Government of **Western Australia**
Department of **Mines and Petroleum**

RECORD 2012/9

THE PROPOSED DAWN OF LIFE GEOTOURISM TRAIL, MARBLE BAR, PILBARA CRATON, WESTERN AUSTRALIA — GEOLOGY AND EVIDENCE FOR EARLY LIFE

by
K Grey, JDA Clarke, and AH Hickman
with contributions from
DT Andersen and MD Gargano

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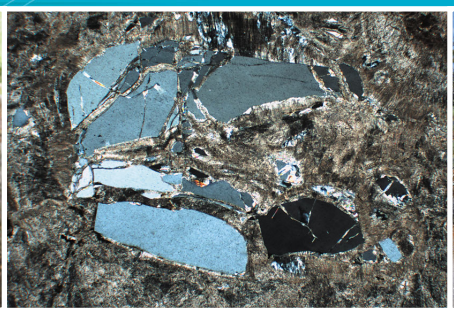

Geological Survey of Western Australia

Government of **Western Australia**
Department of **State Development**

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Perth 2012

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This Record provides a summary of information collected from the Dawn of Life Trail. Future researchers with a legitimate need for more detailed information may apply to the above address.

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The proposed Dawn of Life Geotourism Trail, Marble Bar, Pilbara Craton, Western Australia — geology and evidence for early life

by
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with contributions from
DT Andersen[2] and MD Gargano[1]

Abstract

Stromatolites and other significant features of the Strelley Pool Formation at the Dawn of Life Trail site, between Marble Bar and Nullagine, were mapped by Spaceward Bound Australia participants in July 2011. The site contains a range of stromatolite morphologies and other features of interest that make the locality suitable for development as a geotourism site. Issues such as site protection and possible future activities need consideration before this development can take place. Recommendations are made as to which features could best be incorporated in a heritage trail, and the potential design of such a trail.

KEYWORDS: Dawn of Life Trail, Strelley Pool Formation, Pilbara Craton, Archean, early life, stromatolites.

Introduction

The Pilbara region of Western Australia provides some of the best evidence for the earliest life on Earth. A small number of Archean sedimentary and volcanic rock outcrops in this region contain exceptionally well-preserved, probably biogenic structures that resemble the stromatolites and microfossils found in greater abundance in much younger successions, and which can be compared to microbialites and microbial mats in some modern environments. Satisfying public curiosity about this early evidence of life on Earth, while still protecting critical evidence, presents some interesting land-access challenges.

A handful of key stromatolite and microfossil sites, discovered and documented by workers such as Walter et al. (1980), Lowe (1980, 1983, 1984), Hickman (1980), Buick et al. (1981), Awramik et al. (1983, 1988), Buick (1984), Schopf (1993), Hofmann et al. (1999), Van Kranendonk and Nijman (2001), Grey et al. (2002), Van Kranendonk et al. (2003), Brown et al. (2004), Allwood et al. (2006a, 2007a,b, 2009, 2010), Banerjee et al. (2007), Marshall et al. (2007), Van Kranendonk (2007, 2011), Grey (2008), Grey and Caldon (2008), Wacey (2009), and Hickman et al. (2011), have become some of the most intensively studied localities in the Pilbara.

In recent years, some of these sites have suffered damage, and because they contain such rare and unique fossils and geological structures of exceptional geoscientific and geoheritage value, they were recognized as requiring special management. Therefore, six key Pilbara sites were established as State Geoheritage Reserves by the Western Australian Government (Fig. 1). Access is subject to various conditions and procedures that have been introduced to restrict the level and scope of potentially damaging activities (Grey et al., 2010).

These reserves include the well-known Trendall and Buick localities, which were named after their discoverers, AF Trendall and R Buick, respectively. The Trendall Reserve (State Geoheritage Reserve R50149), in the North Pole Dome area of the East Pilbara Terrane, covers a 2.5 km^2 area of outstanding geoscientific and geoheritage significance within the 3426–3350 Ma Strelley Pool Formation, containing some of the world's most abundant and best preserved evidence for early life on Earth (Hofmann et al., 1999; Grey et al., 2002; Allwood et al., 2006a; Van Kranendonk, 2007; Hickman et al., 2011). The Buick Reserve (State Geoheritage Reserve R44710) is also

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located in part of the North Pole Dome, but in an outcrop of the c. 3481 Ma Dresser Formation, and contains what are probably the oldest known stromatolites (Walter et al., 1980). These structures consist of simple domes, their lack of complexity making them more contentious than those in the Trendall Reserve and at two other stromatolite Geoheritage Reserves (Lowe — State Geoheritage Reserve R50150; and Hickman — State Geoheritage Reserve R50151) in the younger Strelley Pool Formation. Two other sites, Awramik (State Geoheritage Reserve R44711) in the Dresser Formation and located close to the Buick Reserve, and Schopf (State Geoheritage Reserve R48969) in the Apex Basalt, are microfossil localities.

In part, the impetus for detailed investigation of the Trendall and other State Geoheritage Reserves in the East Pilbara has come from their importance to the relatively new scientific discipline of astrobiology (Hickman et al., 2011). The study of the origins, evolution, distribution, and future of life in the universe includes research into the origin, early evolution, and diversity of life on Earth, mostly because early life on Earth provides the best model for similar life that may exist or have existed on other planets and moons in the solar system. That is, Earth's Paleoarchean fossil record provides a template for the search for extant and extinct primitive life on other worlds. The Pilbara region, with its record of 3500–3400 Ma surface environments and early life, has previously been used as an analogue for features found on Mars (Brown et al., 2006a,b). As the science of astrobiology has advanced, public interest in ancient fossils, especially those in the low-grade metamorphic rocks of the Pilbara, has increased. As it is unlikely that those sites now designated State Geoheritage Reserves could sustain the impact of numerous visitors, a site that could satisfy public curiosity is needed, particularly one at a more accessible location (Grey et al., 2002).

A site suitable for this purpose was discovered by Geological Survey of Western Australia geologists in 2002, about 1 km west of the Marble Bar – Nullagine Road, 60 km south of Marble Bar, and 50 km north of

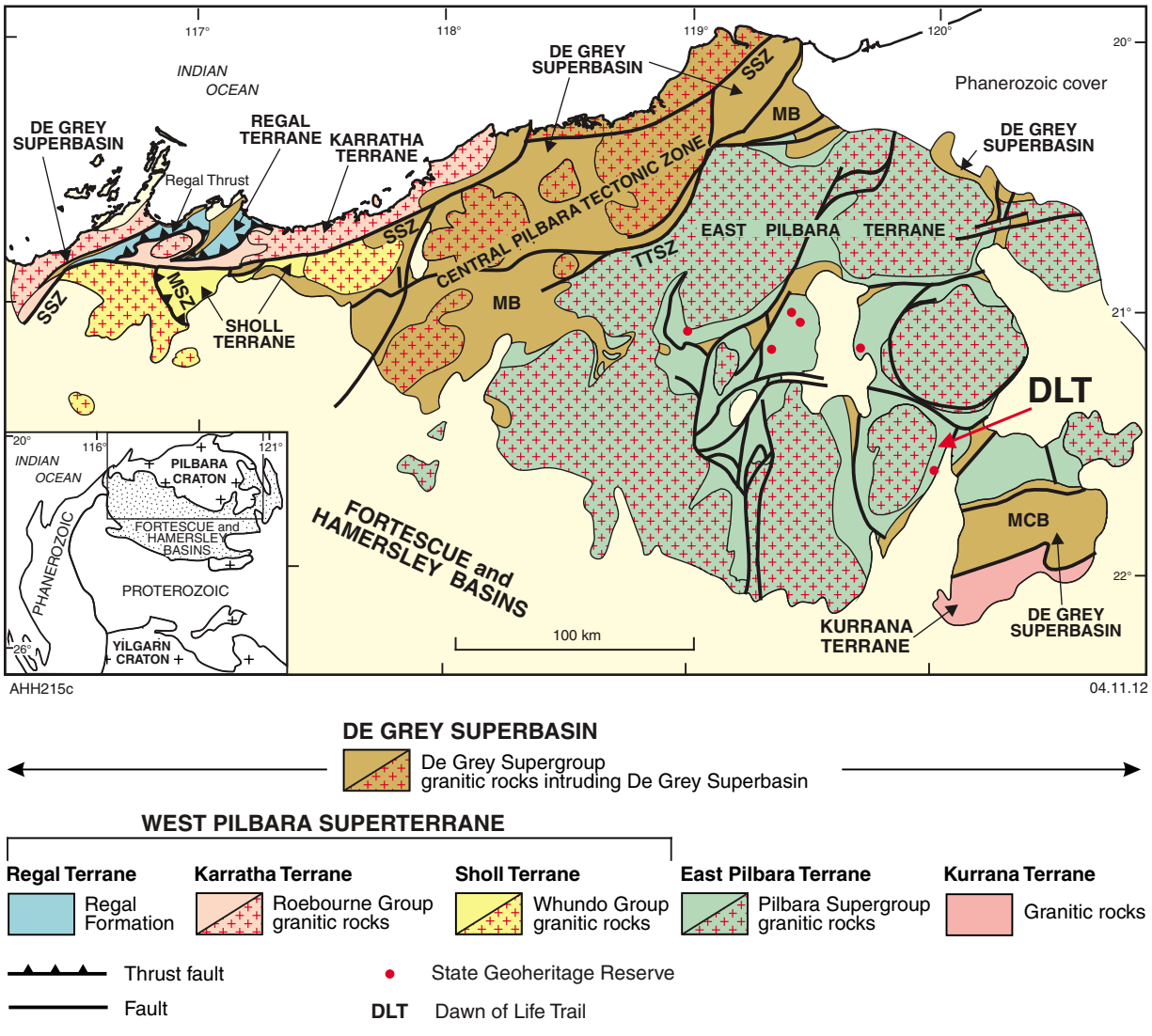

Figure 1. Simplified geological map of the Pilbara Craton, showing the location of the proposed Dawn of Life Trail and State Geoheritage Reserves within the East Pilbara Terrane.

Nullagine; roughly midway between the two townships (Figs 2 and 3). Reconnaissance studies suggested that this site, dubbed the 'Dawn of Life Trail', has the potential for development as a geoheritage trail to educate the public about the global significance of the Pilbara region for the history of life on Earth (Grey et al., 2002; Grey and Caldon, 2008). The site contains abundant examples of structures similar to those in the other Pilbara State Geoheritage Reserves (although slightly less well preserved). The accessibility of the Dawn of Life Trail site will appeal to visitors with only a passing interest, allowing them to be directed away from more critical, less accessible sites, and thus reducing pressure on the protected State Geoheritage Reserves. Additionally, the Dawn of Life Trail has significant potential for the testing of mission-related tools and instruments, and the training of planetary and astrobiology researchers in recognizing 3500–3400 Ma habitable environments and fossil structures on Earth similar to those that might be found in rocks of similar age on Mars. For these reasons, the Dawn of Life Trail site was listed as location 5.2 in a geotourist guide book to the Marble Bar area (Van Kranendonk and Johnston, 2009). However, an inventory of significant features is required, and further investigations of their significance must be carried out, before the site can be further developed.

