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Searching for stromatolites: The 3.4 Ga Strelley Pool Formation (Pilbara region, Western Australia) as a Mars analogue

Jonathan D.A. Clarke [a,*], Carol R. Stoker [b]

[a] Mars Society Australia, c/o 43 Michell St., Monash, ACT 2904, Australia
[b] Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035, United States

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ABSTRACT

Stromatolites are readily identified, outcrop scale indicators of potential biological activity, even though constructed by microbes. Their presence in –J.5 Ga volcano-sedimentary successions of the Pilbara region of Western Australia suggests that they might also occur in similar, Noachian-age successions On Mars. Field and basic laboratory studies of one such occurrence near Nullagine highlight many issues that would be faced by any stromatolite search strategy on Mars. Firstly, the stromatolites are found in local aggregations that make up a very small part of the overall succession, possibly as little as one millionth of the outcrop area. An effective search strategy would require a combination of remote sensing to highlight features with high probability of hosting stromatolites, precision landing, and extensive cross-country mobility, difficult to achieve with a purely unmanned exploration system. Secondly, the limited analytical suite available to any unmanned mission would make conclusive determination of the biogenicity of any stromatolite-like feature on Mars very difficult. This is shown by the controversy over the biogenicity of the Pilbara examples, despite a much greater range of analytical techniques applied to the Pilbara examples. Once possible stromatolites features have been found on Mars, sample return would be imperative to determine their biogenicity.

1. Introduction

Stromatolites (Walter, 1976) are medium to large scale convex, conical, columnar or branching structures constructed by microorganisms. Because they lithify as they form, either by precipitating carbonate or trapping and binding sediments, they have high preservation potential. They can be readily recognised in outcrop and are strong evidence of the presence of microbial communities. The stromatolites may preserve microfossils, organics, and biogenic isotope ratios. As mesoscopic structures they provide sites for preferential sampling in the search of biosignatures.

The Early Archean (3.2–3.6 Ga) supracrustal rocks of the Pilbara (Fig. 1) have been proposed as Mars analogues by various authors on the basis of the preservation of similar surface environments (mafic volcanic, subaqueous, and hydrothermal) in rocks of similar antiquity to the earlier epochs of Mars when its surface was dominated by similar processes and environments (McKay and Stoker, 1989). The evidence for life in the Pilbara rocks at almost 3.5 Ga, most visibly as stromatolites, raises the possibility that similar evidence could be found in coeval rocks on Mars, and makes the Pilbara a prime site not only for studying ancient life but for testing methods and technologies that could be used on Mars and training investigators in the skills necessary to interpret the data.

The Archean stromatolites of the Pilbara have been extensively studied for more than 40 years by numerous researchers with a multiplicity of techniques using large sample masses (e.g. Marshall et al., 2007). Their biogenicity has been often questioned, however the weight and diversity of the evidence, as well as the most parsimonious reasoning, indicates that they are indeed biogenic in origin.

Unlike the Pilbara stromatolites, the data obtained on any martian examples identified by robotic means would most likely consist largely of imagery and limited field analyses, with the possibility of a very small suite of samples being returned to Earth at some stage. This would mean that options for reducing ambiguity and testing alternate hypothesis would be very limited. The possibility for open-ended conclusions would conversely be much greater. Reducing or at least constraining these uncertainties through using the Pilbara stromatolites as analogues for what might be found on Mars is highly desirable.

2. Objectives

Our aims in this paper are to illustrate issues and potential uncertainty in determining whether or not particular features are

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* Corresponding author. Fax: +61 2 62499930.
E-mail address: Jon.Clarke@bigpond.com (J.D.A. Clarke).

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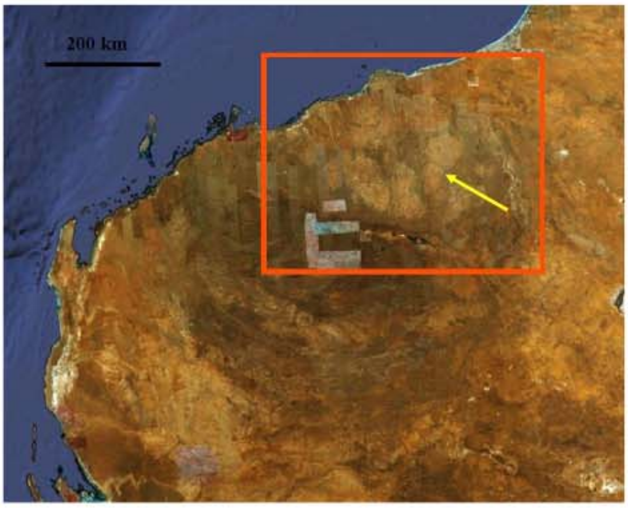

Fig. 1. Study location shown on Google Earth image. Box shows the Pilbara region, arrow the study location.

biogenic through approaching a field example at the level of detail and with similar tools to those that might be used on an unmanned Mars rover. In our paper we will:

(1) Outline the Mars analogue significance of the Pilbara region, in particular its record of ~3.4 Ga surface environments and biosphere.
(2) Summarise what is known about the Strelley Pool Formation (SPF), one of the units that hosts evidence for 3.4 Ga biosphere.
(3) Present results from field observations using primarily imaging, spatial localisation and limited sampling and analysis of a series of stromatolitic outcrops of the SPF.
(4) Discuss what scientific and methodological lessons that can be drawn from ongoing controversies regarding the evidence for a 3.4 Ga biosphere in the Pilbara if stromatolitic features are discovered on Mars.

3. The Early Achean of the Pilbara as a Mars analogue

3.1. Similarity of the Pilbara and early Mars

The Early Archean rocks of the Pilabra (Van Kranendonk, 2007) are approximately coeval with the Noachian/Phyllocian epochs on Mars (Fairén et al., 2010; Bibring et al., 2006). Furthermore, the rocks on the two planets were formed under apparently similar conditions, with surface liquid water, mafic volcanism, and hydrothermal activity present in the environments. As a result both the host lithologies and the surface mineralogy of the Archean of the Pilbara and the Noachian/Phyllocian of Mars are very similar (Brown et al., 2004, 2005, 2010). The Pilbara is one of few terrestrial regions that not only records similar environmental conditions to early Mars, but the record is of similar antiquity.

3.2. Stromatolites on Mars?

Stromatolites are the oldest macroscopic evidence of life on Earth. While not all stromatolite-like structures are biogenic, not all biogenic stromatolites preserve microfossils or biomarkers (Schopf, 2006; Brasier et al., 2006), and both microfossils and biomarkers can be found in non-stromatolitic lithologies (e.g. Marshall, 2007), recognition of stromatolite-like features on Mars would be a major discovery and would provide a focus for subsequent investigations. Therefore numerous researchers have suggested that identification of stromatolitic morphologies be included in the search for life on Mars (e.g. Walter and Des Marais, 1993; McKay and Stoker, 1989), or have drawn parallels between the stromatolites of the Pilbara and what might be found on Mars (e.g. Allwood et al., 2007; Van Kranendonk, 2006).

