factors causing global cooling during the Neoproterozoic. Glaciation, however, occurred a long time after the eruption of the basalts.

Diapirs – potential influence on intra-rift tectonism

Following the initiation of rifting, thick piles of sandy, silty carbonate (eg limestone and dolostone) and evaporite (salt and gypsum) sediments accumulated in shallow seas and lakes. Over most of the Flinders Ranges, these sediments were later deeply buried beneath younger deposits. However, gravitational instability and the mobility of the less dense evaporite minerals under pressure caused disruption and upward movement of these rocks. The material pushed up into overlying younger rocks to form the diapirs of the Flinders Ranges. Intrusion of diapirs occurred episodically over the long period of time during which sediments of the Adelaide Rift Complex were deposited, influencing structural development and patterns and thicknesses of sedimentation. Such effects, often termed 'salt tectonics', are common in many petroleum-bearing basins where they have been imaged on seismic sections, but outcrop examples such as are displayed by many cross-sections of different orientations in the Flinders Ranges are very rare. For this reason, the Flinders Ranges are visited by international geoscientists in order to better understand petroleum reservoirs. Further movement of diapirs took place during the Delamerian Orogeny, after sedimentation had ceased.

Rhythmites

At several outcrop sections of the Elatina period of glaciation evidenced by the Elatina Formation, very fine-grained reddish sandstone contains thin, rhythmic laminations that have been interpreted as tidal cycles in ebb-tide deltas. The best-studied site is in Pichi Richi Pass (Figure 1), where cycles representing a 60-year period with strongly seasonal climate have been measured. In addition, magnetic measurements on the fine-grained haematite in samples of this sandstone with known orientation have determined that this site was in the northern hemisphere close to the equator at the time of the Elatina glaciation. There are competing hypotheses to account for such low-latitude glaciation. The information from these rocks also helps identify the rotation speed of Earth during the Neoproterozoic (it was faster than today).

Acraman asteroid impact

The Acraman asteroid impact event was an extra-terrestrial imposition on the Flinders Ranges (and beyond) at about 580 million years ago. A single layer of debris in red mudstone (the Bunyeroo Formation) is found in locations across the Flinders Ranges. It has been linked to a circular area of shattered rock underlying Lake Acraman in the Gawler Ranges (approximately 300 kilometres to the west) where an asteroid or similar body is interpreted to have collided with the Earth, sending debris of the 1,590 million year old Gawler Range Volcanics high into the atmosphere. These fragments, ranging in size from sand grains to cobbles, then landed on the muddy sea floor and became incorporated into the Bunyeroo Formation at about 580 million years ago. Scientists have identified a marked change in single-celled organisms preserved locally in the sediments before and after the impact.

Canyons and habitats for life forms

Major kilometre-deep canyons were cut into the younger sediments of the Adelaide Rift Complex at several times during the Ediacaran and, possibly, the early Cambrian. The earliest canyons were incised into calcareous siltstone, sandstone and limestone of the Wonoka Formation that overlies the Bunyeroo Formation. Some canyons have cut down through

almost the whole underlying Ediacaran succession. The method of incision has been much debated, the main competing hypotheses being:

- submarine mass-wasting similar to that occurring in modern submarine canyons on many continental shelves; and
- terrestrial erosion after complete evaporation of sea water in a restricted marine basin similar to the Mediterranean Sea during Miocene times.

Various lines of evidence can be mustered to support both hypotheses and additional research is required. The canyons in the Ediacara Member of the geological formation known as the Rawnsley Quartzite (the youngest Ediacaran formation) were not incised as deeply (approximately 250 metres) but provided the environment in which the Ediacara biota were preserved. The Uratanna Formation, the oldest formation related to the early Cambrian marine transgression, occupies similar canyons incised into the Rawnsley Quartzite.

Some scientists consider that there could be a link between the deeply buried, radiogenically-heated and unstable rocks, the mobilisation of diapiric rocks and the canyons (and habitats for life) developed during Ediacaran times.

5 CRITERION (VIII) CONSIDERATIONS

The dawn of animal life

The Adelaide Rift Complex provides an enormous and relatively continuous record of marine environments, in both stratigraphic thickness and area of exposure, spanning a key interval in the history of life on Earth that is unequalled in its exposure, documentation (geological maps and papers), accessibility and geological preservation (lack of major deformation and later alteration) anywhere on Earth. Spanning 330 million years of Earth's history, the Adelaide Rift Complex includes the best documented and possibly the most protracted ice ages in Earth's history together with a globally-famous fossil record of the critical interval that saw multicellular organisms evolve after a long history of microbial life. This rock record in the Flinders Ranges was chosen as the best site on Earth to establish the 'golden spike' marking the base of a new geological time period: the Ediacaran Period. It marks the onset of the Ediacaran revolution in the size of diversity of organisms and the complexity of ecological interactions, followed by further expansion of ecosystems in the early Cambrian, with the rise of skeletal animals and an accelerating increase in the complexity of marine life.