An attempt to undertake a detailed analysis of the local geology and the distribution and diversity of the stromatolites was made in 2008, but failed due to adverse weather conditions. In July 2011, the first stage of investigation commenced through mapping of the site and documentation of significant features, undertaken by members of the Mars Society Australia's Spaceward Bound Pilbara and Shark Bay expedition. This mapping was carried out in partnership with the NASA Ames Research Centre, and funded by grants from CSIRO, the Western Australian Government (through the Royalties for Regions program), the Pilbara Development Commission, and the expedition partners. Such undertakings are labour intensive, and the Spaceward Bound expedition offered both an abundance of personnel, and a range of expertise to carry out the much needed documentation of the site. This investigation was a preliminary test of the site's future

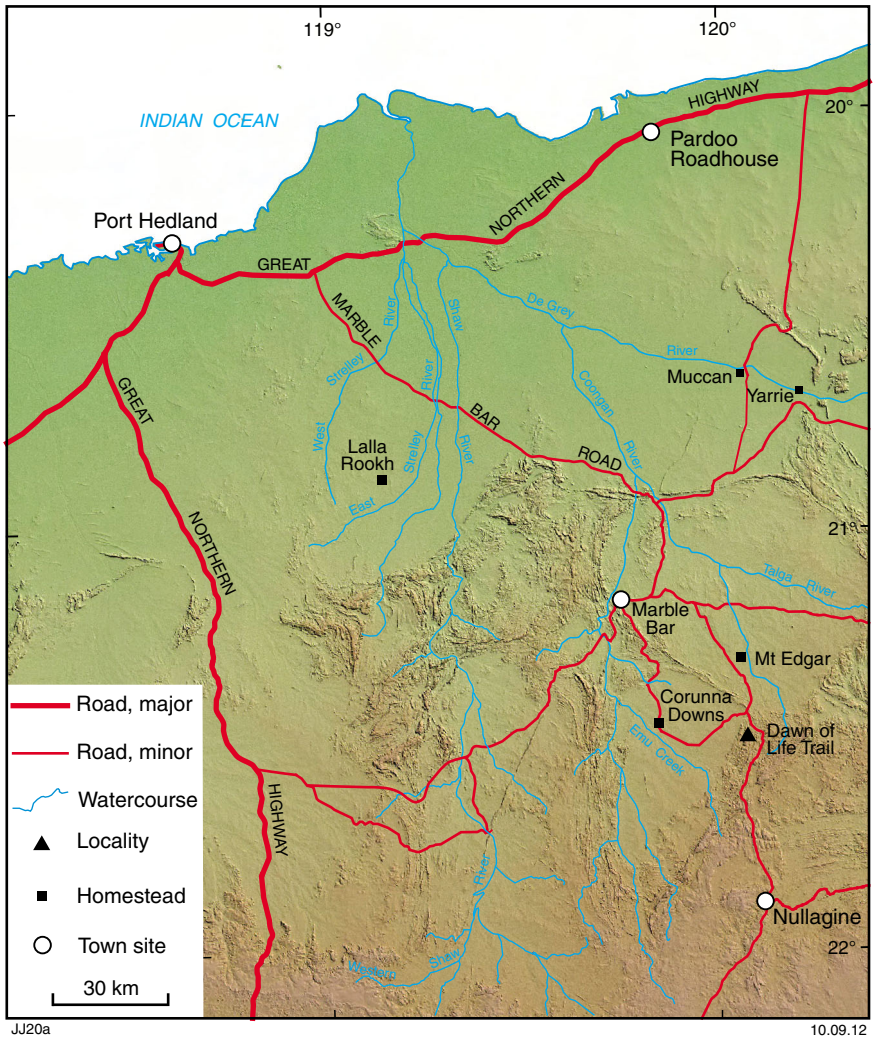

Figure 2. Physiographic location of the proposed Dawn of Life Trail

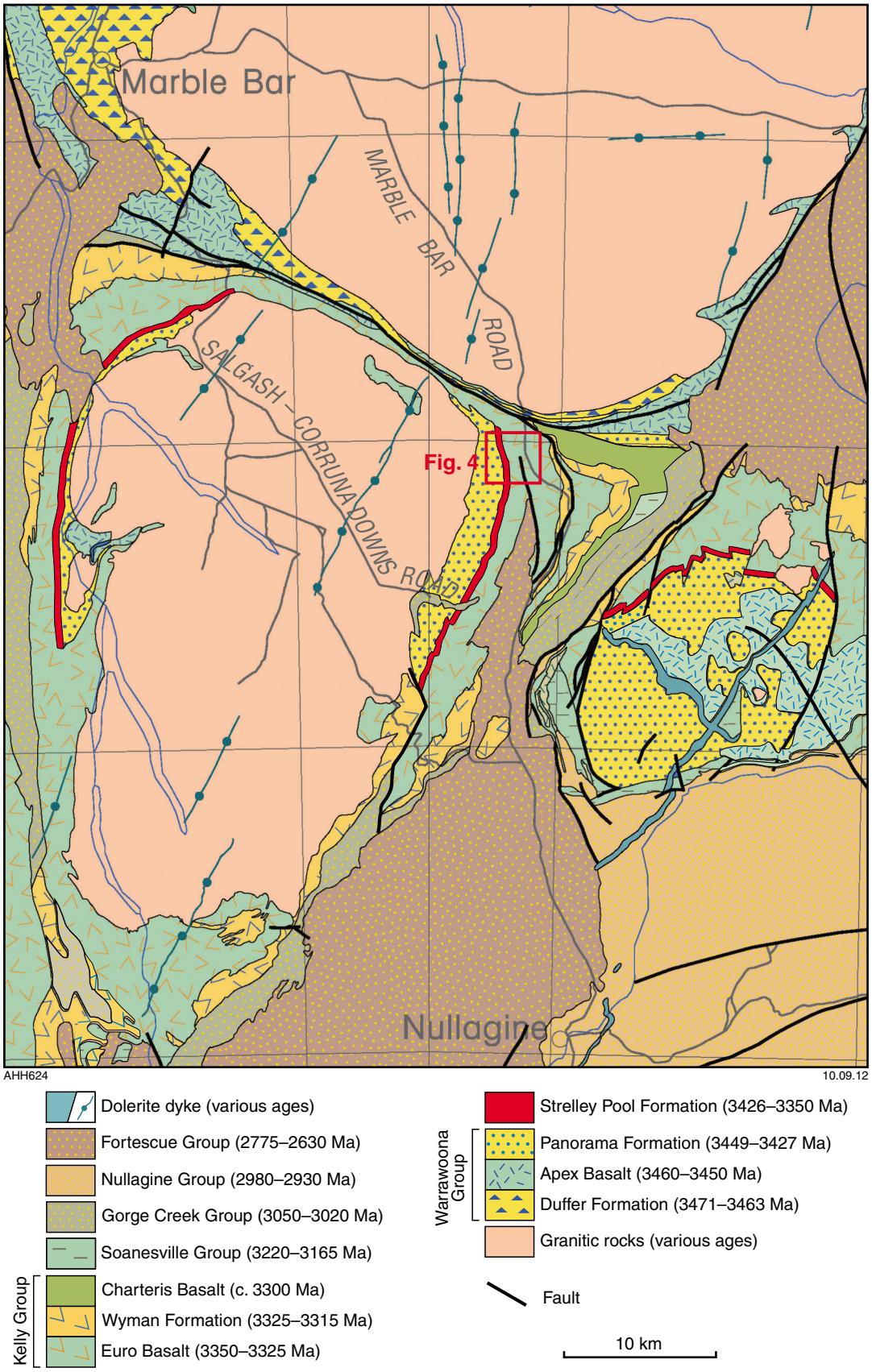

Figure 3. Geological map of the Marble Bar – Nullagine area, showing the geological setting of the proposed Dawn of Life Trail. Box labelled 'Fig. 4' includes the Dawn of Life Trail site.

potential, and also aimed to meet the main objectives of the Spaceward Bound expedition, which were:

- Scientific reconnaissance of the region for future research by planetary scientists and astrobiologists
- Testing of space-related hardware (e.g. the NDX-1 prototype space suit, and the Terra X-Ray Diffraction (XRD) / X-Ray Fluorescense (XRF)) in an environment analogous to what could be found by the forthcoming Mars Science Laboratory Mission
- Field analysis using a Portable Infra-red Mineral Analyser (PIMA-2) instrument, analagous to spectrometers carried by the Mars Exploration Rovers
- Training of educators in planetary science, aerospace education, and astrobiology
- Engagement with the public through media contacts, public lectures, and schools
- Collection of data on the Dawn of Life Trail.

The Spaceward Bound expeditioners spent two days at the Dawn of Life Trail site, the first day spent in reconnaissance, and the second day on mapping and instrument field trials. Data collected on these two days form the basis of this Record.

Site mapping delineated many stromatolite occurrences in the area, together with possible evidence of near-surface hydrothermal activity. Most of the stromatolites are simple domes, but low-relief domes and conical forms are also common, along with weathered columnar stromatolites and rarer compound forms.

Regional geological setting of the Dawn of Life Trail site

The Dawn of Life Trail site is situated in the Kelly greenstone belt, near the southern margin of the Mount Edgar Granitic Complex, in the centre of the East Pilbara Terrane of the Pilbara Craton (Figs 1, 3, and 4; Williams and Bagas, 2007a,b). The East Pilbara Terrane covers 40 000 km^2, and is composed of ten major granite–greenstone domes separated by faults (Hickman and Van Kranendonk, 2004). The tectonic setting of the Pilbara Supergroup (Fig. 5), which represents the entire succession of the East Pilbara Terrane, has no close modern analogues (Hickman et al., 2011); this succession probably resulted from partial convective overturn of upper and middle crust, involving diapiric doming over a period of 300 million years (3525–3225 Ma) (Hickman, 1984; Collins, 1989; Hickman and Van Kranendonk, 2004; Van Kranendonk et al., 2004, 2007a,b).

The Pilbara Supergroup is 15–20 km thick in most greenstone belts, and is composed of three volcanic groups and one sedimentary formation (Figs 3 and 5; Hickman, 2011). The oldest group, the Warrawoona Group, ranges from 3530–3427 Ma (Hickman, 2012), and consists predominantly of basalt, but also contains significant sedimentary units, including the c. 3481 Ma Dresser Formation, which contains domical stromatolites and microfossils (first recorded by Walter et al., 1980 and by Awramik et al., 1983), and a chert unit in the overlying Apex Basalt that yields probable microfossils (first recorded by Schopf and Packer, 1987 and described by Schopf, 1983). The youngest unit of the Warrawoona Group, the Panorama Formation, paraconformably to disconformably underlies the Strelley Pool Formation about 1.5 km west of the Dawn of Life Trail site. The chert unit that outcrops at the Dawn of Life Trail site is a faulted repetition of the Strelley Pool Formation outcrops seen 1.5 km to the west, where stromatolite-like structures were first discovered over 30 years ago (Hickman, 1980). In some areas west of Marble Bar, the youngest formation underlying the Strelley Pool Formation is the Mount Ada Basalt (Allwood et al., 2007a), and in these places 4–8 km of the Warrawoona Group succession is absent due to pre-3430 Ma erosion (Hickman et al., 2011). The Panorama Formation consists of flow-banded, fine-grained and porphyritic rhyolite, fragmental volcanic rocks, and minor banded and black chert, and has been dated at 3449–3427 Ma (Van Kranendonk et al., 2002, 2006; Hickman, 2008). Geochronology from four sites (GSWA 148502, 168913, 168914, 178083) within the Panorama Formation, 1.5 – 3.0 km west of the Dawn of Life Trail site (Fig. 4), indicate an age range of 3433–3427 Ma (Williams and Bagas, 2007a, table 4).

