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Research Paper

Earth's Earliest Biosphere—A Proposal to Develop a Collection of Curated Archean Geologic Reference Materials

JOHN F. LINDSAY,[1,2] DAVID S. MCKAY,[2] and CARLTON C. ALLEN[2]

ABSTRACT

The discovery of evidence indicative of life in a Martian meteorite has led to an increase in interest in astrobiology. As a result of this discovery, and the ensuing controversy, it has become apparent that our knowledge of the early development of life on Earth is limited. Archean stratigraphic successions containing evidence of Earth's early biosphere are well preserved in the Pilbara Craton of Western Australia. The craton includes part of a protocontinent consisting of granitoid complexes that were emplaced into, and overlain by, a 3.51–2.94 Ga volcanigenic carapace—the Pilbara Supergroup. The craton is overlain by younger supracrustal basins that form a time series recording Earth history from approximately 2.8 Ga to approximately 1.9 Ga. It is proposed that a well-documented suite of these ancient rocks be collected as reference material for Archean and astrobiological research. All samples would be collected in a well-defined geological context in order to build a framework to test models for the early evolution of life on Earth and to develop protocols for the search for life on other planets. Key Words: Geologic curated collection—Archean—Western Australia—Early life on Earth. Astrobiology 3, 739–758.

INTRODUCTION

Evidence suggesting the presence of ancient life in a Martian meteorite has drawn attention to the possibility of life on other planets (McKay *et al*., 1996). However, an important lesson learned from this study, and from the subsequent controversy, is that determining biogenicity in the ancient rock record is extremely complex. With the prospect of sample return from Mars in the relatively near future, it is thus important to develop an effective sampling strategy and a set of systematic protocols well in advance. It is also important that we have time to develop the special array of tools that will be needed for the analysis of the returned samples, especially distinctive and robust biomarkers. One of the most cost-effective means of doing this is through the study of Earth's early history and its earliest biosphere.

To that end we are proposing the development of a collection of reference samples from the Archean of Western Australia. This would allow a systematic study of the earliest Earth and its

[1]Lunar and Planetary Institute, Houston, Texas.
[2]NASA Johnson Space Center, Houston, Texas.

biosphere by making sets of well-documented reference samples available to a large number of qualified investigators at no cost.

RATIONALE

It has long been assumed that life evolved opportunistically on Earth in a simple interactive relationship with its environment, sustained, for the most part, by an exogenic energy source (the Sun). There are, however, several threads of evidence that are converging to suggest that the biosphere did not simply evolve on the Earth's surface but was, in a very general way, driven forward to greater complexity by the evolution of the Earth (Brasier and Lindsay, 1998; Lindsay and Brasier, 2002a,b). That is, biospheric evolution was driven by the Earth's endogenic energy resources (as expressed in, for example, plate tectonics), and its long-term survival depends upon those energy resources as well as those of the Sun. If this is so it has fundamental implications, not only for life on Earth, but for the more general problems surrounding the likelihood of life having evolved on other planetary bodies. Small planets, such as Mars, had limited endogenic energy resources to drive crust/mantle interaction and are only likely to have supported life early in their history. This hypothesis also implies that life should have evolved earlier on Mars than on Earth because it cooled more quickly and passed into the optimal biospheric environmental window earlier.

These conclusions have major implications for any strategy to be established in the search for extraterrestrial life. It implies that life on Mars is more likely to have evolved and become extinct early in the planet's history. This suggests that on Mars we must search in the ancient rock record and should be focusing on enduring biomarkers. It is also important that planetary dynamics be considered, which suggest that samples must be collected in a well-constrained stratigraphic or temporal context.

EARTH'S ANCIENT CRATONS

Exposures of rocks reflecting Earth's earliest history are relatively rare at the Earth's surface. Rocks older than 3.0 Ga form only 0.5% of the area of the present continents (de Wit, 1998). However, in the core the Pilbara and Kaapvaal Cratons of Western Australia and southern Africa, respectively (Fig. 1), ancient rocks not only survive but are only gently deformed and metamorphosed. The geology of the Pilbara Craton has been mapped in some detail (Fig. 2) (e.g., Hickman and Lipple, 1978; Van Kranendonk, 1998, 2000) and provides an ideal opportunity to build a framework in which to test models for the early evolution of life on Earth and to develop protocols for the search for life on other planets, especially Mars.

THE PILBARA CRATON

The present Australian continent consists of two major crustal components (Fig. 1) (see Murray *et al.*, 1989). Along the eastern margin of the continent the crust is Cambrian or younger, the product of active margin processes during the Paleozoic. The rest of the continent is much older consisting of a complex of terranes of Archean to Mesoproterozoic age (Rutland, 1976). The Precambrian crust consists of several elements (Shaw *et al.*, 1996) that were amalgamated in the Paleoproterozoic and the early Mesoproterozoic. Western Australia (Fig. 1), which contains the oldest rocks, consists of two well-defined Archean blocks, the Yilgarn and Pilbara Cratons, which were sutured along the Capricorn Orogen at approximately 2.0 Ga as part of an early episode of supercontinent assembly (Columbia) (Rogers and Santosh, 2002). The Yilgarn and Pilbara Cratons both include Paleoproterozoic and Archean rocks, though the Pilbara incorporates a coherent autochthonous stratigraphy that is among the oldest on Earth, extending from 3.5 to 2.8 Ga, the critical period (Fig. 3) during which the Earth's crust was evolving rapidly and life was becoming more widespread. Equally important the Pilbara also preserves a comprehensive supracrustal succession covering the period when the atmosphere and oceans were becoming oxygenated (2.8–1.7 Ga) (Fig. 4). After 2.7 Ga there is abundant evidence for photosynthesis in the form of fossils, especially stromatolites (platform carbonates) (Walter, 1976; Simonson *et al.*, 1993a,b), and stable isotope geochemistry (Buick *et al.*, 1995a; Lindsay and Brasier, 2002a,b) and from biomarkers including cyanobacterial hopanes and possibly eukaryotic steranes (Brocks *et al.*, 1999).

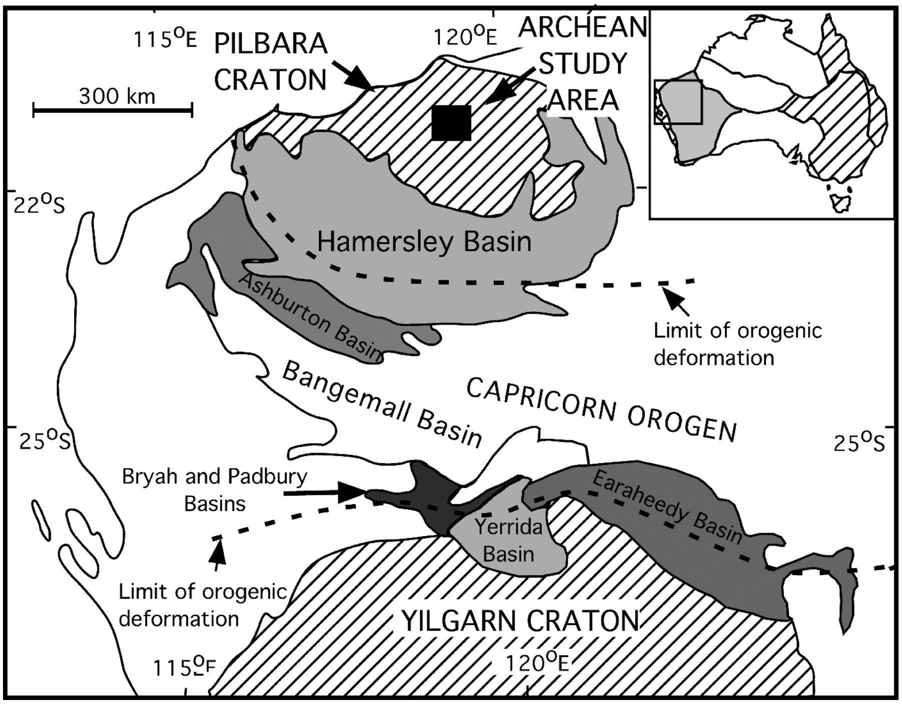

FIG. 1. The Pilbara and Yilgarn Cratons showing the deformed suture zone of the Capricorn Orogen and the distribution of younger sedimentary basins. The proposed North Shaw study area is shown as a black rectangle.