4. Strelley Pool Formation Stromatolites in the study area

The SPF (Hickman, 2008), formerly the Strelley Pool Chert of Lowe (1983) and Van Kranendonk and Morant (1998), has been geologically mapped over about 30,000 km^2 of the east Pilbara. Outcrops of the formation are regionally discontinuous due to folding, faulting, and locally being concealed by unconformably overlying formations. In most areas, the succession of the Strelley Pool Formation is less than 50 m thick and is composed of siliciclastic and volcaniclastic units, laminated grey–white chert mainly representing silicified carbonate rocks, carbonate rocks with only minor silicification, and minor primary black or white chert with crystal fans (interpreted as pseudomorphs after aragonite, gypsum, or barite). Although the formation is extremely thin compared to other >3.2 Ga geological formations of the east Pilbara, which have a combined thickness of >15 km, its scientific importance is exceptional because it contains the most diverse and abundant early Archean fossil assemblage on Earth, and because it provides unique evidence on ca. 3.4 Ga depositional environments and early Archean processes of crustal evolution (Hickman et al., 2011). The Strelley Pool Formation was deposited during a 75-million-year break in volcanic activity (Hickman, 2008), which gave early life the first known lengthy opportunity to flourish on Earth.

The area we examined is known as the Dawn of Life Trail (DLT) of Grey and Caldon (2008), and is site 5.2 in the field guide of Van Kranendonk and Johnson (2009). The area is under study for a geoheritage trail accessible to those interested in the earliest evidence of life on Earth (Grey et al., 2012). In the study area, the succession of the SPF dips very steeply (~60°) predominantly to the east, but local dip reversals indicate some structural complexity. The complexity may be related to faults that separate the DLT outcrop from the main outcrop of the formation 1.5 km to the west (Fig. 2). Low-angle quartz veins which intrude the succession were formed by

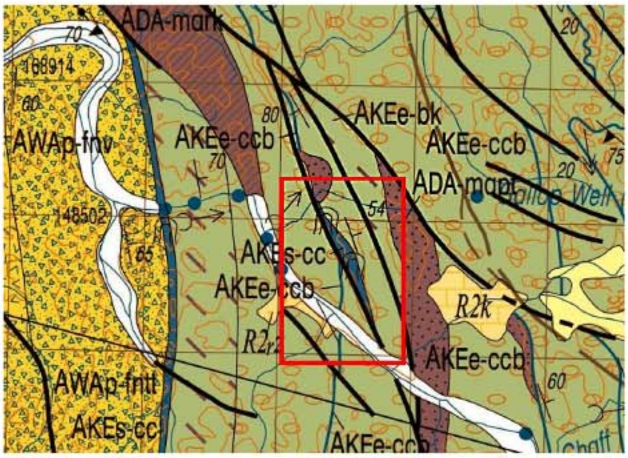

Fig. 2. Geology of the study area (approximate position red box), extracted from Williams and Bagas (2007a). Major Archean Formations are Panorama (3.45–3.427 Ga). Euro Basalt (3.325–3.315 Ga), Strelley Pool (3.325 Ga). Map codes represent: AKEe-bk = Euro Basalt with local pillows. AKEe-bbo = komatiitic Euro Basalt with local spinifex. AKEe-ccb = black chert in Euro Basalt. AKEs-cc = Strelley Pool Formation (main stromatolite-bearing unit). ADA-mapt = ultramafic sills of the Dalton Suite, now altered to serpentinite–chlorite schist. C1 = colluvium, A1c = modern alluvium, R2rZ = silcrete, R2k = calcrete (locally silicified). Grid squares 1 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Typical outcrop at the study area, looking south. Note partial spinifex plant cover, cherty outcrops (often stromatolitic), and siliceous scree between outcrops.

hydrothermal activity along these faults. Stromatolites comprise only a small part of the overall succession at DLT, and this may be a consequence both of their limited primary depositional distribution and post-deposition destruction of primary fabrics by silicification and various other types of alteration. Outcrop thickness at DLT is highly variable, from 5 to 100 m, and a basal conglomerate is locally present (Van Kranendonk and Johnson, 2009).

Paraconformably to disconformably underlying the Strelley Pool Formation is the 3.45–3.427 Ga Panorama Formation of the upper Warrawoona Group. The Panorama Formation consists of flow-banded, fine-grained and porphyritic rhyolite, fragmental felsic volcanic rocks, and minor banded and black chert.

Disconformably to paraconformably overlying the Strelley Pool Formation is the 3.35–3.325 Ga Euro Basalt of the lower Kelly Group. The Euro Basalt is a thick, predominantly basalt succession also containing dolerite and komatiitic basalt, with minor chert, komatiite, clastic and volcaniclastic sediments, all regionally metamorphosed to greenschist facies. In this regard the successions differ from those expected on Mars which are unlikely to have experienced regional metamorphism.

Some local ultramafic rocks forming units parallel or sub-parallel to bedding in the Strelley Pool Formation and the Euro Basalt are most likely the same age as the Euro Basalt, but larger intrusions probably belong to the 3.18 Ga Dalton Suite (Van Kranendonk, 2006). The ultramafic rocks have been regionally metamorphosed to form serpentinite–chlorite and carbonate–tremolite schists.

An extract from the geological map of the region (Williams and Bagas, 2007a) is shown in Fig. 2. This shows how, in the study area, the SPF has been structurally interleaved with the Euro Basalt.

5. Methodology

The work was undertaken as part of the 2011 Spaceward Bound Pilbara Expedition, part of the goals of which were to map the DLT site (Grey et al., 2012). The expedition members included planetary and geoscientists, biologists, engineers, and teachers, and most were engaged in the mapping procedures. We traversed the site looking for stromatolites which occurred in low but prominent chert ridges. The chert outcrops were walked until no more stromatolites were visible. Each occurrence was photographed using a camera with a linked GPS and the positions plotted as a .kmz file in Google Earth. Clusters of images defined the outcrops hosting stromatolites. The outcrops were correlated to features visible in the Google Earth image. Polygons showing the main stromatolite localities were defined based on the photograph coordinates and topographic features.

Because of the need to preserve the site, no rock hammering was carried out. All samples collected were of loose blocks and were as small as possible. Sample numbers are therefore small compared to normal field investigations, but reflect the limited number of analyses generally obtained during unmanned exploration of the Mars surface.