Regionally, the Strelley Pool Formation (Hickman, 2008; formerly the 'Strelley Pool Chert' of Lowe, 1983; Van Kranendonk and Morant, 1999) is a succession of siliciclastic and volcaniclastic assemblages, laminated grey-white chert formed from silicified carbonates, carbonate rocks with only minor silicification, and minor primary black, white, and jaspillitic chert with crystal fans (pseudomorphs after aragonite, gypsum, or barite). The unit is 20–100 m thick in most greenstone belts of the East Pilbara Terrane (Hickman, 2008), although it may locally be up to 1000 m thick (Van Kranendonk, 2010a). In the East Strelley and Panorama greenstone belts, a reasonably consistent vertical succession of facies has been recognized and up to five informal members have been described (Lowe, 1983; Van Kranendonk, 2000, 2006, 2010b; Allwood et al., 2007a; Wacey et al., 2010a), although the relationship of these subdivisions to the section at the Dawn of Life Trail site is still unclear. The formation is up to 30 m thick in the southwestern corner of Mount Edgar[1] (Fig. 4), where it disconformably overlies the Panorama Formation (Williams and Bagas, 2007a). A basal conglomerate is often present, and in some areas contains fragments of jaspilitic chert recycled from Panorama Formation rocks (Van Kranendonk and Nijman, 2001; Van Kranendonk and Johnston, 2009); however, this conglomerate has not been observed at the Dawn of Life Trail site. The formation shows lateral changes of thickness consistent with deposition in shallow-water marine and fluviatile environments (Hickman et al., 2011) and is thought to have been deposited during a major hiatus in volcanism (Williams and Bagas, 2007a).

[1] Capitalized names refer to standard 1:100 000 map sheets, unless otherwise indicated.

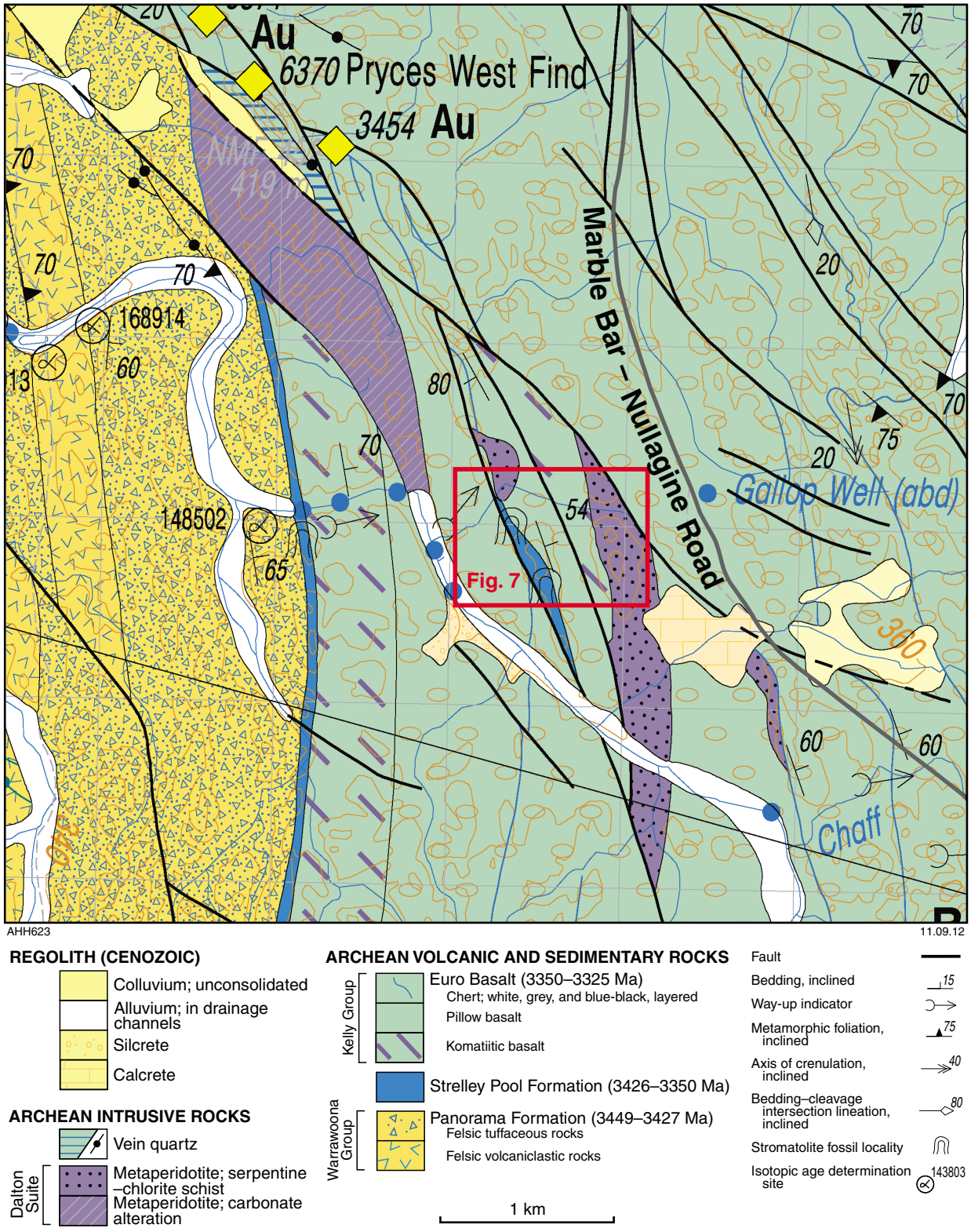

Figure 4. Geology of the Kelly greenstone belt in the vicinity of the proposed Dawn of Life Trail. Box labelled 'Fig. 7' corresponds to the Dawn of Life Trail site. After Williams and Bagas (2007b).

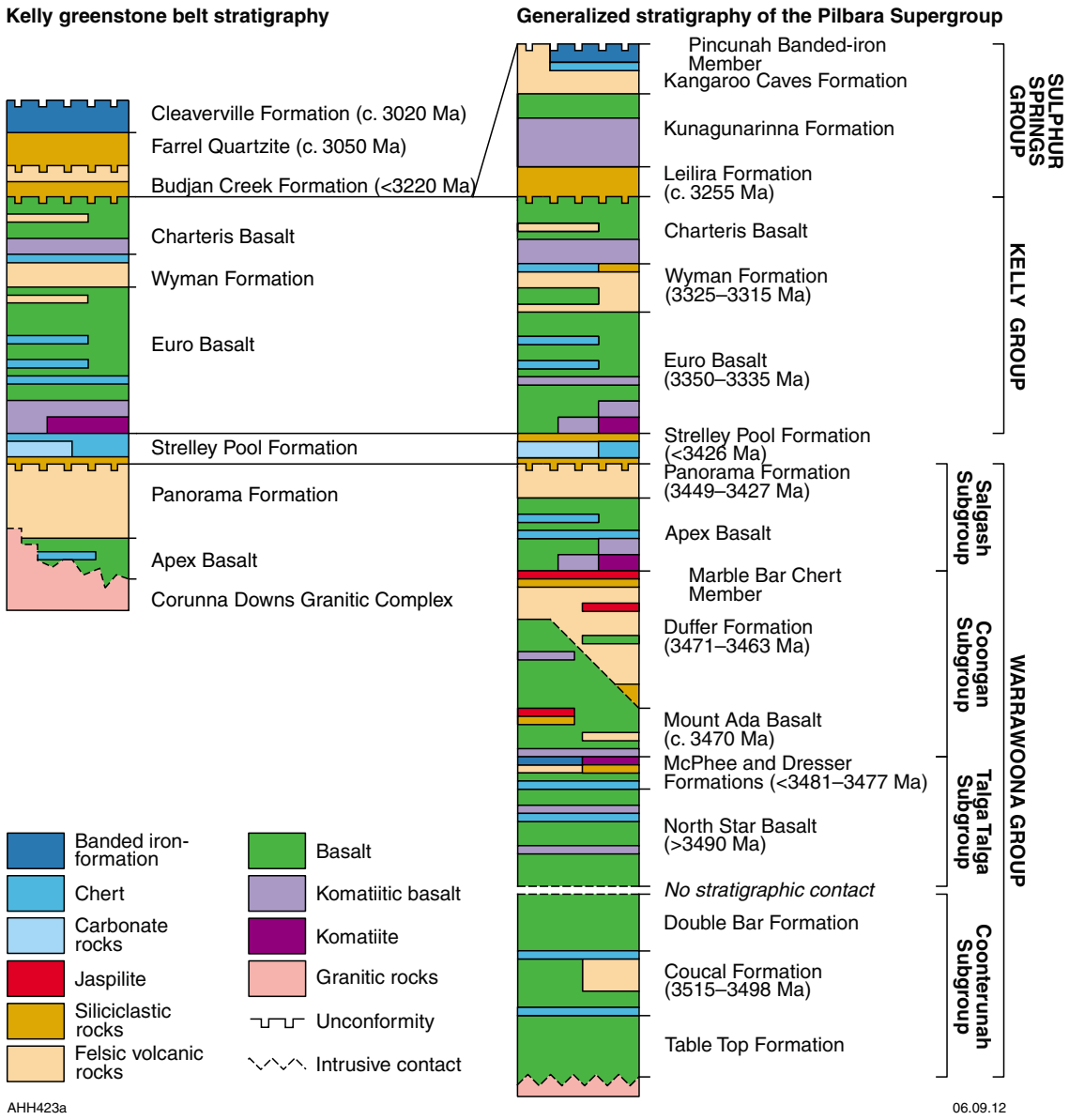

Figure 5. Stratigraphy of the Kelly greenstone belt, compared to the generalized stratigraphy of the Pilbara Supergroup within the East Pilbara Terrane.

The age of the Strelley Pool Formation is constrained to between 3426 and 3350 Ma, based on precise U–Pb isotope geochronology conducted on both underlying and overlying formations (Hickman, 2008).

The Strelley Pool Formation is disconformably to paraconformably overlain by the 3350–3325 Ma Euro Basalt of the Kelly Group (Fig. 5). The Euro Basalt is a thick, predominantly basaltic succession also containing komatiite, komatiitic basalt, numerous thin chert units, and local clastic and volcaniclastic sedimentary rocks, all metamorphosed to greenschist facies. The Euro Basalt is conformably overlain by the 3325–3315 Ma Wyman Formation, a unit of felsic volcanic rocks and volcaniclastic sedimentary rocks. East of the Dawn of Life Trail site, the Wyman Formation is overlain by the Charteris Basalt, a formation similar in composition to the Euro Basalt. At various places across the East Pilbara Terrane, the Kelly Group is unconformably overlain either by the 3255–3235 Ma Sulphur Springs Group or by the 3220–3165 Ma Soanesville Group. Microfossils have been recorded from the upper part of the Kangaroo Caves Formation of the Sulphur Springs Group (Rasmussen, 2000), and microbial mats and microfossils have been reported from the lower part of the Soanesville Group (Duck et al., 2007).