EARTH'S EARLIEST VOLCANO-SEDIMENTARY RECORD

The rocks of the Pilbara Craton form the earliest lithologic succession on the Australian continent and, along with the overlying supracrustal succession, would form the focus of the proposed sampling program. Most of the best exposures of this early sedimentary record occur in a relatively limited area covered by a single 1:100,000 map sheet, the North Shaw map sheet (Van Kranendonk, 1998, 2000) (Fig. 2), which encompasses the main study area considered in this paper. Further regional information from flanking areas can be obtained from the 1:250,000 Marble Bar map sheet (Hickman and Lipple, 1978), which includes the North Shaw sheet. The area is somewhat remote and only accessible by four-wheel drive vehicle.

THE NORTH SHAW STUDY AREA

Granitoid complexes

The study area is underlain by parts of the Shaw, Yule, and Carlindi granitoid complexes, which are broadly ovoid in plan, 25–110 km in diameter and 40–60 km apart (Fig. 2). The complexes consist of several mappable plutonic or gneissic units (Bettenay *et al.*, 1981; Van Kranendonk, 2000; Van Kranendonk *et al.*, 2002). Structural and geophysical analyses suggest that the granitoid complexes form structural domes as part of a continuous, midcrustal layer extending from ~14 km beneath the intervening supracrustal units (Hickman, 1984; Van Kranendonk, 2000). Components of the complexes are coeval with felsic volcanic horizons in the Pilbara Supergroup (the carapace above the granitoids) (Williams and Collins, 1990) and have intrusive or sheared intrusive contacts with them indicating an intimate synchronous development.

The plutons

Three granitoid intrusions are exposed within the supracrustal succession—the North Pole Monzonite (~3.458 Ga), Strelley Granite (~3.238 Ga), and Keep it Dark Monzonite (~2.936 Ga) (Fig. 3)—and form discrete plutons unrelated to the granitoid complexes (Fig. 2). The geometry and geochronology of these plutons suggest that they are synvolcanic laccoliths formed along with the supracrustal units and can be related directly to the lithostratigraphy and to the hydrothermal massive sulfide bodies discussed in a following section.

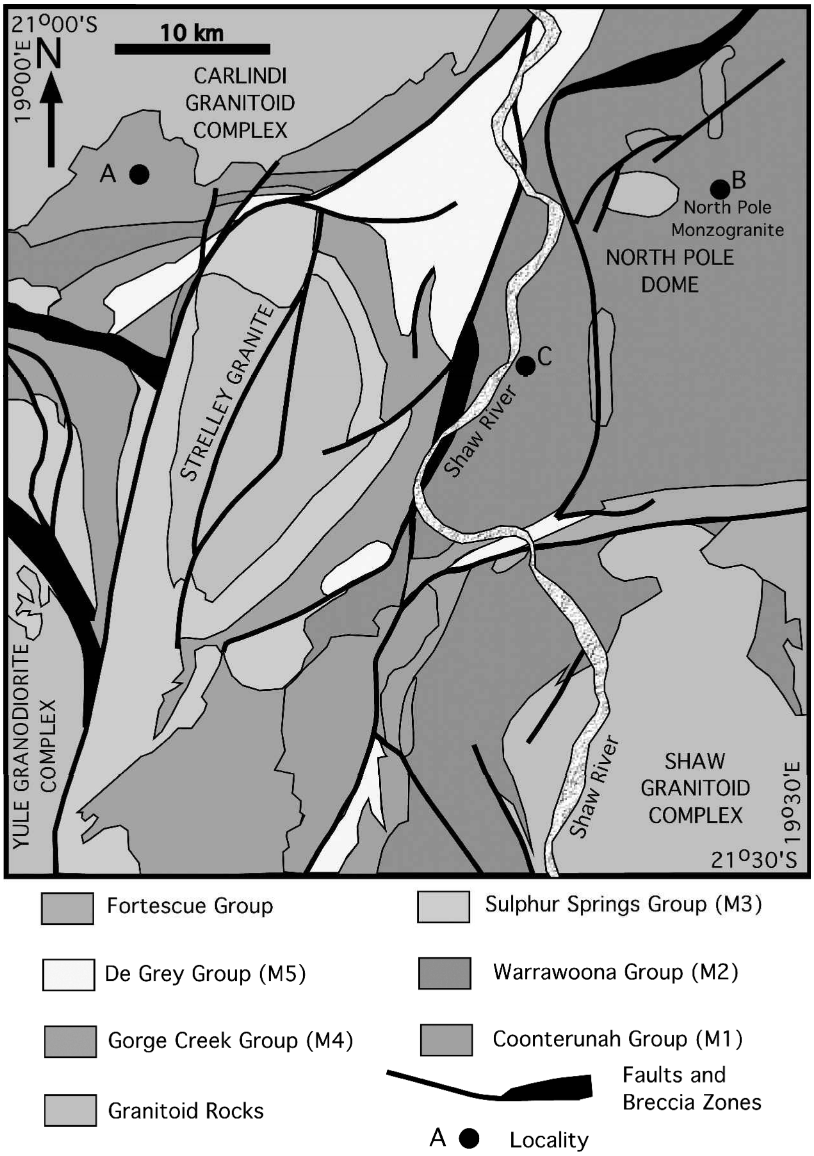

FIG. 2. Simplified map of the proposed North Shaw study area showing the main lithologic units (groups). The sinuous Shaw River almost bisects the area. Adapted from Van Kranendonk (2000).

THE STRATIGRAPHIC RECORD

The term "greenstone" or "greenstone belts" has generally been applied to the largely volcanigenic stratigraphic intervals preserved as a carapace overlying the granitoid complexes. The Archean stratigraphic record preserved in the greenstone carapace in the study area can be divided into five unconformity or intrusion-bound groups or megasequences (Fig. 3). They are tectonically defined units and not eustatically controlled (Van Kranendonk *et al.*, 2002). The megasequences of the Pilbara Supergroup were deposited over a time period between approximately 3.51 and approximately 2.94 Ga. They were deposited unconformably one above the other and consistently dip away from the domal granitoid complexes. The dips of the bedding gradually decrease with decreasing age, suggesting that they were deposited as thickening wedges adjacent to growing granitoid diapirs (Hickman, 1975, 1983, 1984; Van Kranendonk, 2000). Granitoid diapirism appears to have continued until after 2.7 Ga as the overlying remnants of the Hamersley Basin succession are preserved as synclinorial remnants (Hickman, 1984; Van Kranendonk *et al.*, 2002).

Despite local complex faulting, the supracrustal megasequences are relatively well preserved such that their ages and stratigraphic relationships are well established (Williams and Collins, 1990; Van Kranendonk, 2000). Metamorphic grade decreases away from the granitoid complexes from a maximum of middle to lower

GROUP/MEGASEQUENCE	FORMATION/BASIN	AGE	GRANITES
Supracrustal Basins unconformity	Earaheedy Bryah Padbury Yerrida Ashburton Hamersley	c.1.9-1.7 Ga c.2.0 Ga c.2.0 Ga c.2.2-1.9 Ga c.2.2-1.8 Ga c.2.8-2.2 Ga	
M5 DE GREY GROUP unconformity	Lalla Rookh Sandstone	c.2950 Ma	3
M4 GORGE CREEK GROUP unconformity	Pyramid Hill Formation Honeyeater Basalt Paddy Market Formation Corboy Formation Pincunah Hill Formation		
M3 SULPHUR SPRINGS GROUP unconformity	Kangaroo Caves Formation Kunagunarrina Formation Leilira Formation	3238-3235 Ma	H 2
M2 WARRAWOONA GROUP oldest unconformity	Euro Basalt Strelley Pool Chert Panorama Formation Apex Basalt Duffer Formation Dresser Formation Mount Ada Basalt McPhee Basalt	3458 Ma 3471-3463 Ma	H H 1 H
M1 COONTERUNAH GROUP	Double Bar Formation Coucal Formation Table Top Formation	3515 Ma	H

1. North Pole Monzonite (c. 3.458 Ga), 2. Strelley Granite (c. 3.238 Ga), 3. Keep it Dark Monzonite (c. 2.936 Ga), H= Hydrothermal System

FIG. 3. Simplified stratigraphy of the Archean rocks exposed in the proposed study area (adapted from Van Kranendonk, 2000). Arrows indicate dated period of activity of the granitoid complexes as distinct from the plutons, which are shown in cartoon form.

amphibolite facies at the contact, to lower greenschist and prenhite-pumpellyite facies. Lower greenschist facies is by far the most widespread metamorphic grade in the study area.