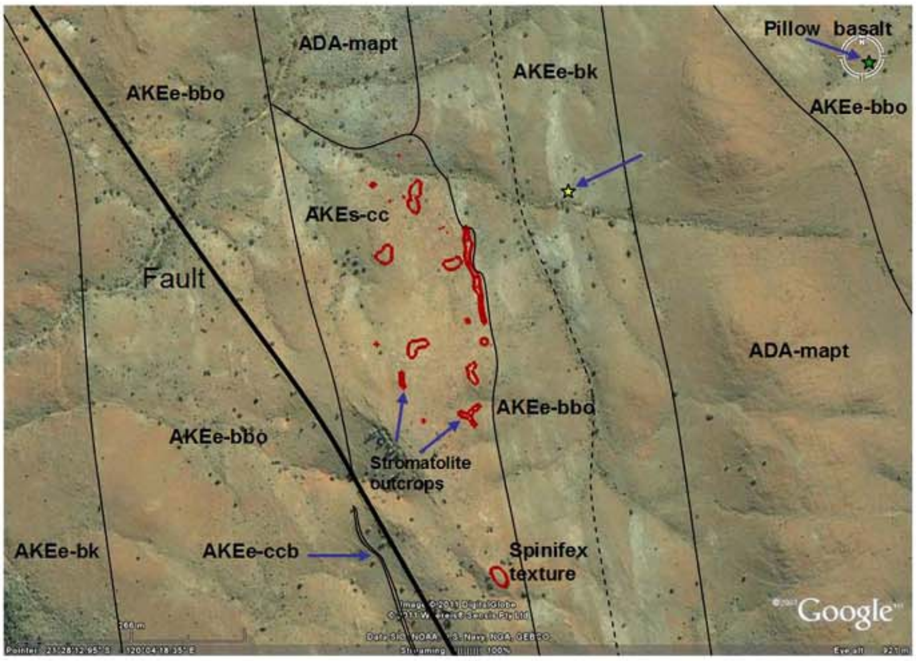

Fig. 4. Locations of stromatolite outcrops in the DLT area shown by red outlines on a Google Earth image. AKEe-bk = komatiitic Euro Basalt. AKEe-bbo = pillow basalt of Euro Basalt. AKEe-ccb = black chert of Euro Basalt. AKEs-cc = Strelley Pool Formation (main stromatolite-bearing unit). ADA-mapt = metaperidotite of the Dalton Suite, now altered to serpentinite–chlorite schist. Image width 1064 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Representative stromatolite morphologies at the DLT. (A) Laterally-linked conical stromatolites passing up into near-horizontal stromatolitic laminae. (B) Convex to conical stromatolite with possible filled central cavity (arrowed). A geology hammer provides scale. (C) Branching columnar stromatolites (arrowed). (D) 3-D "egg carton" laterally-linked conical stromatolites.

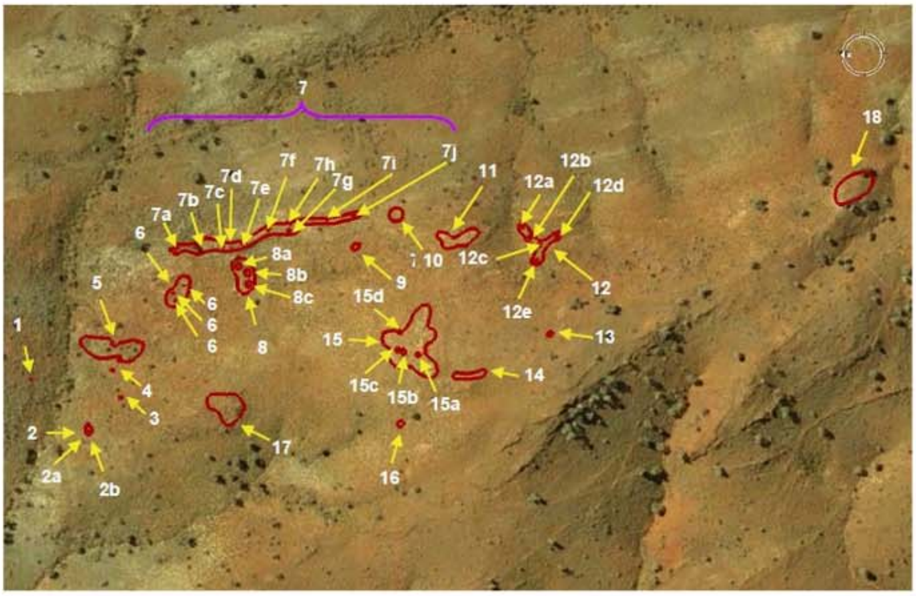

Fig. 6. Map of numbered stromatolite outcrops in the study area. Note that the base image from Google Earth has been rotated through 270o relative to the previous base images. Image width 544 m.

6. Results

6.1. Exposures

The main silicified portion of the SPF in the study area forms a low hill, with individual chert beds forming small steep outcrops that shed siliceous fragments (Fig. 3). These mantle the surface obscuring the intervening lithologies. Other lithologies occur as exposures in the banks and beds of small gullies and creeks. Approximately 25–30% of the surface is covered by low Spinifex plants (*Triodia* sp.).

Stromatolitic chert outcrops were both fine-grained and preserved fine laminations, and locally are clearly replacing carbonates. Some beds of coarser-grained carbonate marble were