The succession at the Dawn of Life Trail site has been intruded by subparallel ultramafic intrusive rocks that have been metamorphosed to serpentinite–chlorite and carbonate–tremolite schists. These ultramafic rocks are assigned to the Dalton Suite, which elsewhere in the Pilbara Craton has been dated at 3182 Ma (Van Kranendonk et al., 2010).

Residual bodies of calcrete and silcrete are present in the area (Williams and Bagas, 2007a), and locally fill deep fractures in the bedrock.

Methods

The proposed Dawn of Life Trail site is located at MGA 196000E 7622900N, approximately 1.5 km west of the abandoned Gallop Well and 59.5 km from Marble Bar on Highway 138. This falls onto the southwest corner of Mount Edgar 1:100 000 sheet (WA Sheet 2955), which forms the northwest corner of the Nullagine 1:250 000 sheet (SF 51-5) (Williams and Bagas, 2007a,b; Figs 1–4 and 6). Access is currently by four-wheel drive (4WD) vehicles only, following a wheel track that leaves Highway 138 at MGA 197753E 7622467N. The westwards distance from the highway to the trail site is approximately 1.2 km. The area of interest lies on the northern and eastern slopes of a chert ridge, and extends for about 1 km along strike to the south (Fig. 4).

The site survey began with several multiperson parties traversing an area of about 1 km by 0.5 km surrounding the Dawn of Life Trail area where stromatolites had been recorded previously. Stromatolitic outcrops consisted mainly of low ridges of silicified limestone and chert, underlain and overlain by volcanic rocks. Features on the ground were found to be correlatable with features visible on the available satellite imagery and orthophotography. Exposures were walked in all directions until no more stromatolitic outcrops could be located. All occurrences were photodocumented, and their coordinates were logged using handheld Global Positioning Systems (GPS).

Individual fossil occurrences were then examined in more detail, and the positions of well-preserved structures were plotted both onto aerial photograph imagery (Fig. 7) and as a .kmz file in Google Earth. In general, stromatolite-hosting outcrops were defined by clusters of images on Google Earth. Polygons showing the main stromatolite localities were defined based on photograph coordinates and topographic features (Fig. 7). A more detailed geological map of the area was then drawn using data collected by the same method, with control from the existing 1:100 000 scale geology map (Williams and Bagas, 2007b), supported by additional field data and analyses using PIMA and Terra equipment.

The position of other features that might be of interest to tourists, such as pillow basalts and spinifex-textured rocks, were also recorded (Fig. 7). Based on the results obtained from the above methods, a proposed walking trail route was plotted that passed a selection of these significant features (Fig. 7).

Geology of the Dawn of Life Trail site

The Dawn of Life Trail site lies in the southwest corner of the Mount Edgar 1:100 000 sheet, where a stromatolitic horizon on the eastern slopes of a chert ridge can be traced for about 1 km along strike to the south (Williams and Bagas, 2007b). The locality has been mentioned previously in publications discussing the need for management of Pilbara geoheritage sites (Grey et al., 2002, 2010) and the potential for geotourism (Grey and Caldon, 2008), but so far the geoscience of the site has only been described briefly. Van Kranendonk and Johnston (2009) provided a brief description and illustrations of the Dawn of Life Trail site as locality 5.2 in a tourist guide to the Marble Bar area.

At the site, the main silicified portion of the Strelley Pool Formation forms a low hill, with individual chert beds forming small, steep outcrops that shed siliceous fragments downhill (Fig. 8). This scree mantles the surface, obscuring the intervening lithologies. Other lithologies are exposed in the banks and beds of small gullies and creeks. Approximately 25–30% of the surface is covered by low spinifex (*Triodia* sp.). To the west of the stromatolitic carbonate and chert unit, and across a major fault, is altered metabasalt of the Euro Basalt, which stratigraphically overlies the Strelley Pool Formation (Fig. 9). The outcrop of the Strelley Pool Formation at the Dawn of Life Trail site is therefore an inlier surrounded by Euro Basalt, and the fault along its western margin has a downthrow of at least 500 m on its western side. The stromatolites and carbonate rocks are restricted to the stratigraphic top of the Strelley Pool Formation, which is overlain firstly by a thin unit of mafic volcaniclastic rocks (Fig. 9), and then by serpentinized peridotite and komatiitic basalt of the Euro Basalt (Kelly Group). The succession dips predominantly to the east, but a local reversal of dip indicates some structural complexity. Low-angle quartz veins cut through the succession.

The stromatolitic chert is fine grained, preserves fine laminations, and locally replaces carbonate rocks. Elsewhere, the chert is coarser grained and does not preserve any fine detail. This may be due either to a different depositional environment or to diagenetic, hydrothermal, or metamorphic overprinting. Diagenetic alteration is common in Pilbara successions, but is often below lower-greenschist facies grades, which is one reason for the exceptional preservation found in some areas. Therefore, the limited occurrence of stromatolites in this area may result either from original distribution patterns, such as those caused by limited habitats, or from incomplete preservation.

Stromatolite morphologies at the Dawn of Life Trail site

Stromatolites are laminated organosedimentary structures built by microorganisms, principally cyanobacteria (although for Archean stromatolites, the relative roles of cyanobacteria and other bacteria and Archaea remain unclear), and they are one type of microbialite found in the fossil record and today (Burne and Moore, 1987). Modern stromatolites have diverse morphologies, although their shapes are not as varied as those found in parts of the fossil record, and inhabit a range of environments, including shallow-water marine, lacustrine,

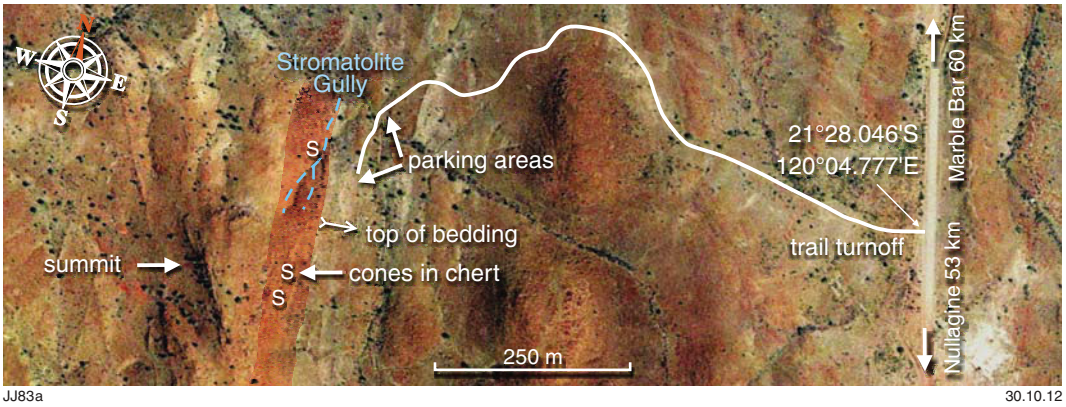

Figure 6. Access to, and main features of, the Dawn of Life Trail (after Van Kranendonk and Johnston, 2009).

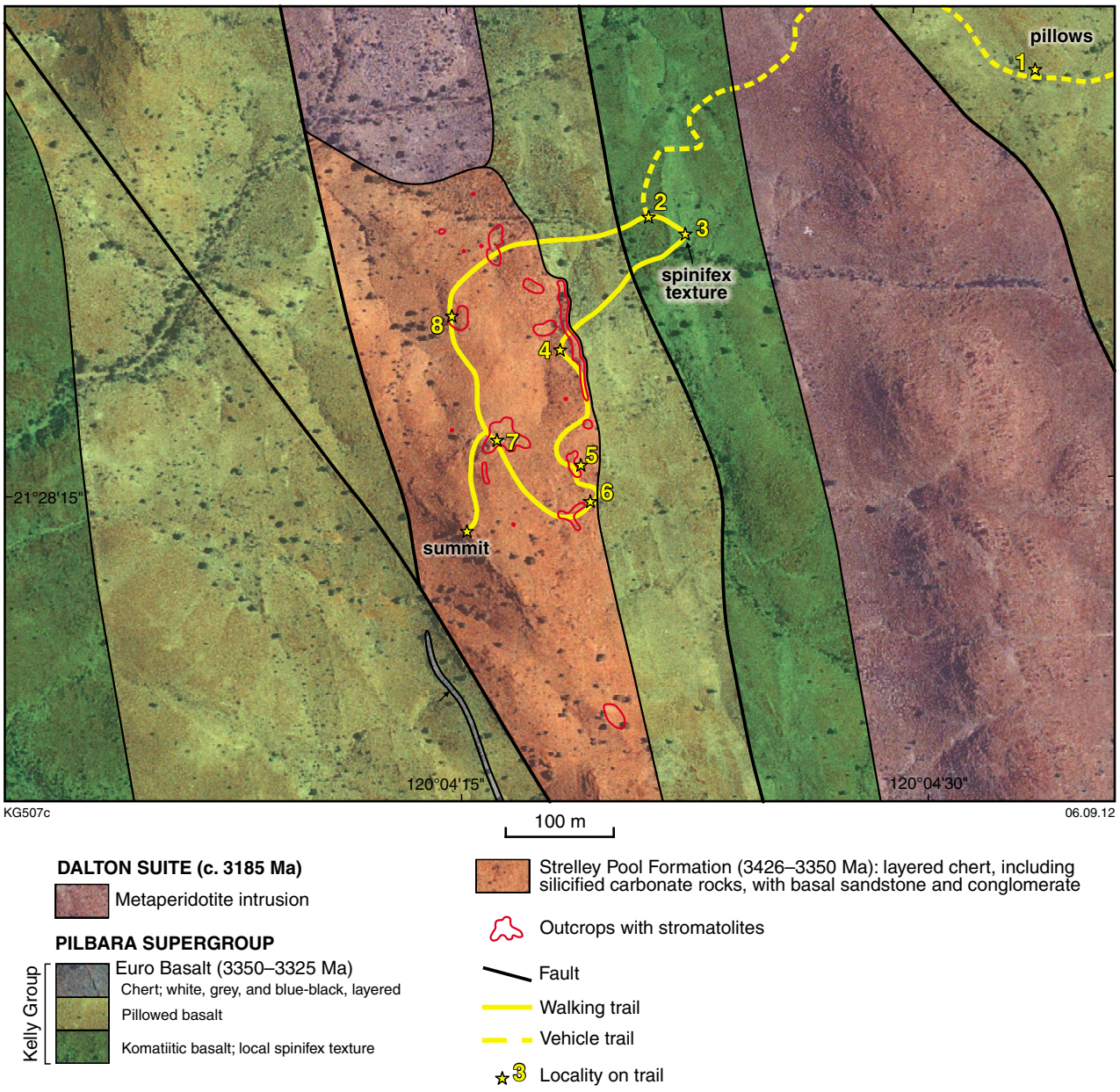

Figure 7. Geology of the Dawn of Life Trail area, showing the proposed trail route and main features, including stromatolite localities.