Megasequence 1—Coonterunah Group

The Coonterunah Group includes the earliest known stratigraphic succession (~3,515 Ma) preserved on the Pilbara Craton (Buick *et al.*, 1995b; Van Kranendonk and Morant, 1998). The lower contact is intrusive with the 3,468 Ma granitoid rocks of the Carlindi Granitoid Complex. The succession consists of three formations (Van Kranendonk, 2000).

Tabletop Formation. The Tabletop Formation consists entirely of thick basaltic units. They are mainly fine-grained tholeiitic lavas, although some gabbroic intrusions have been identified. The basalts are mostly featureless, although pillowed units are present indicating a submarine setting.

Coucal Formation. The Coucal Formation, which is ~2 km thick at its maximum, consists largely of fine-grained doleritic andesite, basalt, and felsic volcanic units (Fig. 5). Thin chert (Fig. 6) and impoverished cherty banded iron formation (BIF) units are present throughout the formation. These are the earliest known sedimentary units in the Pilbara Craton and offer the earliest opportunity for the preservation of ancient life.

Double Bar Formation. The Double Bar Formation, which conformably overlies the Coucal Formation, consists of fine-grained tholeiitic basalts with interbedded basaltic volcaniclastic rocks. Some basalts are pillowed, suggesting a submarine setting. The volcanics retain their basaltic textures but have been altered significantly by low-grade metamorphism (Van Kranendonk, 2000).

Megasequence 2—Warrawoona Group

The Warrawoona Group is separated from the underlying Coonterunah Group by a widespread angular unconformity, the oldest evidence on Earth for emergence (Buick *et al.*, 1995b) (Fig. 3). The Warrawoona Group is dominantly volcanic in origin but includes some clastic sedimentary rocks.

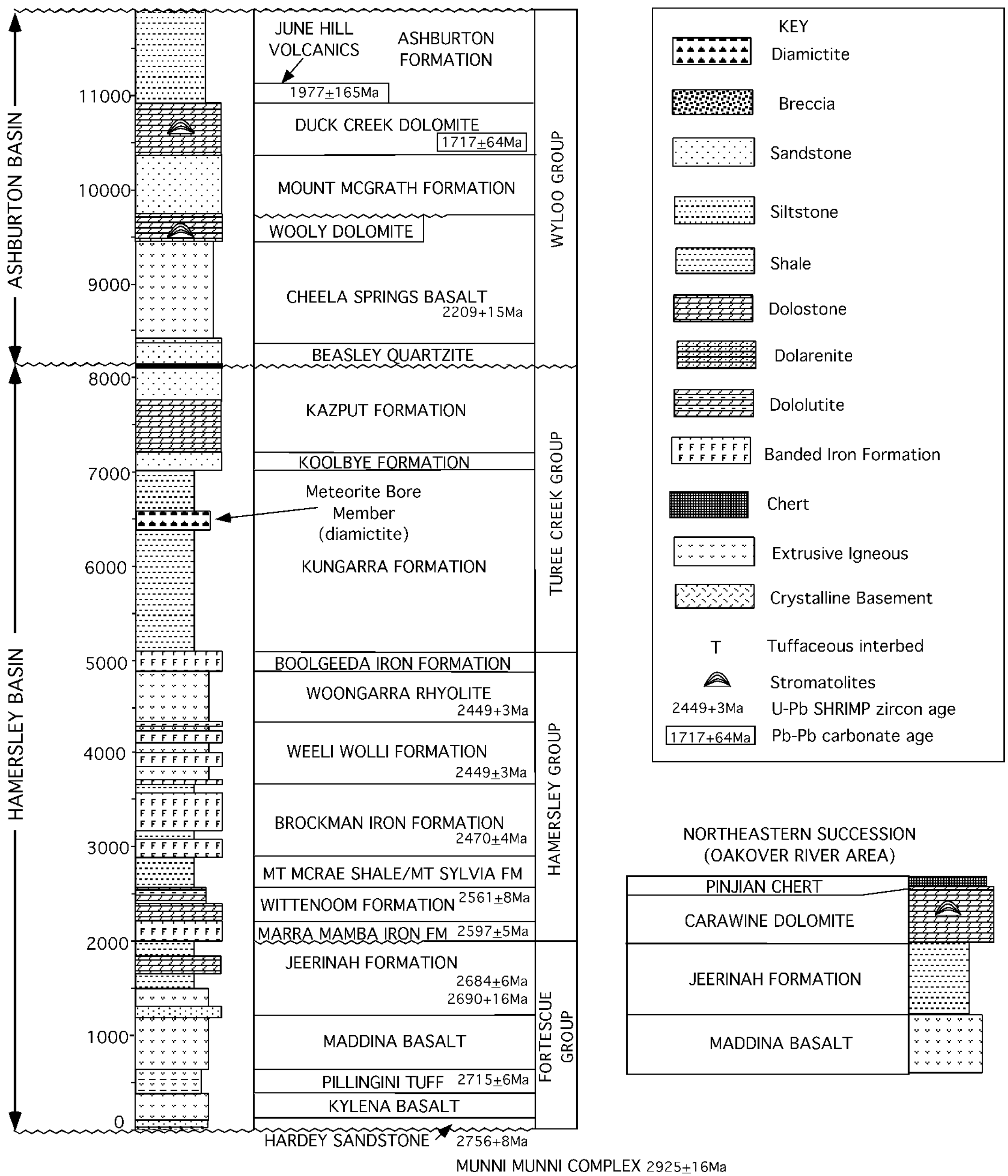

FIG. 4. Simplified stratigraphy of the Hamersley and Ashburton Basins of Western Australia (after Lindsay and Brasier, 2002).

McPhee Basalt. The McPhee Basalt, which is dated at 3,477 Ma and reaches a maximum of 3 km in thickness, is relatively limited in outcrop (Van Kranendonk *et al*., 2002). It consists largely of basalts and schists and is only exposed in the southern part of the study area adjacent to the Shaw Granitoid Complex where the contact is intrusive. A thin unit of impoverished cherty BIF forms a distinctive cap to the formation.

Mount Ada Basalt. The Mount Ada basalt consists of 3–4 km of massive tholeiitic basalt and dolerite intrusions that are exposed in the southeastern corner of the study area. Its lower contact with the Shaw Granitoid Complex and North Pole Monzonite is intrusive. For the most part volcanic textures are well preserved in the basalts.

Dresser Formation. The Dresser Formation is only recognized in the North Pole Dome where it reaches a maximum of 1,000 m in thickness (Van Kranendonk *et al*., 2002). The formation consists of massive and pillowed mafic volcanics in-

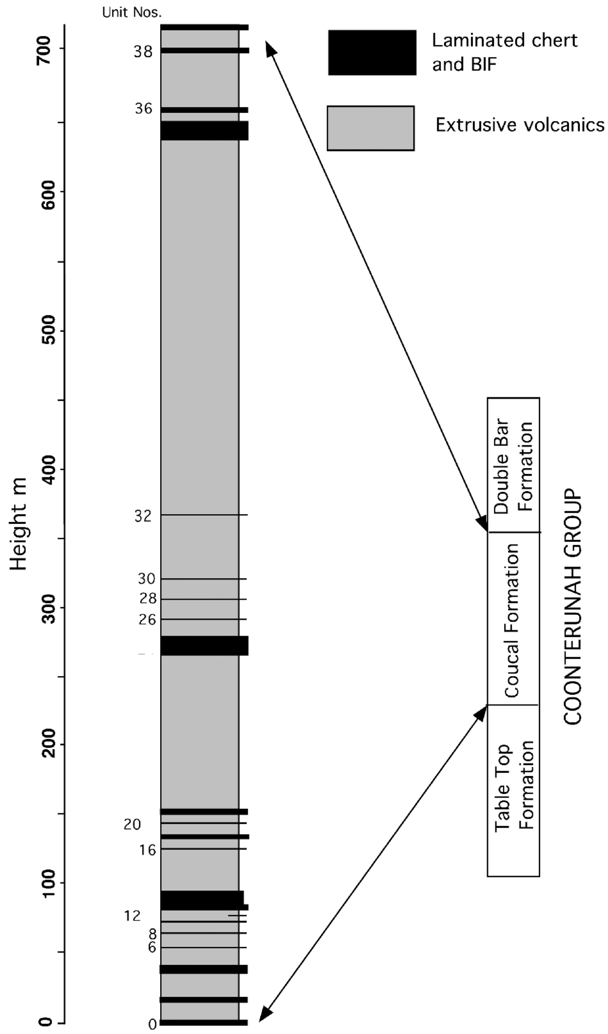

FIG. 5. A measured section through the Coucal Formation (locality A, Fig. 2). The formation is dominated by basic volcanic rocks with some felsic volcanic rocks and thin (<10 m) hydrothermal cherts between flows.

terbedded with units of chert, sandstone, conglomerate, barite, and minor carbonate (Fig. 7). The individual chert-barite beds vary from 5 to 40 m in thickness. Associated with these unusual sedimentary facies are structures that have been interpreted as the world's oldest stromatolites (Fig. 8) and associated microfossils (Dunlop *et al.*, 1978; Walter *et al.*, 1980; Buick *et al.*, 1981; Groves *et al.*, 1981; Walter, 1983). It is perhaps significant that this distinctive unit is fed by a deep-seated system of hydrothermal dykes (Fig. 9).