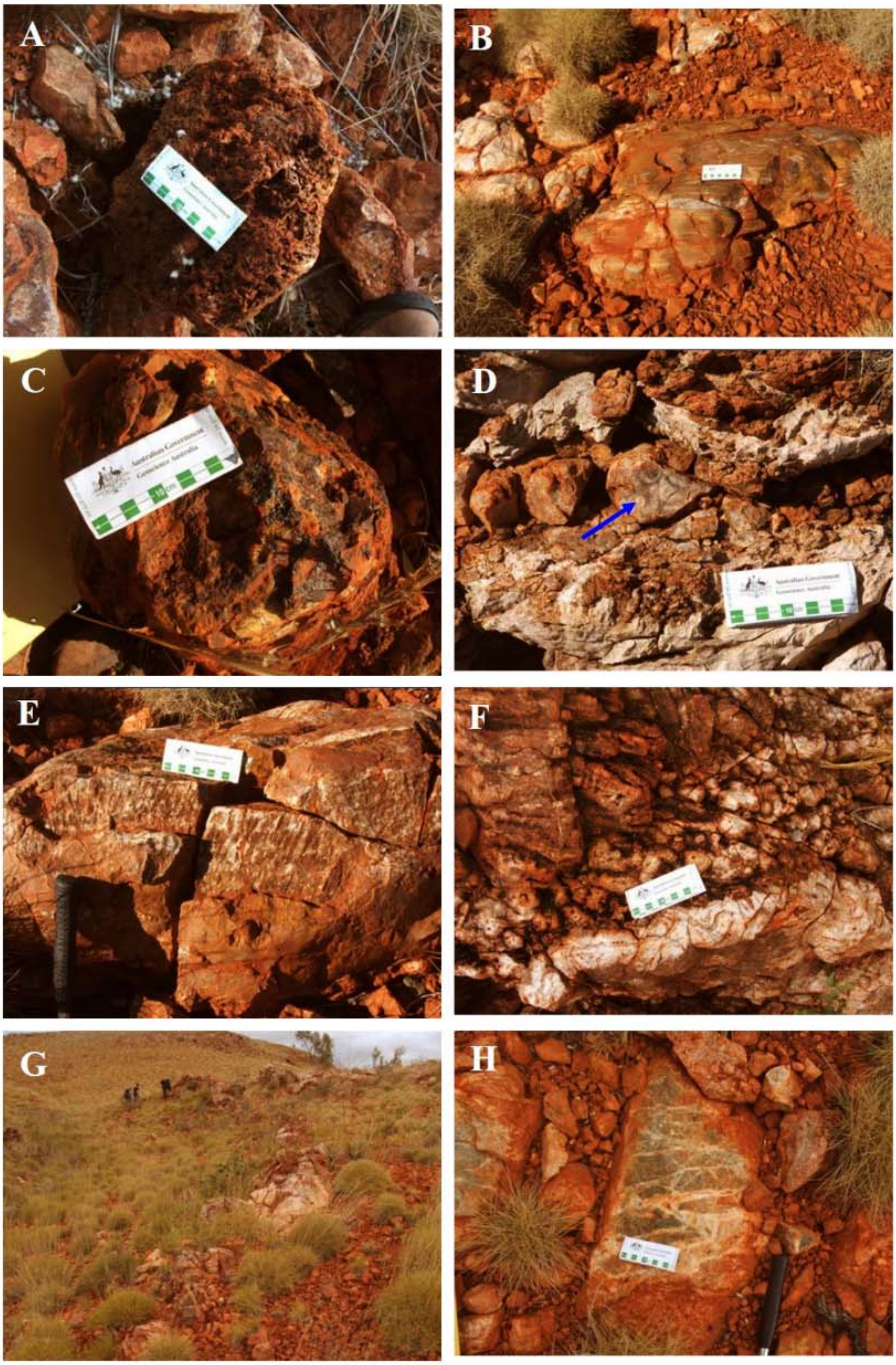

Fig. 7. Hydrothermal vent features. (A) Euhedral quartz filling a cavity (location 16). (B) Goethite-stained laminated to low-relief stromatolitic chert, possibly relacing sulphides (location 15). (C) Possible hydrothermal breccias (location 14). (D) Botryoidal cavity-filling quartz (arrowed), location 5. (E) Cross section of mound of hollow columns of nail-hole barite quartz and carbonate, possibly associated with hydrothermal venting (location 14). (F) Looking down on hollow columns of nail-hole barite quartz and carbonate and associated cavity filling quartz (location 5). (G) Cross-cutting, low angle bucky quartz vein connecting two stromatolite horizons (location 7 in foreground, and location 8 middle distance). (H) Quartz-veined and silicified basalt (location 7).

preserved. Elsewhere cherts were coarser grained and did not preserve fine detail. We suggest that this is due to either a different depositional environment or diagenetic, hydrothermal or metamorphic overprinting. The limited occurrence of stromatolites may therefore either reflect originally limited habitats or be a preservational artefact.

6.2. Mapping

A more detailed geological map of the area (Fig. 4) was drawn up from data collected by the method described above with control from the existing 1:100,000 scale geology map (Williams and Bagas, 2007a. Outcrops were plotted on the same map. In general the detailed mapping confirms the earlier regional mapping.

6.3. Stromatolites

In total 97 different stromatolitic features were imaged. The most common stromatolite morphologies (based on Preiss, 1976) were domes (45 imaged – 46%). These were followed by low relief domes (26 imaged – 27%) and cones (24 imaged – 25%). Least common were the "Micky Mouse ears", formed by adventitious cones that grow on the flanks of larger cones. (2 imaged – 3%). Typical stromatolite morphologies are shown in Fig. 5.

6.4. Site description

Thirty eight stromatolite locations were identified and photographed. These were grouped in 18 outcrops or clusters of outcrops (Fig. 6). They consist of:

Outcrop 1: Small outcrop of stromatolites.
Outcrop 2: Scattered small outcrops of stromatolites.
  Outcrop 2a – small outcrop of stromatolites.
  Outcrop 2b – small outcrop of stromatolites.
Outcrop 3: Small outcrop of stromatolites.
Outcrop 4: Small outcrop of stromatolites.
Outcrop 5: Small outcrop of stromatolites associated with mounds of bladed barite, quartz, and carbonate quartz, possible hydrothermal mound.
Outcrop 6: Scattered small outcrops of stromatolites.
  Outcrop 6a – small stromatolite outcrop.
  Outcrop 6b – small stromatolite outcrop.
  Outcrop 6c – small stromatolite outcrop.
Outcrop 7: Laterally extensive stromatolite outcrop showing silicified and primary limestone stromatolites with throughgoing laminae, also altered marble beds.
  Outcrop 7a – low relief laminar stromatolites and small conical forms.
  Outcrop 7b – small conical stromatolites, some micky mouse ears.
  Outcrop 7c – small domical stromatolites with disrupted laminae.
  Outcrop 7d – small stromatolites, some strongly conical, others apparently growing on a slope, indicated by a growth angle of less than vertical.
  Outcrop 7e – Outcrop 6f – partially silicified domical and conical stromatolites, some growing on slope.
  Outcrop 7g – diverse, partially silicified domical and conical stromatolites, some growing on slope, some with disrupted laminae.
  Outcrop 7h – partially silicified stromatolites.
  Outcrop 7i – partially silicified stromatolites.
  Outcrop 7j – partially silicified stromatolites.
Outcrop 8: Scattered small stromatolite outcrops.
  Outcrop 8a – small stromatolite outcrop.
  Outcrop 8b – small stromatolite outcrop.
  Outcrop 8c – small stromatolite outcrop.
Outcrop 9: Small stromatolite outcrop.
Outcrop 10: Small stromatolite outcrop.
Outcrop 11: Large stromatolite outcrop with low domes and small laterally linked conical stromatolites cartons, nearby are volcanic breccias.
Outcrop 12: scattered outcrops and float of stromatolites in black chert. Dip reversal evident between different outcrops.
  Outcrop 12a – small black chert stromatolite outcrop.
  Outcrop 12b – small black chert stromatolite outcrop.
  Outcrop 12c – small black chert stromatolite outcrop.
  Outcrop 12d – small black chert stromatolite outcrop.
  Outcrop 12f – small black chert stromatolite outcrop.
Outcrop 13: Possible hydrothermal mound, associated with mounds of bladed barite, carbonate, and cavity filling quartz.
Outcrop 14: Low amplitude yellow-stained chert stromatolites.
Outcrop 15: Cluster of domical silicified stromatolite outcrops, some in black chert, locally yellow-stained, at top of hill.
  Outcrop 15a – white chert stromatolites.
  Outcrop 15b – grey cherty stromatolites.
  Outcrop 15c – black chert stromatolite outcrop.
  Outcrop 15d – black chert stromatolite outcrop.
Outcrop 16: Outcrops of diverse stromatolites (cones, domes), also quartz after platy quartz and euhedral cavity filling quartz