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Figure 8. **Typical outcrop of the Dawn of Life Trail seen from the top of the ridge looking south. Note the partial spinifex cover, silicified rocky outcrops, and siliceous scree between outcrops.**

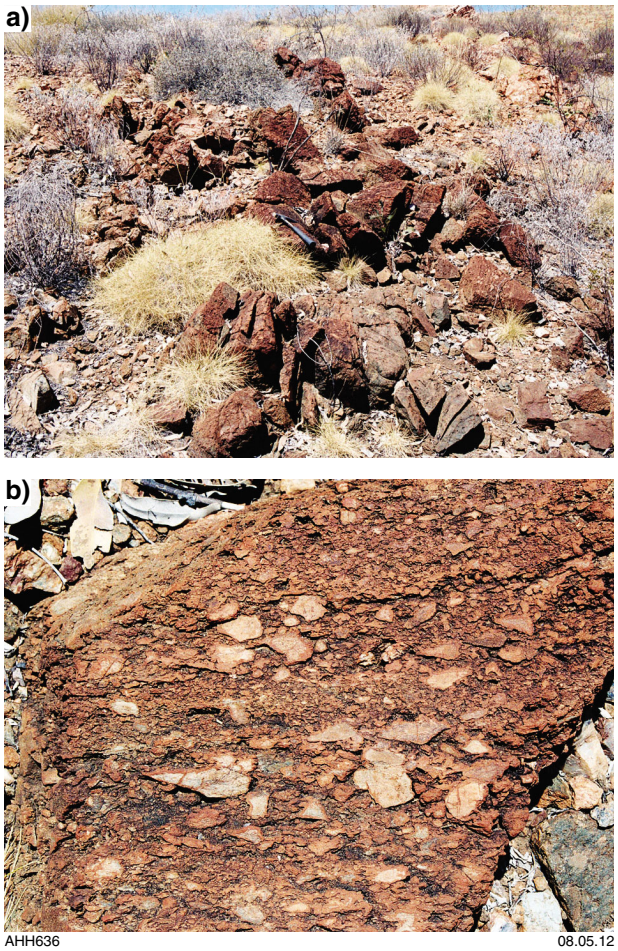

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Figure 9. **Basaltic volcaniclastic unit at the stratigraphic base of the Euro Basalt: a) general view of a basaltic breccia outcrop, 100 m southwest of locality 2 (chert of the Strelley Pool Formation is exposed top right); scale shown by hammer; b) close-up view of fragmental textures in one of the blocks shown in a).**

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Figure 10. Pustular mat stromatolites: a) small domes of pustular mat in plan view, in places weathering to hollow tubes; b) detail of surface covered by pustular mat stromatolites.

Figure 11. Laterally linked conical stromatolites, passing up into near-horizontal laminae (laminae are recrystallized).

Figure 12. Parallel, laterally linked, conical or ridged stromatolites, with a good vertical profile though cone.

and hydrothermal hot-spring settings. Most of these settings tend to be extreme environments that exclude more advanced organisms that compete with, graze on, or burrow into, microbial mats. Before the evolution of higher organisms, stromatolites occupied a much wider range of habitats.

A diverse assemblage of stromatolites is present at the Dawn of Life Trail site, and can be compared to forms documented from better studied sites, such as the Trendall Reserve (Hickman et al., 2011). The stromatolites are well preserved in vertical section, but bedding-plane exposures are far less common at the Dawn of Life locality. Small domical stromatolites are common in partly silicified laminated carbonate rock, although the most numerous stromatolite morphology recognized from the site was coniform and locally slightly elliptical, with individual structures reaching up to 50 cm in height.

The range of stromatolite morphologies recorded seen at the Dawn of Life Trail site is shown in Figures 10–18. In total, 97 different stromatolitic features were imaged. The most common non-layered stromatolites were domes (45 imaged — 46%). These were followed by low-relief domes (26 imaged — 27%) and cones (24 imaged — 25%). Least common were compound stromatolites consisting of laterally linked, conical or ridged stromatolites, seen mainly in vertical profile and generally only partly silicified (two imaged — <2%). Layered stromatolites were common at the base of some of the forms that developed greater relief. Among the conical types were examples of three-dimensional 'egg-carton' stromatolites (small, laterally linked, conical stromatolites), similar to those recorded previously at the Trendall Reserve.

In summary, the following types were recognized:

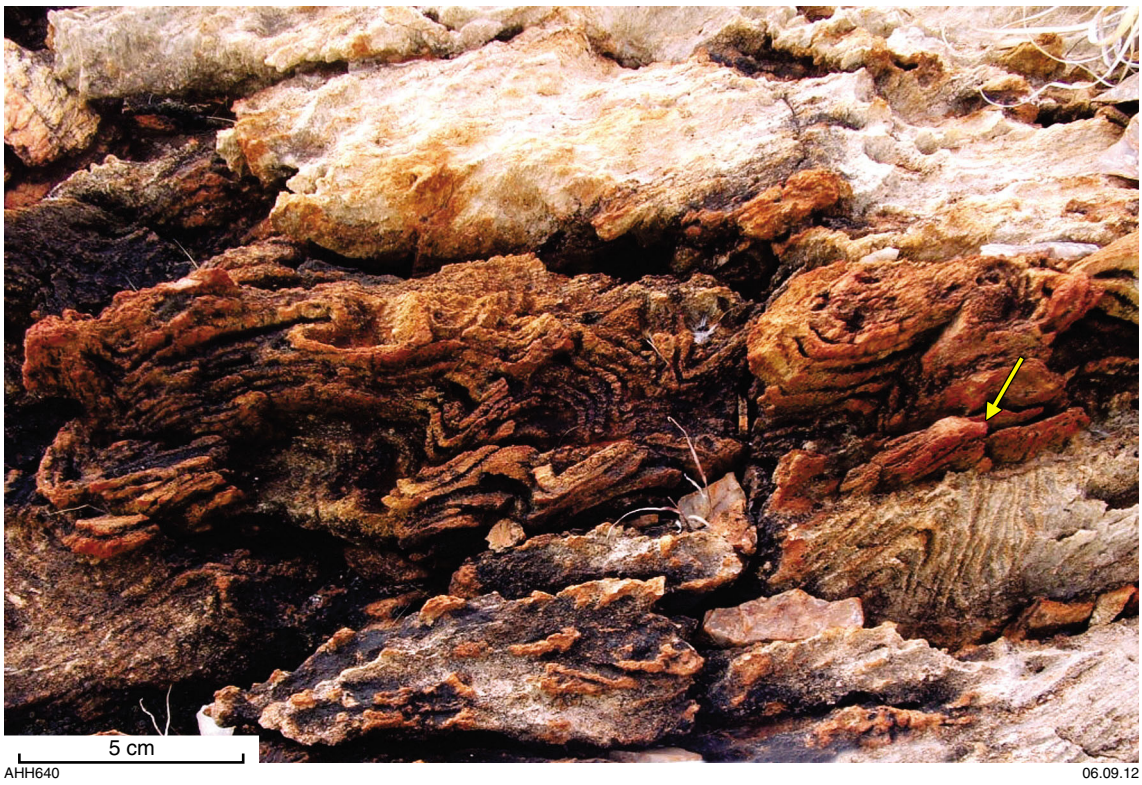

Figure 13. Undulating conical or ridged stromatolites, mainly in tangential view with the vertical profile of a cone arrowed; only partly silicified.

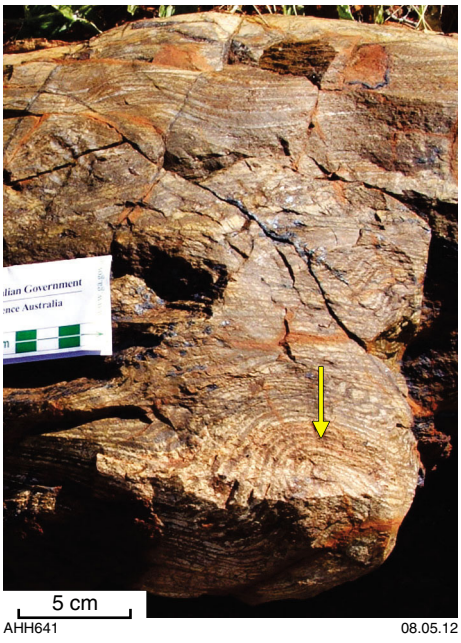

Figure 14. Layered stromatolites, with plan view of a conical stromatolite arrowed

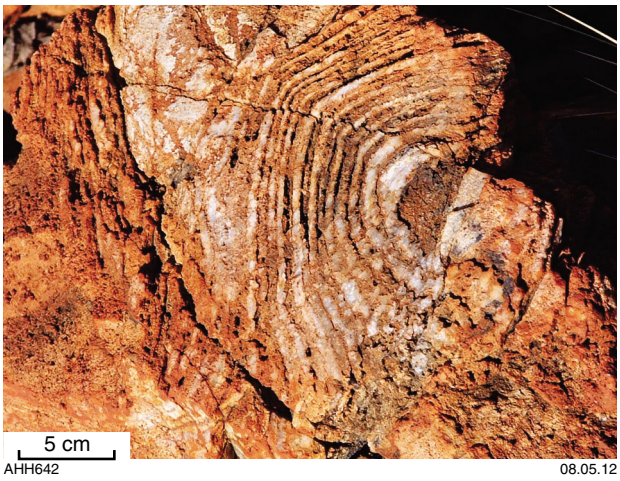

Figure 15. Oblique profile of conical or ridged stromatolites

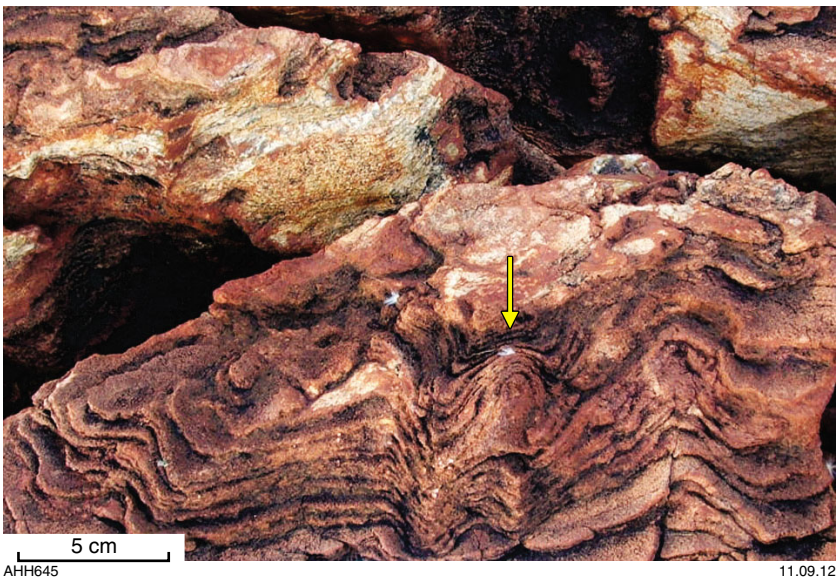

Figure 16. Weathered surface of a small stromatolite demonstrating that the three-dimensional shape is conical (arrowed), and that the flanks are much steeper than the angle of repose.

Figure 17. Three-dimensional, weathered, and inclined 'egg carton' stromatolites, consisting of small, regularly spaced conical stromatolites.