Duffer Formation. The Duffer Formation is best exposed in the southeastern portion of the study area where it consists largely of felsic schist and agglomerate. The agglomerates, which have been locally interpreted as welded ignimbrites, are bedded in meter-scale units. The Duffer Formation has a depositional age of approximately 3.47 Ga (Thorpe *et al.*, 1992; McNaughton *et al.*, 1993; Nelson, 1997, 1998, 1999, 2000, 2001) and rests conformably on the Mount Ada Basalt.

Apex Basalt. The Apex Basalt is well exposed in the northeastern corner of the study area and over large areas on adjacent map sheets. The formation is dominated by pillowed basalts, which are largely tholeiitic. The pillows are well developed and preserve vesicular rims, chilled margins, and concentric cooling cracks. Hyaloclastic breccias are also present within the assemblage. Doleritic flows and intrusions are common, and doleritic dykes occur locally.

Interbedded with the volcanics are a number of chert horizons, which are ~10 m in thickness

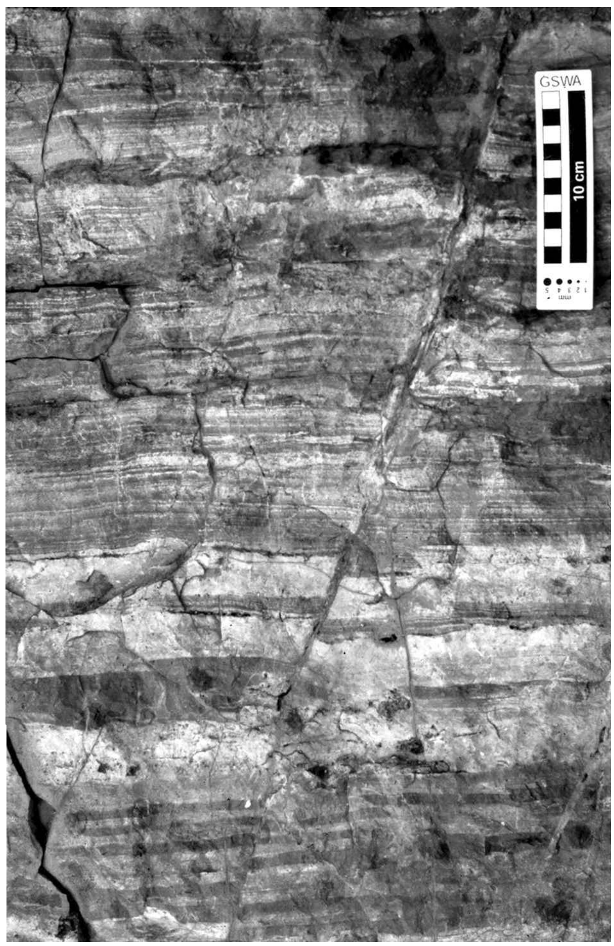

FIG. 6. Laminated cherts from the lower Coucal Formation (locality A, Fig. 2). Cherts form the earliest sedimentary rocks in the Pilbara succession. Some units are as much as 10 m thick. Scale bar = 10 cm.

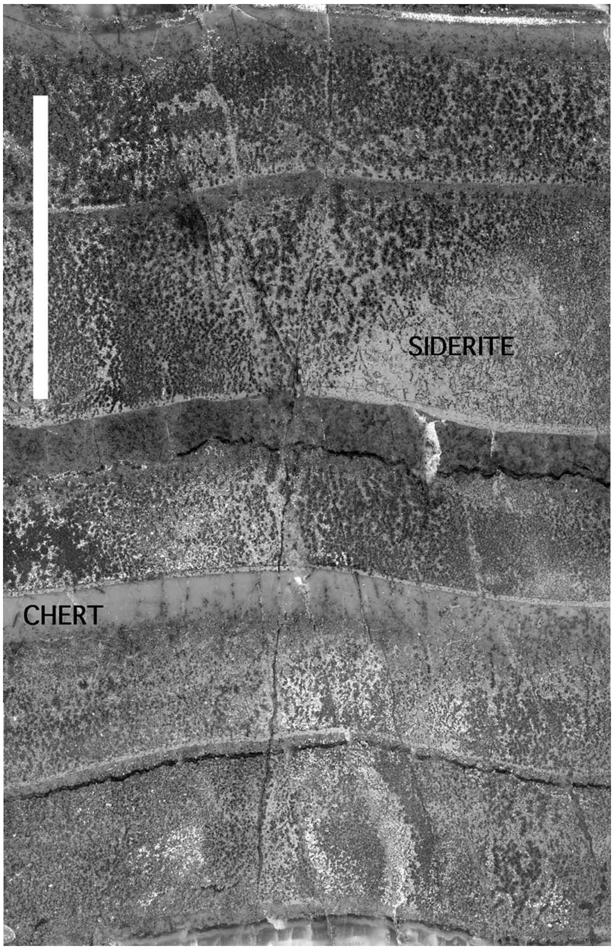

FIG. 7. Bedded sedimentary carbonate and silica from the Dresser Formation (locality B, Fig. 2). Scale bar = 5 cm. The rock consists of well-bedded units that begin with orange/yellow iron-rich carbonates and grade upward to pale green silica. The unit reflects geochemical changes in response to pulsing or cycling of the hydrothermal system. Elsewhere carbonate and chert form alternating beds.

and usually well laminated, mainly black and white chert. Numerous chert dykes cut across the underlying stratigraphy and terminate at the level of the chert horizons. Close to Marble Bar exposures of the Apex chert contain what was initially believed to be Earth's oldest morphological fossil assemblage (Fig. 10) (Schopf and Packer, 1987; Schopf, 1992, 1993), a claim recently disputed by more detailed analysis (Brasier *et al.*, 2002) (see following section on Paleontology).

Panorama Formation. The Panorama Formation (3,458–3,434 Ma), which is best exposed in the northern part of the study area near the Shaw River, is dominated by felsic volcaniclastic rocks with small volumes of felsic lavas and some chert interbeds (Hickman, 1983; Thorpe *et al.*, 1992; Nelson, 2000). The formation is strongly altered and intensely silicified having been exposed to temperatures as high as 350°C (Cullers *et al.*, 1993). A large volcanic vent within the Panorama Formation is preserved in the northwestern part of the outcrop area (Van Kranendonk, 2000).

Strelley Pool Chert. The relationship of the Strelley Pool Chert (Lowe, 1983) to the underlying units varies from conformable to unconformable. In the northeast the contact with the underlying Coonterunah Group forms an angular unconformity with pronounced paleorelief (Buick *et al.*, 1995b). The formation consists of carbonate, silicified carbonate, and clastic rocks (Fig. 11). The cherts and carbonates both have well-developed sedimentary structure that have been described as wavy laminated cherts or carbonates and stromatolites (Fig. 12) (Lowe, 1983; Hofmann *et al.*, 1999), although, as discussed in a following section, there is some concern as to whether they are biogenic (Lowe, 1994; Lindsay *et al.*, 2003a,b).