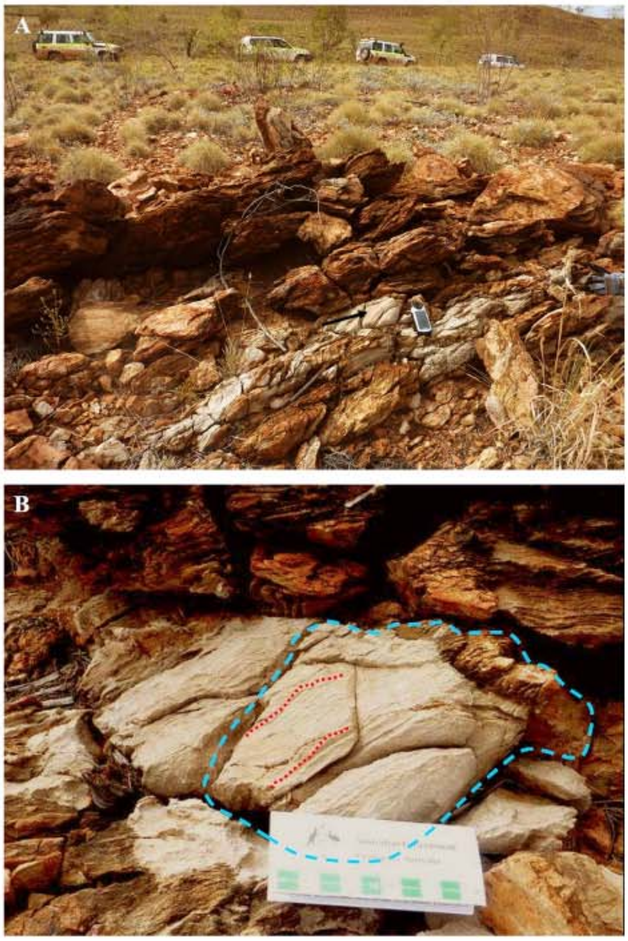

Fig. 8. (A) Outcrop of partially silicified stromatolitic limestone. Limestone is very light grey, silicified material is standing out from the surface. Location of loose block arrowed. Hand-held GPS provides scale. (B) Close up of loose block (outlined in blue) with visible stromatolitic layering (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggestive of a high level hydrothermal vent with boiling water (quartz pseudomorphs after platy calcite).

Outcrop 17: Area of yellow-stained and gossanous laminar silica and low stromatolites, this is interpreted as another hydrothermal vent.

Outcrop 18: southernmost stromatolite outcrop.

Of these, seven small outcrops in two clusters (12 and 15) were black in appearance, suggesting preserved carbonaceous matter. Five outcrops had evidence for exhalative activity, two (5 and 13) had mounds of hollow columnar stromatolites and cavity-filling quartz, two (14 and 17) had horizontal laminated to low amplitude yellow-stained (probably goethitic after pyrite) stromatolites. A fifth site had platy quartz and euhedral cavity filling quartz, suggesting deposition in the boiling zone of a hydrothermal systems (Dong et al., 1995).

6.5. Hydrothermal features

Several chert localities show signs of near surface hydrothermal activity. These include quartz pseudomorphs after platy quartz, euhedral quartz (Fig. 7A), goethite-stained laminated to low-relief stromatolitic chert (possibly relacing sulphides, Fig. 7B), apparent hydrothermal breccias (Fig. 7C), botryoidal cavity-filling quartz (Fig. 7D and F) and nail hole columns of bladed barite, carbonate and quartz (Fig. 7E and F). These features are closely associated with stromatolite localities, consistent with the suggestion (Van Kranendonk, 2006) that the stromatolite locations the Pilbara are associated with areas of hydrothermal activity. Some cross-cutting quartz veins are associated with silification of basalts interlayered with the cherts (Fig. 7G and H).

One outcrop selected for further study consisted of undulating laminated to stromatolitic and partially silicified limestone (Fig. 8) but no specifically convex or conical stromatolites, although conical and low stromalolites occurred in the same bed laterally several metres away and in both underlying and overlying beds. One loose block on the outcrop was collected for slabbing on a diamond saw, and thin sectioning. Selected subsamples were analysed using the Integrated Spectronics Portable Infrared Spectrometer (PIMA). This instrument is an optical spectrometer that operates in the Short Wavelength Infrared band (1300–2500 nm wavelength range), and readily identifies minerals associated with hydrous alteration, including sulphate, carbonates, clays and micas (Thompson et al., 1999). Onboard spectral matching software suggests compatible minerals. Offcuts were analysed using the InXitu Terra field-portable X-Ray Diffraction (XRD) instrument (Sarrazin et al., 2008).

6.6. Petrography

Five millimetre-scale laminations were visible on the slabbed surface of the collected sample, cross-cut by thin carbonate and quartz veins and with a local calcrete rind (Fig. 9). Optical spectroscopy demonstrated that the carbonate is dolomite, making this sample a dolostone. Silicification zones are distinguished on the weathered surface by being more resistant to dissolution and thus standing above adjacent carbonate lithologies. On the sawn surface the silicified zones are greyer in colour than the dolostone.

Two thin sections were cut and examined using a Leica Orthoplan Pol petrographic microscope. In thin section the 5 mm scale parallel laminae are composed of alternating coarse and fine dolomite. These have been locally replaced by microquartz, and contain lesser and greater amounts of silica, respectively. An anastomosing non-penetrative cleavage defined by yellowish to reddish brown, microcrystalline to cryptocrystalline material, probably a phyllosilicate. These are oriented at ∼30° to the primary layering.