Figure 18. Plan view of conical 'egg carton' stromatolites, showing lateral linkage between the cones.

- Pustular mat stromatolites (Fig. 10): these are small, domical stromatolites that probably formed as a low-relief mat, similar to modern forms seen today at Shark Bay. In some mats, the blister-like surface forms due to the accumulation of gas below the mat surface.
- Laterally linked cones (Figs 11 and 12): many of these structures are seen only in vertical profile, but occasional short sections preserved three dimensionally demonstrate that they are conical rather than ridged.
- Undulating conical or ridged stromatolites (Fig. 13–16): many stromatolites begin with flattened laminae that gradually develop into undulose forms, and finally into more complex structures like domes and cones.
- 'Egg carton' stromatolites (Figs 17–18): these are smaller, laterally linked, conical stromatolites (<10 cm high) preserved in three dimensions, which show the original topography. In some examples, the cones are elongate in plan view, indicating a response to current activity.
- Layered stromatolites (Fig. 14): simple layered mats were probably very common in the depositional environment, and did not necessarily develop into more complex morphologies. The mats would have played a significant role in stabilizing the sediment.

Other features of interest

Besides stromatolites, there are other features of geological interest along the trail. These include features developed after the stromatolitic sediments were lithified, such as small euhedral quartz crystals that formed in a hydrothermal vein (Fig. 19); staining of stromatolitic chert by goethite, a weathering product from iron (Fig. 20); hydrothermal breccias (Fig. 21); cavity infill by botryoidal chert (Fig. 22); radiating barite crystals (Fig. 23); and quartz veins that cut the stratigraphy (Fig. 24).

In this part of the Kelly greenstone belt, the Euro Basalt contains many pillow basalt units throughout its 4 km thick succession (Williams and Bagas, 2007a). This is a very important feature as pillow basalts are proof of subaqueous lava eruption. The observation that the shallow-water to subaerial Strelley Pool Formation is overlain by a volcanic succession containing pillow basalts provides proof of at least 4 km of basin subsidence between 3350 Ma (the age of the top of the Strelley Pool Formation) and 3325 Ma (the age of the top of the Euro Basalt). In other parts of the East Pilbara Terrane, the Euro Basalt is up to 9 km thick. Somewhat rubbly outcrops of pillow basalt are present a few metres from the access track, 450 m west of the Marble Bar – Nullagine Road (MGA 196940E 7623300N). The basalt in these pillow lavas is vesicular and amygdaloidal, with the amygdales being filled by quartz, carbonate minerals, and chalcedony.

Figure 19. Euhedral hydrothermal quartz filling an open cavity

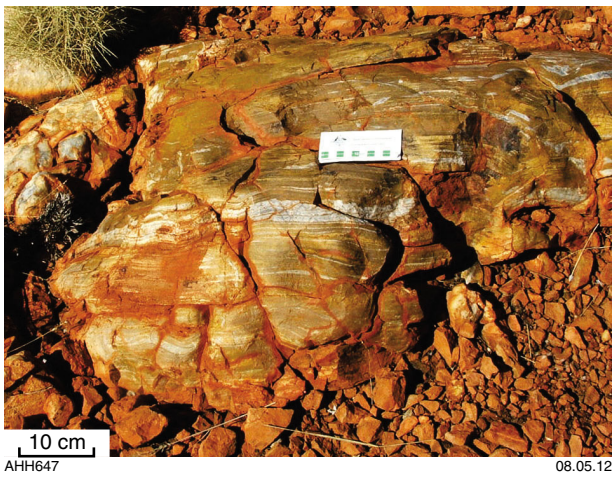

Figure 20. Goethite-stained, laminated to low-relief stromatolitic chert, with goethite possibly replacing sulfides.

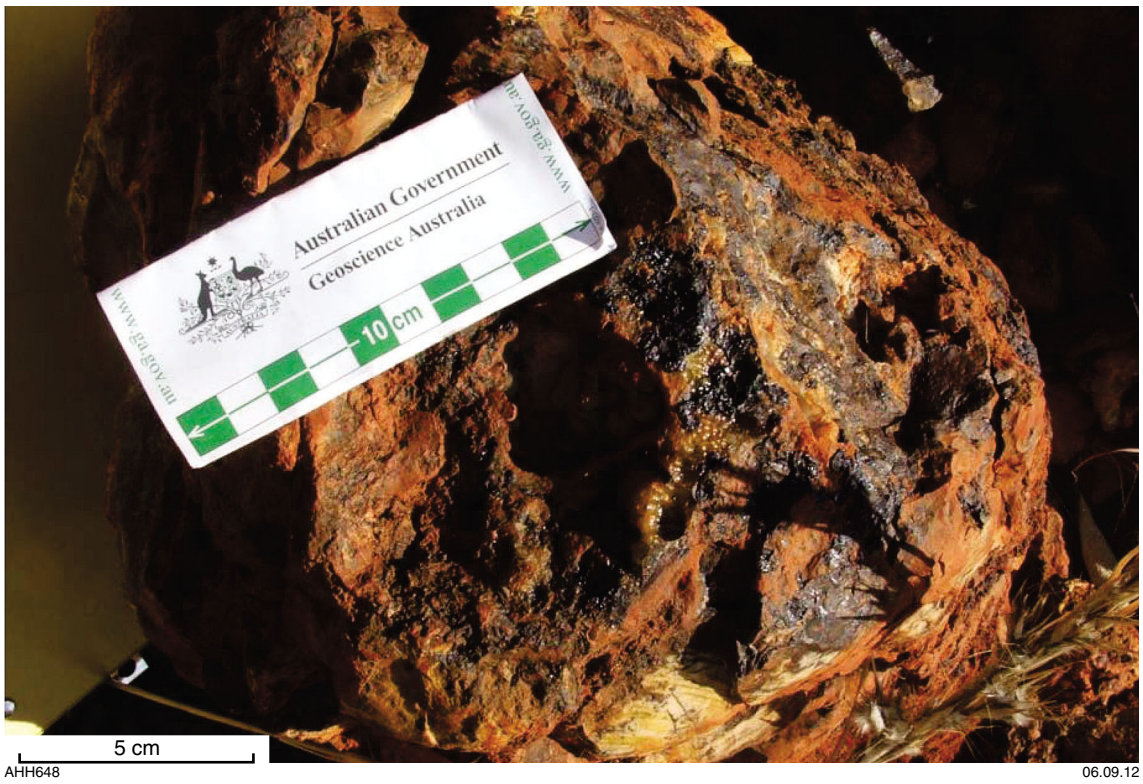

Figure 21. Possible hydrothermal breccia

Figure 22. Coarse, botryoidal quartz completely filling a former cavity

Figure 23. Low mound composed of radiating barite crystals

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Figure 24. Vein of bucky quartz, which cuts stratigraphy at a low angle and connects two stromatolite horizons.

The pillows are 0.3 – 1.0 m across, have well-developed variolitic margins, and their morphology indicates way-up to the east.

About 1.2 km west of the Marble Bar – Nullagine Road, at locality 3 (MGA 196630E 7623147N) on Figure 7, the Euro Basalt contains flows of spinifex-textured komatiite. Layers of sheaf (platy olivine)- and random spinifex-texture beneath fine-grained flow tops define the northerly strike of the ultramafic lavas, and indicate that way-up is to the east.

The summit of the ridge (Fig. 7) to the southwest of the Dawn of Life Trail site provides a spectacular panorama of the site and surrounding countryside, and provides views of numerous features, justifying its inclusion as part of the trail (Figs 7 and 25). The summit is 420 m above sealevel. To the north, on a bearing of 015°, is Mount Edgar, a rocky pinnacle lying in the middle of a plain underlain by granite. To the northwest, on a bearing of 300°, is the historic gold mining area of Warrawoona, about 25 km south of Marble Bar, which is within a chain of greenstone ridges. To the west, on bearing 270°, the Second World War Corunna Downs Airstrip, a popular tourist destination accessible from Marble Bar, lies on another extensive plain underlain by granite. A very notable feature of the landscape is that all the highest hills to the south and east are approximately the same height (400–450 m ASL), and many have flat tops. These have been interpreted as the remnants of an ancient land-surface (Jutson, 1950), which was subsequently dissected during the formation of the region's current relief (Pillans, 2007).

Suggestions for a heritage trail

The suitability of the site for a heritage trail, as suggested by earlier investigations, was confirmed by the investigation carried out by the Spaceward Bound expedition, with the key features outlined below. The proposed location of the walking trail, positioned to highlight evidence for early life, variations on stromatolite morphology, and other geological features of interest, is shown in Figure 7. The total distance traversed is about 0.86 km, with a total climb of 20 m along the length of the trail. The climb to the lookout point at the summit of the ridge is an additional 60 m height.

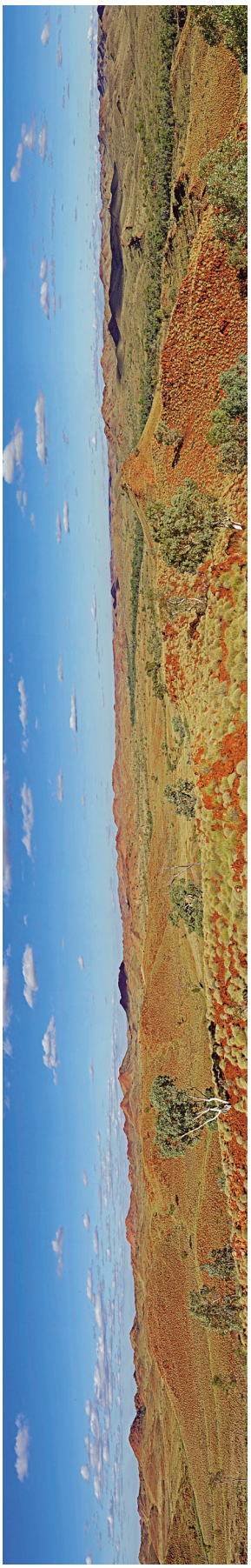
Specific features identified as suitable for inclusion in a walking trail include the following (although other features can be added once the main pathway route has been determined):

1. Pillow lavas: accessible from the vehicle track leading to the site (MGA 196940E 7623300N)

2. Walking trail-head area: this is the suggested parking area (MGA 196620E 7623172N)

3. Spinifex textures in komatiite, adjacent to the parking area (Fig. 7)

4. Main stromatolite location: a laterally extensive stromatolite outcrop, showing silicified and primary limestone stromatolites with through-going laminae, and altered marble beds. Stromatolite morphologies



include low-relief laminar stromatolites, and conical and domical stromatolites with disrupted laminae

5. Second stromatolite location: outcrops here show silicified stromatolites with low domical forms and laterally linked conical stromatolites. Volcanic breccias are exposed nearby. This corresponds to Location 5.2.1 of Van Kranendonk and Johnston (2009)

6. Crystal fans and conglomerate (MGA 196565E 7622883N). This corresponds to Location 5.2.2 of Van Kranendonk and Johnston (2009)

7. Third stromatolite location: in these outcrops are low-amplitude to domical silicified stromatolites, some hosted by black chert, which are locally goethite stained, with goethite possibly replacing sulfides

8. Hydrothermal vent: this locality shows low-amplitude stromatolites, with goethite-stained laminated silica.

9. View across site from the summit of the ridge (at 196490E 12377060N) showing typical east Pilbara landscape (optional).