Euro Basalt. The Euro Basalt consists dominantly of basalts of tholeiitic and high-Mg composition that rest conformably on the Strelley Pool Chert (Van Kranendonk, 2000). The formation reaches a thickness in excess of 9 km in the northeastern part of the study area. The basalts are pillowed and bedded on a kilometer scale. The formation also includes some komatiite and felsic volcaniclastics as well as thin cherts and volcaniclastic units.

Megasequence 3—Sulphur Springs Group

The Sulphur Springs Group consists of three formations (Fig. 3) that, in contrast to the previous two Groups, contain a significant proportion of clastic sedimentary rocks, some quartzose.

Leilira Formation. The Leilira Formation consists predominantly of clastic sedimentary rocks with only small volumes of felsic to intermediate extrusive rocks interbedded. The clastic rocks are predominantly sandstones, but vary from siltstone to coarser pebbly sandstone. Compositionally, the sandstones are quartzose or volcanic lithic rocks. Locally, laminated cherts formed by the silicification of felsic volcanic ash and siltstone are abundant.

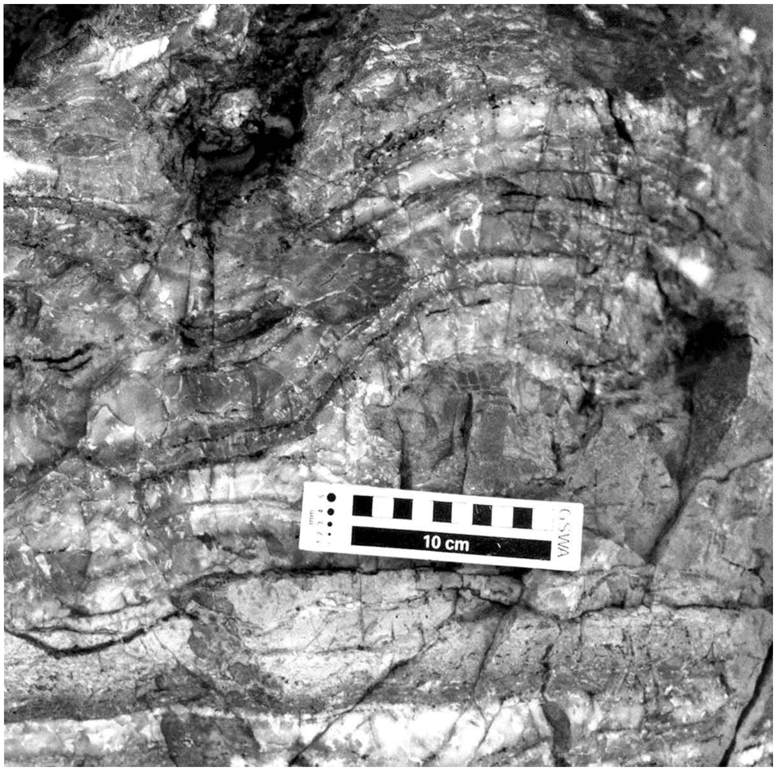

FIG. 8. Stromatolitic structures in the Dresser Formation (locality B, Fig. 2). The original barite has been largely replaced by chert. Scale bar = 10 cm.

The Leilira Formation represents a significant change in depositional patterns as it is the oldest unit in which clastic sediments are the dominant lithology. It reflects the growing volcanic carapace and in particular the exposure of the granitoid core to weathering and erosion, the first signs that a true crust was developing.

Kunagunarrina Formation. The Kunagunarrina Formation reaches a maximum of 2.4 km in thickness and consists predominantly of high-Mg basalts and komatiites. Locally andesitic and felsic units are present, especially near the top of the formation. A thick chert unit (~10 m) in the middle of the formation separates lower Mg

FIG. 9. Exposures of the Dresser Formation in the North Pole Dome area (locality B, Fig. 2) showing large chert-barite feeder dykes. The dykes consist of black chert and coarse bladed barite. Note the vehicle for scale.

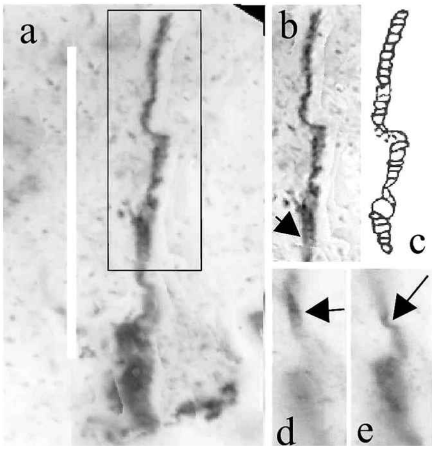

FIG. 10. "Microfossils" from the Apex chert near Marble Bar. a: computer-generated digital automontage of putative beggiatoan *Eoleptonema apex* Holotype (Schopf, 1993), combining the most-sharply focused images from successive focal planes. **b** and **c:** Original manual photomontage and interpretative sketch (Schopf, 1993), which omits lower structure at arrow in (b). **d** and **e:** New single images showing continuity of original and newly imaged and automontaged structures. Reprinted with permission from *Nature* (Brasier *et al.*, 2002). Copyright 2002 Macmillan Publishers Ltd.

basalts at the base of the formation from komatiites towards the top.

Kangaroo Caves Formation. The Kangaroo Caves Formation, which reaches a maximum thickness of 1.5 km, is best exposed towards the center of the study area. The formation is complex and consists of a succession of andesitic volcanics and dacitic to rhyolitic sills and extrusives. A chert interval up to 100 m thick forms a distinctive marker at the top of the formation. Close to the center of the study area, at Sulphur Springs, the massive chert is overlain by a polymict megabreccia that rests upon a sharp erosional contact (Hill, 1997; Vearncombe *et al.*, 1998).

Hosted within a 200-m dacite unit immediately beneath the marker chert are six sulfide ore bodies spaced at regular intervals of 5–7 km around the margins of the Strelley Granite (Morant, 1998). They consist of pyrite, sphalerite, chalcopyrite, and galena with smaller amounts of other sulfides (Vearncombe *et al.*, 1995, 1998; Vearncombe, 1996; Morant, 1998). The sulfides, which were deposited in a black smoker hydrothermal setting, occur in association with growth faults developed around the Strelley Granite, the intrusion of which was syndepositional with the Kangaroo Caves Formation (Vearncombe, 1996; Brauhart *et al.*, 1998; Brauhart, 1999).

Megasequence 4—Gorge Creek Group

The Gorge Creek Group consists of five formations (Fig. 3) that show much greater lithologic diversity than earlier megasequences. In particular, this interval includes, for the first time, a significant thickness of quartzose sandstone as well as a variety of other clastic sedimentary rocks.

Pincunah Hill Formation. In the western part of the study area the basal Pincunah Hill Formation consists of thinly bedded BIF with small amounts of laminated chert, red to gray shale, and siltstone. This basal unit is up to 1 km thick in the western part of the area but wedges out and disappears in a short distance eastward. The upper

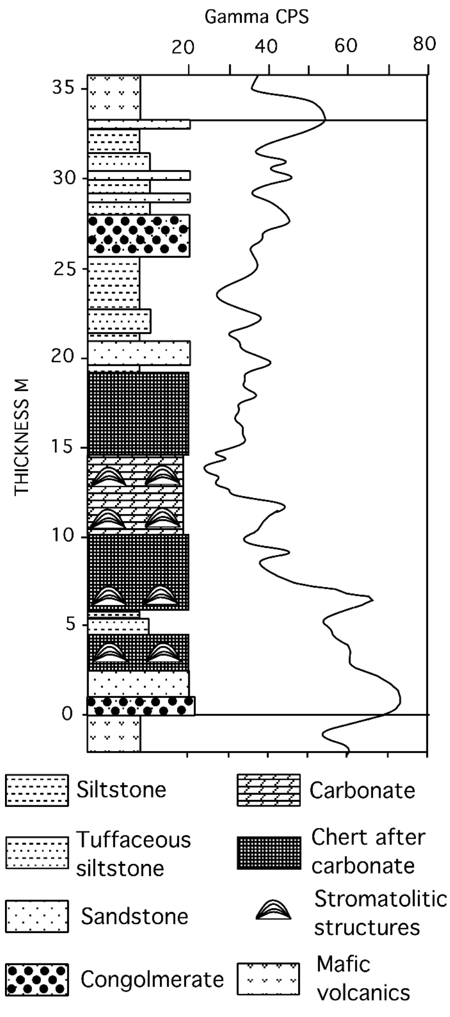

FIG. 11. A measured section through the Strelley Pool Chert showing the location of stromatolitic structures and the carbonate interval (adapted from Van Kranendonk, 2000) (locality C, Fig. 2). The gamma log to the right shows continuity across the chert-carbonate.