Nowhere else on our planet can one, in a single sedimentary succession:

- walk through successive layers of sedimentary rock representing ancient, pre-animal life to the Ediacaran 'explosion of life' and then the Cambrian 'explosion of life';
- observe evidence of early life forms in some of the best-documented and best-preserved exposures on Earth;
- understand the environmental context and setting of these early life forms;
- straddle the Precambrian-Cambrian boundary and compare the influence of animal life on either side of this boundary; and
- examine evidence of two of the great 'explosions of life' known for Earth, including the best known evidence of the Ediacaran 'explosion'.

The accessibility of these well-preserved evolutionary 'highlights' with their different depositional environments and their presentation in one unified geological succession are unrivalled.

Phenomena that complement World Heritage properties

The Adelaide Rift Complex record complements and enriches geological evidence of ancient life sourced from three existing outstanding World Heritage fossil site properties at Mistaken Point, Canada (deep marine macro-organisms); Chengjiang, China (some of the earliest, unequivocal body fossils of animals); and the Burgess Shale, Canada (a rich diversity of soft-bodied life forms).

The Adelaide Rift Complex of the Flinders Ranges:

- preserves life forms from palaeoenvironments very different from existing World Heritage properties;
- provides exceptional and continuous environmental, evolutionary and palaeoecological contextual information at the time of the emergence of animal life;
- includes macroscopic fossils in a spectacular preservational setting, which record evolution of animal life prior to the Ediacaran 'explosion';
- uniquely provides remarkable palaeoecological records for the Ediacaran 'explosion of life' and evidence for more than 80 life forms, Earth's richest-known assemblage of this age;
- provides an almost continuous stratigraphic record that demonstrates the rising influence of marine ecosystems in their palaeoenvironments and on other life forms over time; and
- records in shallow and near-shore waters the Cambrian 'explosion of life', including some of the first archaeocyatha reefs and the earliest known corals.

The Adelaide Rift Complex is the only setting on Earth where two ancient 'explosions of life' are found in one near-continuous stratigraphic succession.

Natural radioactive heat phenomena

The 'hot rocks' of Arkaroola form part of the basement to the Adelaide Rift Complex and have generated geological processes and landforms not found anywhere else on Earth. They owe their origin to the emplacement, at some 1,580 million years ago, of granitic rocks rich in radioactive potassium, uranium and thorium minerals and the generation of heat during the decay of these elements. Some influence of magmatic heat has also been suggested.

The unique (and uncommon) phenomena include:

- the research finding for radiogenic-heat melting of sediments to form the British Empire Granite at about 440 million years ago;
- a massive subterranean fracturing ('explosion') event that brecciated a 1 kilometre by 10 kilometre part of the basement rocks (pre-360 million years ago);
- a radiogenic heat-generated geothermal site evidenced by the British Empire Granite, the brecciation event and the Mount Gee plumbing system and geyser deposits that may have lasted for 400+ million years;
- Mount Gee, the only three-dimensional fossil exposure of an interconnected epithermal plumbing system caused by radiogenic heat (and possible magmatic heat) known for Earth; and
- Paralana Hot Springs, a modern example of the continued heating of subterranean waters by radiogenic heated 'hot rocks'.

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7 GLOSSARY

The following provides a select glossary (and list of abbreviations) for terminology used in this report.

Note: Definitions marked with an '*' are sourced from Jackson, J.A. (Ed) (1997) *Glossary of Geology*, Fourth Edition, American Geological Institute, Alexandria, Virginia.

Adelaide Rift Complex May also be known as the 'Adelaide Geosyncline' or 'Adelaide Fold Belt' or 'Adelaide Rift Belt'. The term 'Adelaide Rift Complex' has been adopted for this report but may change for a World Heritage nomination.

Archaeocyatha* Any marine organism belonging to the phylum Archaeocyatha and characterized chiefly by a cone-, goblet-, or vase-shaped skeleton composed of calcium carbonate.

Arkaroola Throughout this report, the term 'Arkaroola' and the features linked to that term refer to those located within the Arkaroola Protection Area. Located in the Northern Flinders Ranges, the Arkaroola Protection Area was established through special legislation, the *Arkaroola Protection Act 2012*. It encompasses the majority of the Arkaroola Pastoral Lease and a small portion of the Mount Freeling Pastoral Lease. Figure 1 shows the location of the Arkaroola Protection Area.