Significance of the Dawn of Life Trail

The six Pilbara localities that are now State Geoheritage Reserves contain some of the world's best evidence for ancient life on Earth. This evidence is provided by fossil stromatolites, microfossils, and a range of analyses using sophisticated geochemical techniques. Although stromatolites are widespread throughout Earth's geological record from the Neoarchean (2800 Ma) onwards, Paleoarchean (3600–3200 Ma) stromatolites, such as those found in the State Geoheritage Reserves, are very rare (Hickman et al., 2011). The proposed Dawn of Life Trail not only provides another site for detailed scientific study, but, if properly managed, has potential as a geotourism site that can showcase the evidence for early life to the public. The structures seen at the Dawn of Life Trail site and their significance are best understood through reference to the more extensively studied structures at the Trendall locality.

Debates about biogenicity

Although several researchers (Lowe, 1994; Grotzinger and Rothman, 1996; Lindsay et al., 2003a,b, 2005; Brasier, 2009; Wacey et al., 2010a–c) have suggested that the Paleoarchean stromatolites of the Pilbara are abiogenic, formed solely by physical processes (such as current activity forming ripple marks) or chemical precipitation, available evidence now strongly favours a biogenic origin. This evidence has mainly been gathered from Trendall and the other reserves, but similar features are also displayed at the Dawn of Life Trail site.

Figure 25. Panoramic view, looking south from the ridge summit to the southwest of the Dawn of Life Trail. The view ranges between southwest and southeast. A more detailed explanation of landmarks seen in the image is given in the text.

Stromatolites were first described from the Pilbara Paleoarchean by Lowe (1980) and Hickman (1980), from a stratigraphic unit since named the Strelley Pool Formation, and by Walter et al. (1980) from an older unit since named the Dresser Formation of the Warrawoona Group. Subsequently, Buick et al. (1981) argued that the Dresser Formation structures were abiogenic, and Lowe (1994) changed his interpretation of the structures he had discovered in 1980, instead arguing that they were abiogenic.

Awramik et al. (1983) described microfossils from the Dresser Formation, which later became the subject of dispute (Buick, 1984, 1988, 1991; Awramik et al., 1988; Awramik, 1992). Major reviews and assessments of the evidence for and against a biogenic origin for these and many other structures were published in Schopf (1983) and Schopf and Klein (1992). Another significant microfossil discovery was subsequently reported from chert in the Apex Basalt by Schopf and Packer (1987) and Schopf (1993). Further discoveries of microfossils and probable microbial mats in either the Strelley Pool Formation or underlying and overlying formations (Rasmussen, 2000; Van Kranendonk and Nijman, 2001; Banerjee et al., 2007; Allwood et al., 2009; Wacey et al., 2010a–c; Sugitani et al., 2010) generally support interpretations that microbial life was common and widespread by the time of the formation of the stromatolites at the Dawn of Life Trail site. No evidence has yet been found for microfossils at the Dawn of Life Trail locality, but some of the local black chert would be worth investigation in this regard.

As described in Hickman et al. (2011), the Trendall locality was discovered in 1984, but it was not until the publication of Hofmann et al. (1999) that the locality became widely known and was established as one of the most significant early life locations discovered to date, paving the way for a flood of investigations. Stromatolites at the Trendall Reserve are more numerous, more morphologically diverse, and more complex than recorded elsewhere at this time, and they form individual biostromes that can be traced over a strike length of at least 10 km and beyond the reserve extent. Many of the Trendall structures are preserved in three dimensions, providing a clearer understanding of morphology, and enabling structures at other sites in the Strelley Pool Formation (often poorly preserved and displayed in only two dimensions) to be identified as stromatolitic (Hickman, 1980, 2008; Lowe, 1980, 1983; Zegers, 1996; Van Kranendonk and Johnston, 2009). As discussed by Hickman et al. (2011) and outlined below, the Trendall Reserve provides considerable evidence to support a biogenic interpretation for many of the laminated structures observed there, and analogous structures are present at the Dawn of Life Trail site. The Trendall Reserve is unsuitable as a geotourism location; the critical faces are not very extensive in area, and their features are too precious to risk damage. Moreover, the locality is remote and difficult to access, which would place visitors unfamiliar with Australian outback conditions at considerable risk. The more easily accessible Dawn of Life Trail will allow geotourists to examine many of the features that provide critical evidence for evaluating the biogenicity of the structures without risking damage of critical exposures.

Conical stromatolites as indicators of biogenicity

Large, conical stromatolites are some of the most significant specimens found at the Trendall Reserve (Hofmann et al., 1999, fig. 2A,B; Allwood et al., 2006a,b, 2007a,b, 2009; Hickman et al., 2011, figs 8c, 13c,d, 16a). They are up to 1 m high and are mainly preserved in vertical cross-section, although, in some cases, short sections show three-dimensional preservation of the conical laminae around the axis (Hickman et al., 2011, figs 8b, 17a,b). While the larger conical stromatolites found at the Dawn of Life Trail site (Figs 12–15) do not match those at the Trendall Reserve in terms of size and level of preservational detail, some are preserved three dimensionally, and they have many of the other features described below. Similar short sections of three-dimensional preservation can be seen at the Dawn of Life Trail site (Figs 13 and 16).

A second type of conical structure found at the Trendall Reserve consists of numerous well preserved and closely spaced small conical stromatolites often referred to as ‘egg-carton’ stromatolites. Similar ‘egg-carton’ forms occur at the Dawn of Life Trail site (Figs 17 and 18). The Trendall Reserve cones are about 10 cm in height (Hofmann et al., 1999, fig. 2D); although the Dawn of Life Trail small cones are of similar dimension to those at Trendall, they are generally more steeply inclined, perhaps in response to a stronger current flow or a steeper paleoslope. The three-dimensional preservation of ‘egg-carton’ structures leaves little doubt that they are conical. Because it is difficult to produce cones naturally without the involvement of biological processes (Hofmann et al., 1999; Batchelor et al., 2004; Petroff et al., 2010; Hickman et al., 2011), the presence of conical stromatolites, and especially the presence of the same two cone types at both localities, is important evidence for interpreting these structures as biogenic.

Moreover, living stromatolites resembling Strelley Pool conical stromatolites are known from several modern environments. These include Yellowstone National Park, where the mechanism of cone formation has been studied (Walter et al., 1976), and Lake Untersee in Antarctica, the first location to be discovered where modern large conical stromatolites are currently forming (Andersen et al., 2011).

Differential features

Most cones and other stromatolitic structures initiate from points on a flat surface, usually developing above layered stromatolites that can be several centimetres thick (Fig. 14). It is rare for cones or columns to originate above pre-existing topographic features, such as crystal fans and ripple marks (Allwood et al., 2009), but where draping over irregularities does occur, upward accretion

is not generally maintained (Allwood et al., 2007b). Large conical structures maintain their profile because accretion is greatest at the cone axis (Batchelor et al., 2004). Many of the Dawn of Life Trail conical stromatolites display these features, and it is possible to trace the synoptic profile of the cones in vertical section within outcrop (Figs 11 and 12).

Cones of similar dimension, or of varied size, may develop on individual bedding planes. New cones may also originate at higher bedding-plane levels between existing cones, or even develop on the flanks of existing cones. Some of these features can be observed at the Dawn of Life Trail site, although they are generally poorly preserved and not always easy to detect. The Trendall Reserve, on the other hand, contains classic examples of such structures, such as the adventitious column (a small column developed in an unusual place and subsidiary to the main structure) commonly referred to as 'Mickey Mouse ears', which consists of two adjacent and partially linked cones situated on the flank of a much larger cone (Hofmann et al., 1999, figs 2B,C; Hickman et al., 2011, figs 18b–d, 21). In this case, although the lower laminae of the adventitious column are continuous with those of the main cone, the middle laminae of the large cone terminate abruptly against the wall of the small cone and upper laminae drape over it. The adventitious cone had a profile several centimetres higher than that of the main cone flank.

Differential features, such as those described above, are incompatible with non-biological precipitation as deposition from a fluid should form a single continuous sheet, and therefore cannot be satisfactorily explained by invoking differential precipitation (Allwood et al., 2009; Hickman et al., 2011).

Cone spacing and alignment

Another feature supporting a biological origin is the regular spacing of stromatolite cones, a feature best illustrated by the 'egg-carton' stromatolites. Small cones at the Dawn of Life Trail site also display such patterns, although only small areas can be seen in plan view (Figs 17 and 18). Petroff et al. (2010) attributed this regular spacing to control by competition for nutrients.

Many conical stromatolites are characteristically slightly elliptical or polygonal in plan view, probably due either to growth on a local paleoslope or to a preferred current direction during their growth (Hofmann et al., 1999). This feature is well developed in conical stromatolites at the Trendall Reserve, but can also be seen at the Dawn of Life Trail site (Fig. 15).

Lamina steepness

Another important feature of both large and small cones is that the laminae are considerably steeper than the angle of repose (Fig. 16). This is the angle at which a slope becomes too steep for particles to remain in situ without some sort of binding agent, such as a microbial mat (Hofmann et al., 1999; Hickman et al., 2011, fig. 23).

Variations in lamina thickness

Some authors have argued that laminae in the Strelley Pool Formation cones are isopachous (equal in thickness throughout their length) and that such a feature is diagnostic of abiotic precipitation (Pope and Grotzinger, 2000; Lindsay et al., 2003a,b). Close examination of vertical profiles of laminae from the Dawn of Life Trail site show that the laminae in these stromatolites are not isopachous (Figs 12 and 16), and instead thicken both in the crestal zones and in troughs between the cones (Hofmann et al., 1999; Allwood et al., 2006a; Van Kranendonk, 2007). Variations in laminae thickness within one of the Trendall Reserve conical stromatolites have been measured and plotted; these data clearly show that the laminae vary in thickness along their length, dividing, pinching out, and becoming intercalated and lensoid (Hickman et al., 2011, figs 16a,b). Such a pattern is typically biogenic.

Axial zones

Another characteristically biogenic feature of conical stromatolites is the presence of an axial zone (Hofmann et al., 1999; Hickman et al., 2011, figs 19, 20; Grey, unpublished data). Axial zones form as a second-order feature at the axis tip of each lamina, and consist of a narrow region in which there is a distinct steepening of the slope just below the apex; the apex itself is commonly lensoid with one or more laminae laterally offset as they are stacked. This feature has been found in living conical stromatolites, with the mechanism for its formation described by Walter et al. (1976). The presence of an axial zone indicates that a biological process must have been involved in cone formation, as physical and chemical processes alone cannot account for the formation of axially zoned conical stromatolites. Although Hofmann et al. (1999) originally reported that axial zones were not present in Strelley Pool Formation conical stromatolites, a narrow but distinctive axial zone has now been recognized in the large conical stromatolites of the Trendall Reserve (Hickman et al., 2011, fig. 20). So far, no axial zones have been observed in conical stromatolites preserved at the Dawn of Life Trail site, but the narrowness of this feature suggests that it is unlikely to be exposed in vertical profiles in the field.