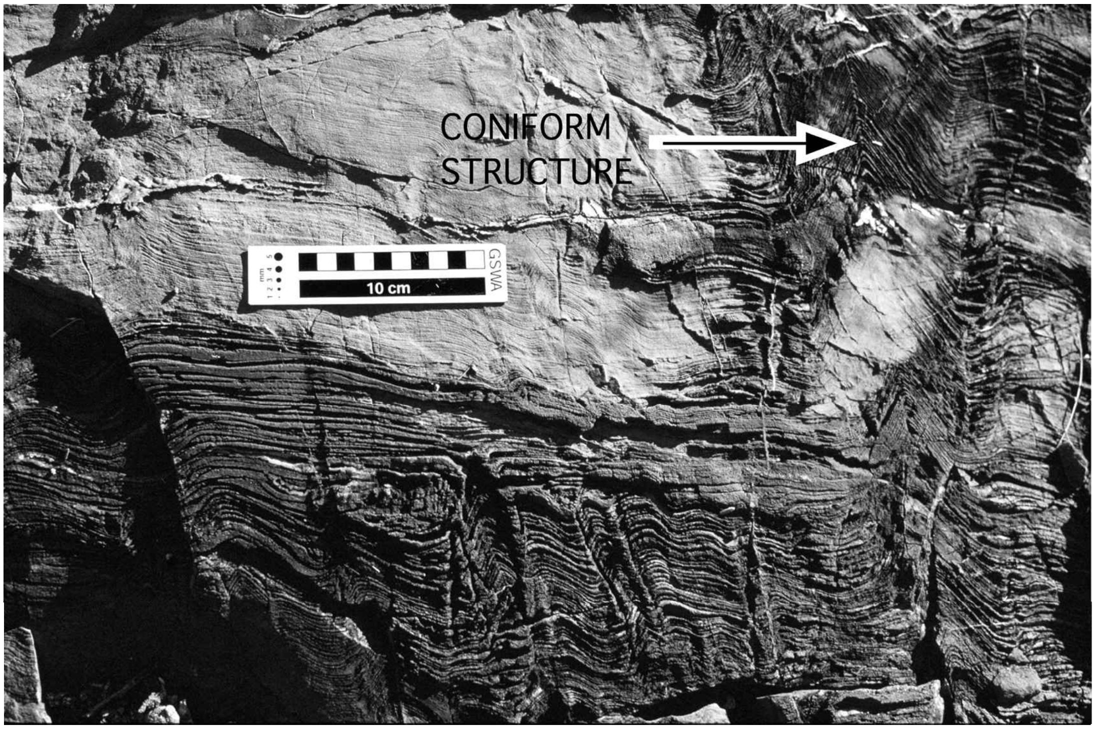

FIG. 12. Stromatolitic carbonates in the Strelley Pool Chert (locality C, Fig. 2). Laminae are isopachous and the apex of the cone is ruptured and veined by secondary carbonate (arrow). Scale bar = 10 cm.

part of the formation consists largely of red or purple shale (Van Kranendonk, 2000).

Corboy Formation. At its thickest, in the eastern part of the study area, the Corboy Formation includes a number of distinct facies developed across major growth faults (Wilhelmij and Dunlop, 1984; Wilhelmij, 1986). Here the formation consists of a basal quartzose sandstone abruptly overlain by conglomerate interbedded with graded sandstone units, red shale, and coarse sandstone. The formation is capped by massive sandstone and conglomerate. The unit was deposited as a series of small, prograding, shallow marine fan deltas (Wilhelmij, 1986; Hill, 1997; Van Kranendonk, 2000).

Paddy Market Formation. In the western part of the study area the Paddy Market Formation is dominantly cherty BIF with minor ferruginous shale. Further east the formation becomes more shale-rich, although much of the shale has been replaced by chert. Sandstone is present in small amounts in beds up to 10 m thick. Towards the top of the formation, in the east, the cherts contain felsic volcanic material that is overlain by up to 200 m of massive dacite (Van Kranendonk, 2000).

Honeyeater Basalt. The Honeyeater Basalt, which consists entirely of basalt and dolerite, conformably overlies the Paddy Market Formation. The lower part of the formation consists of high-Mg basalt interbedded with dolerite, whereas higher in the formation, the basalts are largely tholeiitic and interbedded with dolerite (Glikson and Hickman, 1981a,b; Glikson *et al*., 1991).

Pyramid Hill Formation. The Pyramid Hill Formation is limited in areal extent. It is found in the north central part of the study area east of the Strelley Granite. The formation consists of red and black shales that, when heavily silicified, grade into laminated black and white chert (Van Kranendonk, 2000). The Gorge Creek Group is capped by a well-bedded BIF.

Megasequence 5—De Grey Group

The De Grey Group consists of a single formation, the Lalla Rookh Sandstone (Fig. 3), which is dominated by clastic sedimentary rocks that contain a significant quartzose component. The Lalla Rookh Sandstone, which rests on a well-defined unconformity above the Gorge Creek Group, reaches a maximum thickness of

3 km (Krapez, 1984). In the north central part of the study area the formation consists entirely of coarse clastic sediments and minor shale, whereas to the south the predominate fill is lithic and feldspathic sandstone (Chan, 1998). These rocks provide the first clear evidence of stream activity in the Pilbara succession (Krapez, 1984; Van Kranendonk and Collins, 1998; Van Kranendonk, 2000).

THE PILBARA SUPRACRUSTAL SUCCESSION

The late Archean and early Paleoproterozoic basins that rest upon the ancient cratonic blocks of Western Australia (Fig. 1) form a time series associated with the formation and ultimate disassembly of one of Earth's earliest major continental masses. This was followed by the suturing of the Pilbara and Yilgarn Cratons along the Capricorn Orogen as a new supercontinent evolved in the Paleoproterozoic (Rogers and Santosh, 2002). These basins contain an important sedimentary record of the early Earth, including some of Earth's earliest stromatolites and platform carbonate deposits (Simonson *et al.*, 1993a,b), organic-rich black shales (Brocks *et al.*, 1999), and BIF (Trendall, 1983, 1990). The stratigraphic and structural framework is well constrained by radiometric ages (Arndt *et al.*, 1991; Barley *et al.*, 1997; Trendall *et al.*, 1998), providing a record at a critical time in Earth history when the atmosphere was first becoming oxygen-rich (Lindsay and Brasier, 2002a,b).

The Late Archean-Early Paleoproterozoic Hamersley Basin, which lies close to the southern margin of the Pilbara Block (Trendall, 1983, 1990; Blake and Barley, 1992), overlies a normal crustal thickness (30–40 km) (Drummond, 1981). The basin began to subside at approximately 2.8 Ga following an episode of crustal extension. The architecture of the basin fill is complex and polyphase with major erosional surfaces separating areally extensive megasequences/supersequences (Trendall, 1990; Krapez, 1996). During Fortescue and Hamersley Group time (Fig. 4), sedimentation began in a rift setting, in a siliciclastic-starved environment. The later stages of Hamersley Basin sedimentation (Turee Creek Group times) record the early transition from a passive margin to a foreland basin setting and with it the establishment of a terrigenous sediment supply (Tyler and Thorne, 1990). The succession is largely marine. Evidence of eustasy appears for the first time in the sedimentary succession of the Hamersley Basin (Lindsay and Brasier, 2002a,b).

The geometry and sequence stacking pattern of the succession are both very similar to younger intracratonic basins (see Lindsay *et al.*, 1993). The Hamersley Basin is thus the first basinal setting preserved on the Australian craton in which marine sediments, and in particular platform carbonate rocks, have been preserved in a response to broad, regional, crustal subsidence and where deposition is controlled by eustasy.