Benthic* Pertaining to the substrate or organisms living on or in the substrate; also, said of that environment.

Bilaterian An animal having bilateral symmetry. (https://www.merriam-webster.com/dictionary/bilaterian)

Bioherm* A moundlike, domelike, lenslike, or reeflike mass of rock built up by sedentary organisms (such as corals, algae, foraminifers, mollusks, gastropods, and stromatoporoids), composed almost exclusively of their calcareous remains, and enclosed or surrounded by rock of different lithology; eg an organic reef or a nonreef limestone mound.

Bioturbation* The churning and stirring of a sediment by organisms.

Breccia* A coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix; … the fragments have sharp edges and unworn corners. …

Brecciation* Formation of a breccia, as by crushing a rock into angular fragments.

Cambrian 'explosion'/Cambrian 'explosion of life' Also known as the 'Cambrian radiation'.

Criterion (viii) 'be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features' (see http://whc.unesco.org).

Deposition* (a) The laying, placing, or accumulation of any material; specif. the constructive process of accumulation into beds, veins, or irregular masses of any kind of loose rock material by any natural agent, such as the mechanical settling of a sediment from suspension in water, the chemical precipitation of mineral matter by evaporation from solution, or the accumulation of organic material on the death of plants and animals. (b) Material that is deposited; a deposit or sediment.

Depositional* (a) Pertaining to the process of deposition; eg a "depositional basin" or a "depositional surface". (b) Formed by the process of deposition; eg a "depositional topography".

Diamictite* A comprehensive, nongenetic term … for a nonsorted or poorly sorted, non-calcareous, terrigenous sedentary rock that contains a wide range of particle sizes, such as a rock with sand and/or larger particles in a muddy matrix; eg a tillite or a pebbly mudstone. …

Ediacaran 'explosion'/Ediacaran 'explosion of life' Also known as the 'Ediacara biota radiation event'.

Epithermal* Said of a hydrothermal mineral deposit formed within about 1 kilometer of the Earth's surface and in the temperature range of 50°-200°C, occurring mainly as veins. … Also, said of that environment.

Facies* (a) The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; esp. as differentiating the unit from adjacent or associated units. …

Frost wedge* A term used loosely for any ice wedge, whether in perennially or seasonally frozen ground or in fossil form; any wedge-shaped mass whose origin involves cold or freezing conditions.

Geothermal* Pertaining to the heat of the interior of the Earth. …

Geyser* A type of hot spring that intermittently erupts jets of hot water and steam, the result of ground water coming into contact with rock or steam hot enough to create steam under conditions preventing free circulation; a type of intermittent spring.

Glaciation* (a) The formation, movement, and recession of glaciers or ice sheets. (b) The covering of large land areas by glaciers or ice sheets. (c) The geographic distribution of glaciers and ice sheets. (d) A collective term for the geologic processes of glacial activity, including erosion and deposition, and the resulting effects of such action on the Earth's surface. (e) Any of several minor parts of geologic time during which glaciers were more extensive than at present; a glacial epoch, or a glacial stage. "A climatic episode during which extensive glaciers developed, attained a maximum extent, and receded". …

GSSP Global Stratotype Section and Point.

Metamorphism* The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions which have generally been imposed at depth below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated. …

Phyla* The plural of phylum.

Phylum* The primary taxonomic division of the animal kingdom, characterised by organisms that share a major type of body plan implying common ancestry. …

Radiogenic* Said of a product of radioactive decay process, eg heat, lead.

Rhythmite Layers of sediment or sedimentary rock that are laid down with an obvious periodicity and regularity. (https://en.wikipedia.org/wiki/Rhythmite)

Salt tectonics* Any tectonic deformation involving salt, or other evaporates, as a substratum or source layer … .

Sediment* (a) Solid fragmental material that originates from weathering of rocks and is transported or deposited by air, water, or ice, or that accumulates by other natural agents, such as chemical precipitation from solution or secretion by organisms, and that forms in layers on the Earth's surface at ordinary temperatures in a loose, unconsolidated form; eg sand, gravel, silt, mud, till, loess, alluvium. (b) Strictly, solid material that has settled down from a state of suspension in a liquid … .

Sedimentary* adj. (a) Pertaining to or containing sediment; eg a "sedimentary deposit" or a "sedimentary complex". (b) Formed by the deposition of a sediment (eg a "sedimentary clay"), or pertaining to the process of sedimentation (eg "sedimentary volcanism").—n. A sedimentary rock or deposit.