Other indicators of biogenicity

Other details of morphology pointing to a biological origin for the Strelley Pool Formation stromatolites were documented by Van Kranendonk (2007, 2011) and Hickman et al. (2011). These features include branching structures, distinct growth walls on domical stromatolite margins, and interference between stromatolite form and structures produced through current action. Some of these features can be seen by detailed examination of stromatolites at the Dawn of Life Trail site, but not all are readily recognizable in the field.

In addition to the morphological study of stromatolites and microfossils from the Strelley Pool Formation, numerous

geochemical studies of this material have also been undertaken. These are detailed in Hickman et al. (2011), with the net result again supporting a biogenic origin for these structures. So far, similar analyses have not been performed on Dawn of Life Trail samples, other than the preliminary PIMA study reported above. There is clearly scope for additional studies to be undertaken at the Dawn of Life Trail site.

As a result of detailed study of structures at the Trendall Reserve and other Strelley Pool Formation localities, many researchers have concluded that the biogenicity of these stromatolites is beyond reasonable doubt (Hofmann et al., 1999; Allwood et al., 2006a,b, 2007a,b, 2009; Van Kranendonk, 2007, 2011; Hickman et al., 2011). Therefore, Paleoarchean coniform stromatolites were most probably formed by microbial accretion in a similar manner to much younger stromatolites and living microbialites. The range of morphological features observed in these localities indicates dynamic growth within a changing environment. Stromatolites at the Dawn of Life Trail site add to the body of knowledge about these ancient structures, and support their interpretation as evidence for early life.

Future investigations

Before site development can be further advanced, future work options, possible trail location, and site protection issues outlined here, will all require further consideration.

Important questions remain in regard to the local geology, and there is considerable scope for further research in this area. The detailed stratigraphic position of the site in relation to the regional distribution and subdivision of the Strelley Pool Formation needs to be determined, and, if possible, a precise depositional age range for the succession at the Dawn of Life Trail site obtained, preferably using zircon U–Pb geochronology, either on suitable volcanic rocks or using detrital zircons from sedimentary rocks. Further investigations of the local hydrothermal history are also warranted. More detailed studies of stromatolite morphologies are necessary, and should be accompanied by a search for possible microfossils. Finally, there is a need to identify and carry out appropriate geochemical investigations on these rocks.

A trail for the general public

The Dawn of Life Trail site has potential for geotourism with the twin aims of exposing the general public to one of the geoheritage treasures of Western Australia, and assisting in creating better recognition of the intrinsic importance of the sciences of astrobiology and geology. Furthermore, there is a significant demand from the general public for the provision of a location where the evidence for early life can be viewed in the field. Developing the Dawn of Life Trail to satisfy this demand would also help to direct interest away from more vulnerable sites of significant scientific interest, such as the State Geoheritage Reserves, thereby protecting them from damage through oversampling or casual collecting.

The site is easily accessible, reducing the risks created by having inexperienced travellers attempting to visit remote locations. It is close to a main road, within a 1 hour drive of both Marble Bar (60 km) and Nullagine (53 km), and within 3½ hours of Port Hedland. At present, there is no formed track, but wheel tracks are developing into a well-defined track as the site becomes better known. An approach to Main Roads Western Australia some years ago indicated that they would at least consider developing a 'rest area' at the proposed parking site, with a suitable access track and possibly some sort of shade.

Development of the site would benefit the tourism industry in local centres like Marble Bar and Nullagine, with casual enquiries to tour operators, especially those running safari and eco-tours, indicating sufficient interest to consider including such a site in their itinerary. Locals and tour operators could be encouraged to take an interest in conserving the site, in that damage to the locality would be detrimental to them.

Other factors would also need to be considered if further development of the site is to take place. These include the clearing and marking of a proper walking track, and the provision of signage. A few well-chosen illustrations and explanations could point out significant features, help non-specialists understand the significance of the site, and emphasize the need to protect geological sites as part of our heritage.

The trail in science education

The Dawn of Life Trail is also likely to be a significant site for science education. It satisfies many of the concepts embodied in the NASA Spaceward Bound program. This program aims to train the next generation of space explorers by having students and teachers participate in the exploration of scientifically interesting, but remote and extreme, environments on Earth as analogs for the human exploration of the Moon and Mars (Heldmann et al., 2007). The Pilbara region falls into this category and provides the chance for teachers to gain specialist science knowledge and to work with scientists in a field environment. The Dawn of Life Trail could offer an integrated field experience for teachers and students from all levels of education, embracing the skills and knowledge of biology, chemistry, geology, and physics when required.

With the release of the Australian Curriculum (AC) documentation, which is to be mandatory for all Australian schools by 2013 (Australian Curriculum, Assessment and Reporting Authority, 2012), it is apparent that the Dawn of Life Trail can provide activities that directly link to three AC areas: Science Understanding, Science as a Human Endeavour, and Science Inquiry Skills. As one example, within Middle School at Year 8, a module about 'Astrobiology' could be developed, connecting the Pilbara expedition, the Dawn of Life Trail, and the meaning and relevance of stromatolites. The proposed topic would incorporate the Australian Curriculum areas of Biological Sciences (Cells are the basic units of living

things and have specialized structures and functions — ACSSU149), Earth and Space Sciences (sedimentary, igneous and metamorphic rocks contain minerals and are formed by processes that occur within Earth over a variety of timescales — ACSSU153), linked under the theme of Science as a Human Endeavour (Science knowledge can develop through collaboration and connecting ideas across the disciplines of science — ACSHE226).

A series of modules are planned that will focus the students' attention on 'what is life?' This module would begin with a series of discussions about the characteristics of living organisms and would include investigations into cells and cell structure. An integral area would be to examine the understanding of life within a geological timeframe, including information on early life processes with reference to the Pilbara region, and providing examples of biotic structures that are now preserved as fossilized stromatolites. Students would be able to handle different types of rocks and minerals, and then observe the characteristic layering structure that indicates microbial action.

Discussions and activities linking stromatolites to space science would follow, with an emphasis on the connections between conditions on early Earth and those on Mars, and pointing out the reasons why space-science researchers are investigating these areas. Students would use aspects from each of the mentioned content areas to assist them in understanding what these scientists do. Students would then apply practical skills, as required under Science Inquiry Skills, to plan, conduct, and process data from their own experiment. The Dawn of Life Trail would therefore become a very important teaching resource, and would enable an enriching Earth and Space Science field-trip experience if areas along the trail were clearly marked, with references to class materials designed to generate thoughts and discussions about the significance of this region and life on Earth, along with reasons why these areas are a part of our heritage.

By linking the Dawn of Life Trail to the Australian Curriculum, an opportunity could be provided for students to learn about scientists working in this field, and gain a greater understanding of science careers in geoscience and other disciplines that promote an understanding of the early Earth, particularly in locations such as the Pilbara.

Issues for consideration

Issues that need consideration before further development of the site can take place include:

- The need for a better understanding of the science of the site. More detailed investigation of the stromatolites and other features are needed to establish that they are comparable to structures elsewhere. The stratigraphic location of the site should be refined and, if possible, a geochronological age determined. Organic geochemistry should be employed to confirm evidence for stromatolite biogenicity, and a search should be undertaken to see if microfossils can be found.

- Site management. Although the stromatolites at the locality may not be quite as well preserved or as scientifically significant as those at other locations, it is nevertheless an important site. Visitors will need to respect the site and refrain from collecting, although if damage does occur, any losses might not be as disastrous as at other sites. Explanatory notices could be erected along the trail to explain salient features of the site, identify specific features, and stress the need for conservation.

- Land access issues. Preliminary investigations indicate that there are no access issues, but this will need to be formally confirmed. Preliminary investigations showed that there are no registered aboriginal sites within the area of interest. However, now that a specific site has been delineated, traditional owners will need to be consulted, and asked to provide a formal clearance report. The site is located on Corunna Downs Station; an informal approach to the leaseholder some years ago suggested there would be no problem with public access due to the proximity to the main road. The location is close to, but not actually within, the Gallop Well water reserve, but this reserve has long been abandoned and the site's proximity should not cause a conflict of use. A check is needed to determine if there are any current mineral tenures over the site, with approaches made to any leaseholders.

- Access issues. Main Roads Western Australia will need to be consulted about vehicle access. As traffic to the site increases, signage, the turn off from the main road, grading of a better access track to the proposed parking spot, and the construction of a designated parking area will all require attention. The possibility that Main Roads Western Australia would make the site a designated rest area should be investigated further. The issue of developing a properly marked walking trail with explanatory signage also requires investigation.

- Sourcing of materials. If the Dawn of Life Trail becomes a component of the Australian Curriculum, there will be a demand for study materials in large quantities. These cannot be sourced from the known Paleoarchean sites, such as the Dawn of Life Trail and Trendall, due to the need to conserve the evidence found at the sites and the rarity of well-preserved specimens. However, there are many younger sites nearby, for example in the Neoarchean and Neoproterozoic, which contain comparative material that could be sampled without detriment.

Conclusions

The Dawn of Life Trail site provides evidence of Paleoarchean life and, in conjunction with several other Pilbara sites, is key to understanding the origin and diversity of ancient life, especially stromatolites, between 3426 and 3350 Ma. In addition, the Dawn of Life Trail site is ideally located to meet requirements for a public viewing area and significant educational site due to its location near a main road and proximity to the centres of Marble Bar and Nullagine. Even though the site contains features of considerable scientific interest, the

material does not seem to be unique or exceptionally well preserved, and as such may be better able to sustain the demands of public access than the other sites now managed as State Geoheritage Reserves. Making this site publicly available might also channel attention away from more scientifically significant sites.

The preliminary site mapping and inventory of site assets reported here has identified features of scientific interest that require further investigation before the locality can be confirmed as suitable for public access. The Mars Society Australia and Spaceward Bound Pilbara Team hope to continue research activities at the Dawn of Life Trail site. Of immediate relevance to the development of the area is further mapping to extend and infill the dataset presently available. In particular, specific features such as quartz veins, hydrothermal vents, and faults need to be located with greater confidence. These data will be used to further develop the case for development of a formal geoheritage trail at the site.

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Appendix

A note about State Geoheritage Reserves (Western Australia)

State Geoheritage Reserves are created under Section 41 of the Western Australian Land Administration Act 1997, through a Management Order that vests them with the Minister for Mines and Petroleum, for management by the Executive Director of the Geological Survey of Western Australia (the most senior State Government geologist) on behalf of the State Government. Reserves are sites of such outstanding scientific and educational value that their importance is recognized nationally and internationally. Reserve status provides a management process for preventing inappropriate activities, such as unnecessary destructive sampling or any other form of ground disturbance that could reduce or destroy geoscientific value.

Anyone intending to enter a State Geoheritage Reserve, for whatever purpose, should first submit a 'Proposed Activity at a State Geoheritage Reserve' form to the Executive Director of the Geological Survey of Western Australia. Access will normally be granted to parties only wishing to view and photograph features within the reserves, although camping on the reserves, and driving off established roads and tracks is not permitted. There must be no collecting from a Reserve (including collection from scree material) without prior approval (via the issue of a collecting permit) from the Executive Director GSWA.

Full information on management procedures is provided in GSWA Record 2010/13 (Grey et al., 2010), which can be viewed and downloaded free-of-charge through the website of the Department of Mines and Petroleum, at <www.dmp.wa.gov.au/gswapublications>.

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