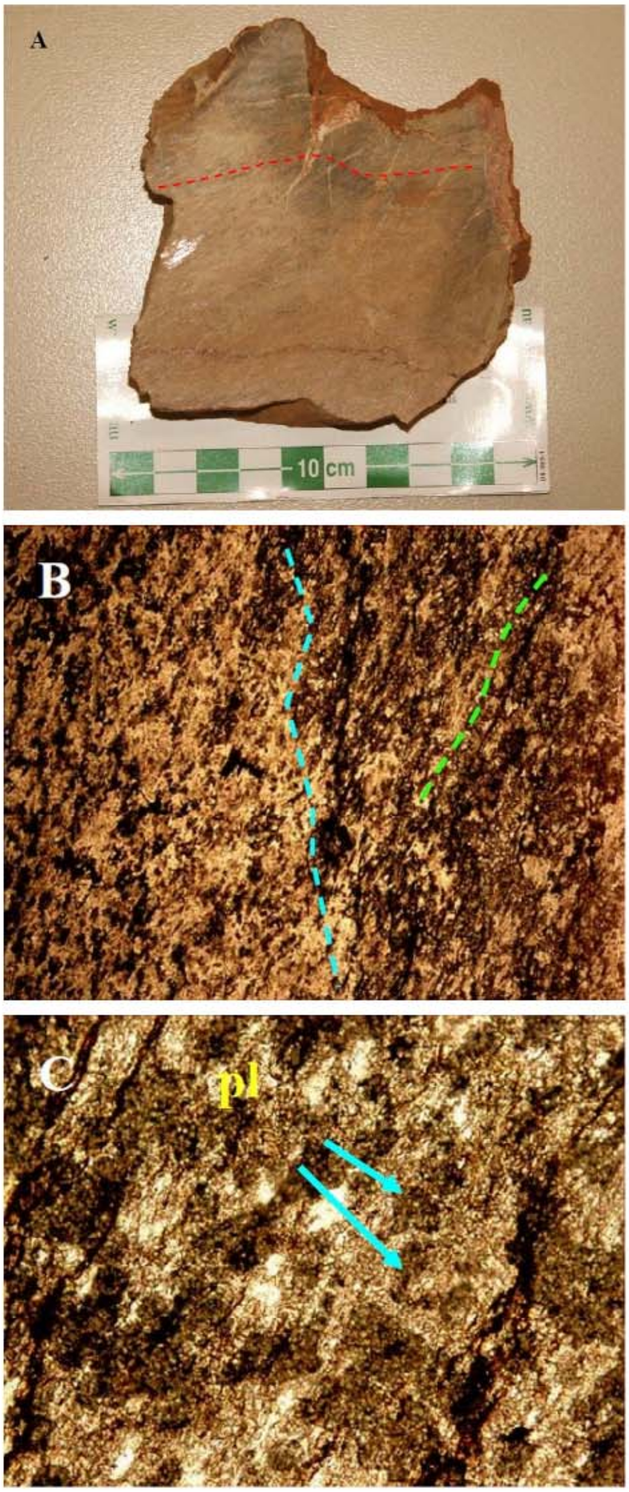

Fig. 9. (A) Sawn face of block of stromatolitic laminated partly silicified carbonate shown in Fig. 3B. Irregular laminae can be seen penetrating through the rock (some outlined in red). Greyer areas have been partially silicified. (B) Alternating coarse and fine laminae, plane light, fine grained laminae on right hand side, coarse grained on left, separated by blue line, cleavage oblique across slide (green line). Field of view 2.5 mm. (C) Plain light, ∼150 1m peloids, representative peloids (pl) arrowed. field of view 1.0 mm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fine-grained talc replaces dolomite throughout, especially in the silicified material. Scattered needles of tremolite occur at random orientations though the samples.

Table 1
PIMA hyperspectral analyses of selected samples.

ID	Location on sample	Unit	Lithology	Mineralogy	Comments
1a	Exterior	Komatiitic Euro Basalt	Weathered ultramafic schist	Tremolite, calcite, tr. Chlorite	Primary mineralogy
1b	Interior	Komatiitic Euro Basalt	Ultramafic schist	Tremolite, calcite, chlorite	Primary mineralogy
2a	Exterior	Euro Basalt	Fine-grained amphibolite	Chlorite, siderite	Primary mineralogy + secondary siderite
2b	Interior	Euro Basalt	Fine-grained amphibolite	Chlorite	Primary mineralogy
3	Exterior	Strelley Pool	Silicified carbonate	Weak carbonate signal	Poor results from rough surface
4	Interior	Strelley Pool	Marble	Calcite	Primary mineralogy
5a	Exterior	Strelley Pool	Mafic schist	Kaolinite, nontronite	No primary mineralogy detected
5b	Interior	Strelley Pool	Mafic schist	Nontronite, phengite	Nontronite weathering, phengite original
6a	Exterior	Komatiitic Euro Basalt	Weathered ultramafic schist	Talc?	Poor results – rough surface
6b	Interior	Komatiitic Euro Basalt	Ultramafic schist	Talc, tremolite	Primary mineralogy
7a	Exterior	Euro Basalt	Fine-grained amphibolite	Gypsum, kaolinite, montmorillonite?	Weathered – no primary mineralogy detected
7b	Interior	Euro Basalt	Fine-grained amphibolite	Chlorite, calcite	Primary mineralogy
8a	Exterior	Strelley Pool	Partially silicified limestone	Talc, hornblende, dolomite	Weathered surface
8b	Interior	Strelley Pool	Partially silicified limestone	Talc, hornblende	Broken surface
8c	Interior	Strelley Pool	Partially silicified limestone	Talc, hornblende, dolomite	Sawn surface
9a	Exterior	Strelley Pool	Strongly silicified limestone	Talc, tremolite, dolomite	Weathered surface
9b	Interior	Strelley Pool	Strongly silicified limestone	Talc, hornblende, dolomite	Broken surface
9c	Interior	Strelley Pool	Strongly silicified limestone	Talc, hornblende, dolomite	Sawn surface

Table 2
Terra XRD analyses of selected samples.

ID	Location on sample	Unit	Lithology	Mineralogy	%	Comments
9a	Exterior	Strelley Pool	Strongly silicified limestone	Quartz	61.7	Weathered surface
				Calcite	8.9	
				Talc	29.4	
9b	Interior	Strelley Pool	Strongly silicified limestone	Calcite	53.7	Broken surface
				Talc	25.0	
				Dolomite	15.2	
				Quartz	6.2	
9c	Interior	Strelley Pool	Strongly silicified limestone	Quartz	100	Sawn surface

Peloids between 30 and 150 lm across of cryptocrystalline dolomite are locally present, some possibly occurring within a clast. Given the close association with convex and conical stromatolites the laminae and the peloids are probably originally microbial.