The Ashburton Basin (2.2–1.8 Ga) disconformably overlies the southern margin of the Hamersley Basin along its the contact with the Capricorn Orogen (Fig. 1) (Thorne and Seymour, 1991). The basin forms the northern margin of the Capricorn Orogen, a deformed zone that developed during ocean closure. Loading of the ocean floor by the approaching Yilgarn Craton led to the development of a west–northwest-oriented foreland basin [McGrath Trough (Horowitz, 1982)] with an uplifted orogenic margin to the southwest (Blake and Groves, 1987; Blake and Barley, 1992) with the result that sedimentation was dominated by an abundant supply of terrigenous clastic material (Mount McGrath Formation). Continued loading of the crust ultimately led to the supply of terrigenous materials being disrupted and producing a prograding carbonate shelf (Duck Creek Dolomite). Basin sedimentation was accompanied by active-margin mafic volcanism (Cheela Springs Basalt).

THE CAPRICORN OROGEN AND ASSOCIATED BASINS

The Yerrida (~2.2–1.9 Ga), Bryah (~2.0 Ga), Padbury (~2.0 Ga), and Earaheedy (~1.9–1.65 Ga) Basins lie to the southeast of the Hamersley and Ashburton Basins and overlie the Capricorn Orogen (Fig. 1) (Occhipinti *et al.*, 1997, 1998; Pirajno *et al.*, 1998; Pirajno and Adamides, 2000). These now fragmentary basins formed along the northern margin of the Yilgarn Craton in a back-arc setting and record the convergence and collision of the Archean Pilbara and Yilgarn Cratons (Tyler and Thorne, 1990; Thorne and Seymour, 1991; Occhipinti *et al.*, 1997, 1998; Pirajno *et al.*, 1998). Because of their active margin settings, the fill of these small basins is dominated by clastic sediments. However, platform carbonate units are preserved in the Yerrida Basin (Gee and Grey, 1993; Pirajno and Adamides, 2000), and a significant thickness of carbonate rocks also occurs in the Earaheedy Basin.

THE ARCHEAN BIOSPHERE

The end of the Archean is formally defined at 2.5 Ga (Plumb, 1991). In reality the Archean world ended at some point in time closer to 2.8 or 3.0 Ga when the first large continental blocks began to assemble. The stratigraphic record preserved on the ancient Australian Craton reflects this major transition. The rock record from the Early Archean is very different from that of the Late Archean in that the early record is predominantly volcanic and hydrothermal in nature ("greenstone"), while the later record is largely clastic and more readily compared with the Phanerozoic record.

Structures and textures of possible biogenic origin that are preserved in the stratigraphic succession in the Early Archean study area are well known and are believed to provide the earliest direct evidence of Earth's biosphere. Stromatolitic structures have been encountered at two levels within the section. The Dresser Formation contains structures preserved in chert and barite intervals that have been interpreted as stromatolites and oncolites (Dunlop *et al.*, 1978; Walter *et al.*, 1980; Buick *et al.*, 1981; Groves *et al.*, 1981; Walter, 1983). The stromatolitic structures occur, for the most part, in layered barite units that developed over swarms of synvolcanic hydrothermal feeder dykes along listric growth faults (Nijman *et al.*, 1998; Van Kranendonk, 2004). Although it has been argued that these structures are biogenic (Walter *et al.*, 1980; Schopf and Walter, 1983; Walter, 1983), their direct association with the feeder dykes leaves room for doubt (Buick *et al.*, 1981). The setting is complex, and there is considerable scope for more detailed contextual research.

The second stromatolitic horizon occurs in the overlying Strelley Pool Chert, a complex unit consisting of at least five members (Lowe, 1980, 1983; Hofmann *et al.*, 1999). The main stromatolitic unit occurs as an 8-m-thick interval in the middle of the formation and appears to have a consistent and widespread pattern of deposition. The structures have been the focus of considerable discussion, and their biogenicity has been questioned (Buick *et al.*, 1981; Lowe, 1995). The structures are complex and varied (Fig. 12), leading to a more recent re-evaluation again suggesting that they are biogenic (Hofmann *et al.*, 1999). However, the laminae are largely isopachous, an indication that they could be abiotic precipitates (cf. Pope and Grotzinger, 2000). Given the intense hydrothermal activity that appears to have taken place throughout the depositional time interval, the structure may well be the product of hydrothermal deposition (Lindsay *et al.*, 2003a,b). In all, our observations suggest that considerably more work needs to be done to establish the depositional context of these stromatolitic structures before they can be confidently ascribed as biogenic in origin.

Structures resembling remarkably preserved bacterial and cyanobacterial microfossils have been found at several localities in and close to the study area (Awramik *et al.*, 1983; Schopf and Packer, 1987; Schopf, 1992, 1993; Rasmussen, 2000). A complex biota of 11 species of filamentous prokaryotes, which are compared with cyanobacteria (Schopf and Packer, 1987; Schopf, 1992, 1993), have been described from the Apex chert close to Marble Bar (21°10.557′S, 119°41.878′E). The taxonomic interpretations are important in that they provide the earliest evidence of morphological life on Earth and support the hypothesis of an early beginning for oxygenic photosynthesis (Schopf, 1999). The structures are almost a billion years older than the oldest known putative cyanobacterial biomarkers (Summons *et al.*, 1999) and occur well before the earliest evidence for the rise in oxygen in the atmosphere (for a summary, see Knoll and Canfield, 1998; Lindsay and Brasier, 2000, 2002a,b). However, in a recent re-evaluation of the original Apex chert material it has been argued that the filaments are not biogenic but are secondary artifacts formed during diagenesis from abiogenic organic compounds generated in hydrothermal chert veins (Brasier *et al.*, 2002; Van Kranendonk, 2004).

Filaments believed to be biogenic in origin have also been reported from the 3.24 Ga Kangaroo Caves Formation (Rasmussen, 2000) where they form part of the Sulphur Springs deposit associated with a black smoker hydrothermal vent system (Vearncombe *et al.*, 1995, 1998). Rasmussen (2000) argued that the filaments are remnants of a hydrothermal biota of thermophilic chemotrophic prokaryotes. Sulfide textures are remarkably well preserved in these complex deposits and are worthy of much more detailed analysis as they may well preserve evidence of the early biosphere.

Finally, there is evidence that hydrocarbons are trapped in these ancient sedimentary rocks, either as fluid inclusions in hydrothermal precipitates, or as bituminous residues in larger cavities in the Kangaroo Caves Formation and in the Lalla Rookh Sandstone (Dutkiewicz *et al*., 1998; Rasmussen and Buick, 2000). Buick *et al*. (1998) also reported carbonaceous globules in cherts from the lower Warrawoona Group. In the Kangaroo Caves Formation, the hydrocarbons occur in hydrothermal barite or within the sulfides of the volcanogenic hydrothermal massive sulfide deposits that were syndepositional with the formation (Rasmussen and Buick, 2000). Textural information suggest that these deposits were precipitated as black smoker chimneys in a submarine hydrothermal setting driven by heat released from the intruding Strelley Granite at approximately 3.24 Ga (Vearncombe *et al*., 1995). Fluorescing fluid inclusions occur in quartz overgrowths in sandstones from the Lalla Rookh Sandstone (Dutkiewicz *et al*., 1998). Rasmussen and Buick (2000) and Dutkiewicz *et al*. (1998) have argued for a biogenic origin for the hydrocarbons; however, an abiotic origin involving, for example, Fischer-Tropsch-type synthesis, appears possible (Brasier *et al*., 2002).

The Late Archean (and Early Paleoproterozoic) record preserved in the Hamersley and related basins is stratigraphically much more coherent than that preserved in the earlier successions. The Hamersley Basin in particular provides a very comprehensive record of the early oxygenation of the atmosphere in the form of large, eustatically controlled, upward-shallowing sequences that include black shales, BIFs, and ultimately, at their tops, biogenic platform carbonates (Lindsay and Brasier, 2002a,b). These depositional cycles contain organic-rich shales at their base that record evidence for some of Earth's earliest biosphere (Brocks *et al*., 1999), BIFs (Trendall, 1983, 1990) that record the rise of oxygen in the atmosphere, and carbonates that document some of Earth's earliest reef-like carbonate structures (Simonson and Hassler, 1996, 1997; Simonson *et al*., 1993a,b).

SAMPLING STRATEGY

The Archean rocks of the Pilbara Craton are thus part of a protocontinent about which the nascent Australian Craton developed. It consists of granitoid complexes overlain by a carapace of synchronously deposited volcano-sedimentary wedges. Resting upon the early Archean protocontinent are a series of supracrustal basins. In all, the sedimentary record of the Pilbara extends from rocks as old as 3.54 Ga to some as young as approximately 1.9 Ga. As summarized in the following paragraphs the sedimentary record of the Pilbara records evidence of the major tectonic and geological events that accompanied the evolution of the Archean biosphere.