Sequence* (a) A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. … (d) A geographically discrete succession of major rock units that were deposited under related environmental conditions. … (e) In sequence stratigraphy, a relatively conformable succession of genetically related strata bounded by unconformitites or their correlative conformities. …

Silicification* A process of fossilization whereby the original organic components of an organism are replaced by silica, as quartz, chalcedony, or opal.

Stromatolite* An organosedimentary structure produced by sediment trapping, binding, and/or precipitation as a result of the growth of and metabolic activity of micro-organisms, principally cyanophytes (blue-green algae). It has a variety of gross forms, from nearly horizontal to markedly columnar, domal, or subspherical. …

Succession* (a) A number of rock units or a mass of strata that succeed one another in chronologic order; eg an inclusive stratigraphic sequence involving any number of stages, series, systems, or parts thereof, as shown graphically in a geologic column or seen in an exposed section. (b) The chronologic order of rock units.

Tabulate coral An extinct form of coral; almost always colonial, forming colonies of individual hexagonal cells known as corallites defined by a skeleton of calcite, similar in appearance to a honeycomb. Adjacent cells area joined by small pores. Their distinguishing feature is their well-developed horizontal internal partitions (tabulae) within each cell, but reduced or absent vertical internal partitions (septae). (https://en.wikipedia.org/wiki/Tabulata)

Thrombolite* A texture of nonlaminated carbonate bioherms characterized by vague clotting, thought to be caused by microbial activity.

8 1–2 AUGUST 'EXPERT WORKSHOP' PARTICIPANTS

(Top to bottom; Left to right)

Ms Felicity Coutts
Ms Marg Sprigg
Prof Jim Gehling
Assoc Prof Malcolm Wallace

Dr Mary-Anne Binnie
Mr Angus Robinson
Emer Prof Ian Plimer
Ms Lily Reid
Mr Justin Payne

Dr Peter Kruse
Prof Malcolm Walter

Dr Steve Hill

Mr Tony Magor
Mr James Holmes
Dr Rosemary Paull
Assoc Prof Victor Gostin

Mr Andrew Rowett
Dr Wolfgang Preiss
Mr Stephen Hore
Ms Liesl Garrett
Mr Matt Dzaugis

Mr Jason Irving
Mr Wayne Cowley
Dr Graeme Worboys
(Source: Josie Langrehr)