6.7. SWIR spectroscopy

Infrared spectra were acquired with the PIMA instrument (Thompson et al., 1999) operating in a spectral wavelength range optimised to detect the products of hydrothermal alteration, in particular hydrated or hydroxyl-bearing minerals, sulphates and carbonates.

Representative PIMA results are contained in Table 1. Chlorite, tremolite, phengite, and calcite were detected on broken (and therefore relatively fresh) surfaces of mafic and ultramafic rocks overlying or interlayered with the SPF. These are consistent with aqueous alteration (chlorite and tremolite) with minor signature minerals of CO_2 alteration (talc and calcite) at lower greenschist grade metamorphism (Powell et al., 1991). Kaolinite, montmorillonite, nontronite, gypsum and siderite were identified on weathered surfaces.

Spectra on sawn and broken surfaces of the SPF mostly consist of dolomite, talc, and hornblende, the same assemblage is present in both silicified and unsilicified SPF. The exception was a bed of marble that was composed of calcite. Exposed surfaces were very rough, some too rough to give a good reading because of scattering of the SWIR beam. However other surfaces showed a similar assemblage to the broken or cut surfaces, dolomite, talc, hornblende, tremolite. This assemblage is suggestive of hydrothermal alteration.

6.8. X-Ray Diffraction

Thin section offcuts were analysed using the InXitu Terra field-portable XRD instrument (Sarrazin et al., 2008). This is the commercial version of the CheMin instrument launched onboard the Mars Science Laboratory (MSL) in 2011. The samples were pulverised in a hand mill, then ground in a pestle and mortar, before being placed in the analytical chamber. The results are shown in Table 2.

7. Lessons for Mars exploration

7.1. Searching for martian stromatolites

The thin stromatolitic chert horizons in the Pilbara make up perhaps 1% of the overall succession. Stromatolites occur over perhaps 1% of the strike distance of these units. Even where stromatolitic, actual stromatolites make up perhaps 1% of the unit. Ancient stromatolites therefore comprise perhaps one millionth of the succession in the Pilbara, and, if present on Mars, at best are likely to occur in similar abundances.

Actively searching for stromatolites on Mars would therefore require the ability to traverse across tens or even hundreds of kilometres to have any likelihood of success. Additionally, unlike in the Pilbara, where the stromatolitic units are steeply dipping, those on Mars are likely to be near horizontal in attitude, resulting in many exposures occurring on the steep walls of valleys and craters.

Knowledge of the depositional environments of the host formations might provide cues to the alert research that stromatolites might be present. Shallow subaqueous chemical sediments would be the most promising, but stromatolites also occur in

Table 3
Rock-analysis instruments carried by past, present and future Mars landers and rovers.

Operation	Instrument or tool	Operational role or data provided	Status	Missions
Sampling	Rock abrasion tool (RAT)	Smooth clear surface for non-destructive analysis	Flown	Mars Exploration Rovers (MERs)
	Robot arm with scoop	Picking up small samples	Flown	Viking, Phoenix
	Corer	Small cores for on-board destructive analysis	On route	MSL
Non-destructive analytical	Colour or multi-spectral stereo camera	Context, morphology	Flown	All missions
	Microscopic imager (ideally colour with internal light source)	Fine structure	Flown	Mars Exploration Rovers (MERs), Phoenix, MSL
	Infrared spectrometer	Mineralogy	Flown	MER
	Mossbauer spectrometer	Iron mineralogy	Flown	MER
	Laser Raman spectrometer	Mineralogy, organic chemistry	Being tested	MAX-C (study only)
	Alpha Proton X-ray (APX) spectrometer	Chemistry	Flown	Mars Sojourner rover, MER
Destructive analytical	X-Ray Diffraction (XRD)	Mineralogy	Pending	MSL
	X-Ray Fluorescence (XRF)	Chemistry	Flown, on route	Viking, MSL
	Laser Induced Breakdown Spectrometer	Chemistry	On route	MSL
	Gas Chromatograph (GC)	Organic chemistry	Flown	Viking
	Mass Spectrometer (MS)	Stable isotope chemistry	Flown, on route	Viking, MSL

hydrothermal systems in volcanic environments (as in the Pilbara), terrestrial springs (Keppel et al., 2011) and even in ephemeral pools between sand dunes (Eisenberg, 2003). Searching for stromatolites on Mars would need a trained mind, experience, and a detailed knowledge of the environments, often quite small, where they may flourish.

Brown et al. (2005) showed that high resolution (5 m or better) hyperspectral imagery was able to map alteration zones associated with feeder veins to the stromatolitic chert horizons. This resolution is greater than that presently available for Mars from existing instruments. Future orbital sensors with this scale of resolution would be useful in planning surface traverses searching for Pilbara analogues on Mars. Likewise surface instruments with similar or better capabilities would be very useful to assist remote selection of which specific outcrops to visit. Therefore ideal exploration systems for stromatolites on Mars would be a vehicle able to traverse tens, preferably hundreds of km of the martian surface, traverse and work on steep slopes, and be supported by high resolution remote sensing systems in orbit and on the vehicle, or possibly onboard a drone. It must carry the range of information allowing characterisation of depositional environments, in particular the textural and structural aspects of rocks, supported by mineralogy and geochemistry. These capabilities would be very challenging for any unmanned missions, not matter how advanced, but would be a given for a crewed mission (see for example Hoffman, 2001; MEPAG HEM-SAG, 2008).

7.2. Studying martian stromatolites

If and when potential stromatolites have been located on Mars, they will probably be analysed by a range of tools instruments similar to those carried by historic missions (Table 3). Most of these, with the exception of the GCMS, provide data equivalent to that collected by a geologist in the Pilbara, with the caveat that, while mineralogy and geochemistry can be determined in the field, most terrestrial geologists prefer to obtain this data in the laboratory, due to the generally greater range, precision and accuracy of laboratory as opposed to field instrumentation, and the greater diversity of sample preparation methods and analytical instruments available. Also noteworthy is the inability to supply in the field the capability of the most basic and useful tools used to study stromatolites, the thin section and the petrographic microscope.

Based on these missions we assume therefore that any future unmanned martian exploration vehicle hunting for stromatolites would have available a stereo colour or multispectral camera system with close up capability and the means to determine position and orientation of samples, Quantitative field determination of mineralogy, bulk geochemistry, and organics can also be assumed. There may also be onboard ability to measure stable isotopes with a mass spectrometer and the ability to carry out mineral, elemental and organic mapping on cut surfaces (MEPAG MRR-SAG, 2009).

An astronaut team could be expected to have a stereo colour or multispectral camera system, with close up capability, the means to determine position and orientation of samples, together with quantitative field determination of mineralogy, bulk geochemistry, and organics. Mass spectroscopy and mineral, elemental and organic mapping on cut sample surfaces would be most likely done at a laboratory at the landing site, the same laboratory may also have the capacity to make and examine thin sections and to perform electron microscopy (MEPAG HEM-SAG, 2008).

These measurements are extremely limited compared to what is possible on the Pilbara samples, historic studies of which have included regional and field hyperspectral mineral mapping (Brown et al., 2004, 2005, 2010), field mapping at all scales (Williams and Bagas, 2007a, 2007b; Van Kranendonk, 2006, 2007), morphometric analysis (Dunlop et al., 1978; Walter et al., 1980; Allwood et al., 2007, 2009), geochemistry (Van Kranendonk et al., 2003; Van Kranendonk and Pirajno, 2003), organic geochemistry (Schopf et al. 2002, Schopf, 2006; Marshall et al., 2007), stable isotopes (Ueno et al., 2001; Shen et al., 2001) and microscopy (Awramik et al., 1983; Schopf, 1993; Sugitani et al., 2010; Banerjee et al., 2007), to name but a few. Not only has there been a diversity of deployed investigative methods and researchers, but a considerable investment of time in the course of very detailed field work and, until recently (Grey et al., 2010), few restrictions on sampling.

Despite this abundant evidence and long history of investigation in the Pilbara, the evidence in the STF and three other horizons in roughly equivalent-aged rocks in the Pilbara (Van Kranendonk, 2007) for a biosphere at ~3.4 Ga has proved contentious and been repeatedly challenged. Notable critiques include Buick (1984), Lowe (1994), Brasier et al. (2002, 2006) and Lindsay et al (2005). Furthermore the discovery of inorganic precipitates that mimic biological features (e.g. Garcia-Ruiz et al., 2003) has raised numerous difficulties regarding the morphological recognition of Archean microfossils. Such debate has led some (e.g. Moorbath, 2005) to adopt the extreme position there is no consensus for life existing prior to 1.9 Ga. However, both the weight and diversity of evidence (Van Kranendonk, 2007) and the most parsimonious interpretation of it (Allwood et al., 2007) points to a diverse biosphere being present on Earth at almost 3.5 Ga.

Table 4
Suggested sequence of increasing sophistication of investigation of any martian stromatolite-like features.

Stage	Activities	Data or sampling required	Orbital and airborne reconnaissance	Unmanned rover	Unmanned sample return	Crewed mission
1	Remote sensing	Hyperspectral, imagery	X	X		X
2	Location of features	Hyperspectral, imagery		X		X
	Characterisation of features	Spatial context, textures, organic and inorganic chemistry, mineralogy		X		X
3	Detailed field investigations	Spatial context, textures, organic and inorganic chemistry, mineralogy, detailed textures, whole rock stable isotopes		Dependent on rover sophistication	X	Not needed
	Preliminary laboratory investigations (on Mars)	Microscopic textures, whole rock stable isotopes high precision and accuracy organic and inorganic chemistry, carried out on drill cores				X
4	Sample collection and return	Short drill cores			X	X
	Detailed laboratory investigations (on Earth)	Ultrastructure, ultra-high resolution, precision and accuracy organic and inorganic chemistry, stable and unstable isotopic measurements, multiple parallel methodologies			X	X

Any stromatolite-like features found on Mars is likely to prove similarly contentious, especially if the data available is confined to the comparatively limited set obtained by an unmanned rover. Return to Earth of an extensive (many kilograms if possible) suite of samples would be essential to provide the diversity and quality of data that is now available from the 3.4 Ga Pilbara stromatolites that sustains the present biogenic consensus.

While difficult to quantify, the diversity and volume of data generated on the Pilbara stromatolites exceeds what could be expected from the initial discovery of stromatolite-like features on Mars by an order of magnitude and the total amount of data collected by several orders of magnitude. The difference in amount of material that could be collected and returned for laboratory analysis would be of a similar scale. Considerable emphasis should be placed therefore on morphometric analysis, both robust qualitative description (Preiss, 1976), and statistical (e.g. Storrie-Lombardi and Brown, 2004). Even on Earth, differentiating between biogenic and non-biogenic features by such means can be difficult (Grotzinger and Rothman, 1996) Spectral techniques (e.g. Blanco et al., 2008) may assist, but the obscuration of biogenic features in such ancient rocks through diagenesis, weathering and alteration, may make such techniques problematic.

8. Future work

Our work in the Pilbara is in its early stages. We intend to return to the site and carry out further mapping to extend and infill the present data. In particular specific features, including quartz veins, hydrothermal vents, conglomerate horizons and faults, need to be located with greater confidence. In parallel to this we plan to better quantify what can and cannot be learned from the type of data that can be collected by field-deployable instrumentation similar to what might be available on a Mars rover mission, compared to the type of data that can be obtained from a even limited suite of returned samples.

Table 4 shows a suggested sequence of investigations that could be used to identify and study stromatolites with the robotic program. We envisage a four stage process:

1. Location of prospective terrain by remote sensing.
2. Location and characterisation of stromatolite-like features by ground traverse.
3. Detailed investigations on Mars establishing spatial and geological context of the possible stromatolites and informing selection of material for return.
4. Sample collection and return to Earth.

All of these stages are important, but given the limitations of field data, collection of well documented samples, free of terrestrial contamination, and their repeatable analysis by diverse methods at the highest technical and procedural standards back on Earth will be essential. Even if the investigations prove inconclusive or negative, it is likely that such samples still provide considerable data on Noachian Mars.

9. Conclusions

The study of the oldest evidence of life on Earth in the Pilbarra region of Western Australia provides an important analogue to compare any morphological evidence of stromatolite forms that may be found on Mars by the Mars Science Lander. As this paper has shown, Archean stromatolites are sparsely distributed even in their known locations and many decades of field mapping by knowledgeable field geologists was required to identify these locations. Even if no stromatilite like features are found by MSL or other future rover missions, this does not mean that such structures do not occur on Mars. Compared to traditional methods of field geology work, rover investigations amount to very sparse sampling, be it measured by distance covered, number of sites documented, or samples collected (Crawford, 2012). Mission simulations involving rovers in terrestrial field sites with data presented to a remote science team has shown that much is missed during a rover investigation of a small site compared to even a quick walk through a site by a knowledgeable human (Stoker et al., 1997). When considering how much terrain must be explored to find the fossil evidence left in the most important rocks, the task of finding evidence demonstrating a record of early life on Mars by a rover mission seems formidable. The MSL mission will most certainly lead to advances in understanding of aqueous processes on early Mars, but definitive evidence of early life will likely require a long term program of human exploration.

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