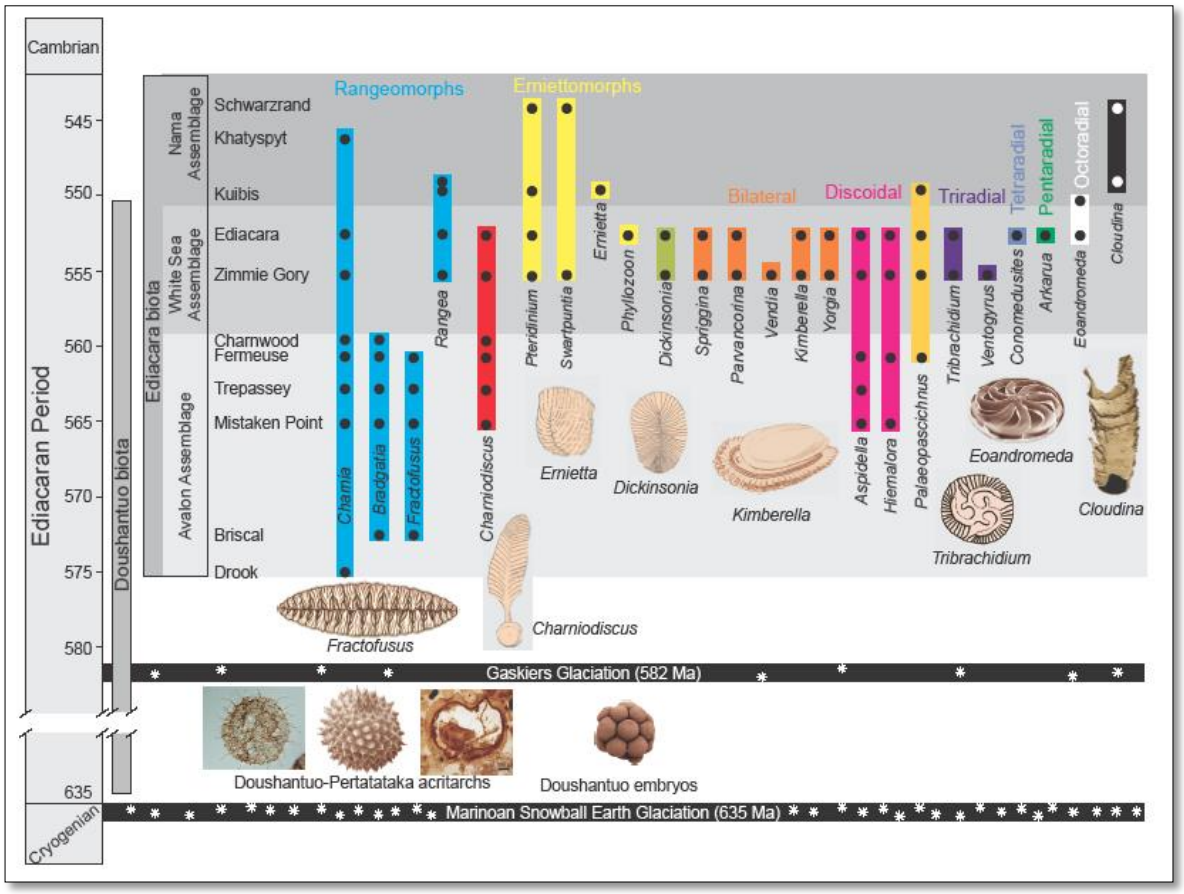
APPENDIX 1 SUPPORTING INFORMATION

Simplified stratigraphic table for the Flinders Ranges

AGE[1,2]	ROCK UNITS	SIGNIFICANT FEATURES AND EVENTS
≥260 Ma	Mount Gee Sinter	*Hydrothermal plumbing system*
~360 Ma	Radium Ridge Breccia	*Hydrothermal explosion*
~440 Ma	British Empire Granite	*Radiogenic heat causing melting (& possibly magmatic heat)*
~500 Ma		*Delamerian Orogeny*
EARLY CAMBRIAN	Lake Frome Group	*Redbeds*
	Wirrealpa Limestone	*Archaeocyatha, small shelly fossils, trilobites*
	Billy Creek Formation	*Redbeds, archaeocyatha, small shelly fossils, trilobites*
	Oraparinna Shale	*Archaeocyatha, small shelly fossils, trilobites*
	Mernmerna Formation	*Archaeocyatha, small shelly fossils, trilobites*
	Wilkawillina Limestone	*Archaeocyatha, small shelly fossils, trilobites*
	Parachilna Formation	*U-shaped burrows*
	Uratanna Formation	*Trace fossils*
~550 Ma	*major unconformity*	
EDIACARAN	Pound Subgroup	
	Rawnsley Quartzite	
	Ediacara Member	*Ediacara biota*
	Bonney Sandstone	
	Wonoka Formation	*Submarine or terrestrial canyons?*
	Bunyeroo Formation	*Asteroid impact*
	ABC Range Quartzite	
	Brachina Formation	
	Nuccaleena Formation	*Cap carbonates*
~635 Ma	*minor unconformity*	
	Elatina Formation	*Glaciation, tidal rhythmites, frost wedges, brecciation*
	Trezona Formation	*Stromatolites*
	Enorama Shale	
	Angepena Formation	*Redbeds*
	Balcanoona Formation	*Stromatolites; Arkaroola and Oodnaminta Reefs*
	Tapley Hill Formation	
~660 Ma	Sturt Tillite	*Glaciation, sedimentary ironstones*
	major unconformity	
~720 Ma	Burra Group	
	Belair Subgroup	
	Bungarider Subgroup	
~790 Ma	Skillogalee Dolomite	*Stromatolites, microfossils, sedimentary magnesite*
	Emeroo Subgroup	
	Callanna Group	
~800 Ma	Curdimurka Subgroup	*Evaporitic sediments*
~830 Ma	Arkaroola Subgroup	*Mafic volcanism*
	major unconformity	
~1,560 Ma	Granites, incl. Terrapinna Granite	*High heat-producing granites*
~1,580 Ma	Granites, incl. Mount Neill Granite	*High heat-producing granites*
~1,590 Ma	Radium Creek Group	*Metamorphosed sedimentary rocks*

Note: 1. Ma = million years old; ≥ = at least; ~ = approximately.
2. Colour coding sourced from the Commission for the Geological Map of the World (CCGM 2016); Application of the colour coding to align with the ages is approximate and indicative only; Ages to align with the colour coding sourced from Cohen et al (2013).

Ediacaran fossil assemblages found at Nilpena and as they are known globally



(Source: Mary Droser and Guy Narbonne; modified from Xiao & Laflamme (2009))