It is here proposed that we develop a carefully documented and curated sample collection from this unique setting. The collection would form the basis for early Earth studies and a focus for astrobiology. The sample set would be designed to reflect the evolutionary succession described above with emphasis placed on cherts lower in the succession and on clastic sediments higher in the succession. Any comprehensive reference collection must reflect diversity of the succession and include rocks from each of the sedimentary environments as well as igneous rocks reflecting the framework in which the protocontinent assembled.

The five megasequences at the North Shaw study area (Fig. 3) are very different and reflect the evolving Early Archean protocontinent. The earliest sedimentary record is limited and dominated by hydrothermally generated laminated cherts and BIFs, which appear as thin interbeds within massive basalts (Coonterunah Group) (Fig. 5). Gradually clastic rocks appear, dominated at first by volcanoclastics followed later by the first evidence of sediments containing detrital quartz derived from true continental granitic crust. Hydrothermally generated laminated chert, carbonate and barite units occur throughout the section. The first evidence of erosion appears at the top of the Coonterunah Group in the form of an angular unconformity (Buick *et al*., 1995b).

The basins that form the supracrustal succession on the Pilbara Craton offer important insights into the closing phases of the Archean and the immediate post-Archean world. Because of their economic importance the basins are well mapped and drill core is readily available (see Lindsay and Brasier, 2002a). The succession provides vital information about the early oxygenation of the atmosphere and the rapid growth of the biosphere that resulted from the assembly of the first continents and the initiation of the plate tectonic cycle. Platform carbonates, whose geometry was determined by eustasy, are widespread and contain considerable information on early oxygenic photosynthesis and the development of the first reef-like structure that are similar in many ways to modern reefs (Simonson *et al.*, 1993a,b; Lindsay and Brasier, 2002a,b).

The collection would consist of three groupings of samples: stratigraphic samples, site-specific samples, and framework samples.

Stratigraphic samples

The stratigraphic sample set would be collected from well-defined settings such as carefully measured and documented sections or from drill core. Samples would be collected from each of the five stratigraphic groups or megasequences. The supracrustal successions preserved in the Hamersley and associated basins would, where possible, be taken from existing drill core or from drill cores obtained for special projects. Where drill core is not available samples would be collected from carefully selected and measured outcrop sections. The samples would concentrate on rocks most likely to host biogenic material. Samples from the Early Archean volcaniclastic carapace would be dominated by cherts that are most likely to preserve fine biogenic structures, but would also include other sedimentary hydrothermal units such as barite and carbonate that would be used in stable isotope and geochemical studies.

Site-specific sample

This sample set would focus on sites where potential biogenic structures have been documented such as the stromatolitic intervals in the Dresser Formation and the Strelley Pool Chert. It would also include detailed sampling of sites such as Chinaman Creek and the Strelley Pool Chert where purported microfossils have been documented (Schopf, 1993) and the sulfide bodies in the Kangaroo Caves Formation that contain possible microfossils as well as evidence of hydrocarbons (Rasmussen, 2000; Rasmussen and Buick, 2000). This would involve a broad sampling around the sites, in measured sections and drill core, to establish the geological context.

Framework samples

While the focus of the collecting would be on material that would help define the character of the Earth's earliest biosphere, it is important that the broad context of the samples be defined. The Archean is a period when the Earth's crust was evolving rapidly, and there is a growing body of evidence to suggest that the evolution of the planet drives the evolution of the atmosphere and biosphere (Lindsay and Brasier, 2002a,b). The framework sample set would include suites of sample from the extrusive volcanic rocks collected along well-documented sections. Sections through the volcanoclastic succession would emphasize the dominant volcanic units (basalts, komatiites, andesites, felsites, and rhyolites) as sources of information on the mantle and evolving crust. This sample set would also include a detailed sampling of the granitoid complexes, which ultimately drove the entire process as well as the later intrusions that were important in driving the hydrothermal systems that may well have been the cradle of early life.

SAMPLE CURATION, CHARACTERIZATION, AND DISTRIBUTION

All samples would be fully documented in the field. Samples would be photographed, and their locations determined using a Global Positioning System receiver. For specialized samples, such as those thought to contain easily contaminated biogeochemical information, the field collection would be modeled on techniques developed by the NASA/National Science Foundation/Smithsonian Institution Antarctic Search for Meteorites program (Harvey and Schutt, 1998).

Characterization

The petrologic and petrographic characteristics of each sample would be determined using thin-section optical microscopy. The quantitative bulk chemical composition of each sample would be measured by x-ray fluorescence spectrometry. Finally, the qualitative bulk mineralogy of each sample would be measured by powder x-ray diffraction.

Data management

An Archean Geologic Reference Materials Database would be produced to fully document each sample. Field documentation would include sampling rationale, supporting references, and field photographs. Documentation would include the results of all analyses, along with images of representative sample surfaces and optical micrographs. The Database would be produced in electronic format and posted on the web. Subsamples of the Archean Geologic Reference Materials would then be made available, at no cost, to researchers in the astrobiology community.

DISCUSSION AND CONCLUSIONS

The Early Archean environment was unique. Recent studies indicate that the atmosphere was largely anoxic with oxygen levels $<10^{-5}$ of the present atmospheric level (Pavlov and Kasting, 2002). There were no large continents, no active or passive margins, and by default no intracratonic basins. Significantly perhaps there are no signs of eustasy. The crust was evolving rapidly, and heat flow was high, leading to the intrusion of large granitoid bodies and the development of a volcanic carapace above them. In turn, this meant that the marine environment was dominated by hydrothermal activity.

In the absence of large continental masses detrital materials other than volcanoclastics are relatively rare in the Early Archean. Significant volumes of quartz sand do not appear in the Pilbara Craton sedimentary record until after 3.2 Ga, presumably as the intruding igneous bodies begin to be unroofed and eroded. There are thus no major accumulations of sedimentary rocks that we normally expect associated with passive continental margins.

With the assembly of the earliest large continents beginning at approximately 3.0–2.8 Ga, the Earth's atmosphere, hydrosphere, and biosphere changed rapidly. Intracratonic basins such as the Hamersley Basin began to develop on the new crustal blocks, opening new shallow-water environments that provided an ideal setting for photosynthesizing organisms and the development of the first carbonate reef structures (Lindsay and Brasier, 2002a,b). Hydrothermal processes, while still important, were thus no longer the only sources of energy available to the evolving biosphere.

The Archean was thus an unfamiliar environment, and unravelling the nature of the earliest biosphere will require development of new approaches and new techniques. Without large continental masses subareal exposures are likely to be rare and short-lived. There is no evidence for stream activity until the De Grey group at approximately 2.9 Ga, at which time braided stream gravels were preserved. Thus models involving early biospheric evolution in "a warm little pond" (Darwin, 1888) or in fresh water seem unlikely. Instead, the focus in the search for the origins of life on Earth should be directed to hydrothermal marine settings involving high temperatures and what would today be hostile geochemical environments with significant concentrations of metallic ions and a largely reducing environment. The risks for the misidentification of abiotic structures and geochemical signatures as signs of ancient life are significant as seen in recent discussions (e.g., Brasier *et al*., 2002; Fedo and Whitehouse, 2002; Schopf *et al*., 2002).

These difficulties suggest that much could be gained by the development of a well-documented collection of Archean rocks that could be made available to all qualified investigators. Until we understand the earliest stages of the evolution of life on Earth we cannot hope to make significant progress in the search for life on other planets such as Mars. Until there is a sample return mission to Mars we must make do with meteorites that come to us largely out of context. An understanding of the Archean Earth can help place those limited samples in a planetary context.

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ABBREVIATION

BIF, banded iron formation.

REFERENCES

Arndt, N.T., Nelson, D.R., Compston, W., Trendall, A.F., and Thorne, A.M. (1991) The age of the Fortescue Group, Hamersley Basin, Western Australia, from ion microprobe zircon U-Pb results. *Aust. J. Earth Sci.* 38, 262–281.

Awramik, S.M., Schopf, J.W., and Walter, M.R. (1983) Filamentous fossil bacteria from the Archaean of Western Australia. *Precambrian Res.* 20, 357–374.

Barley, M.E., Pickard, A.L., and Sylvester, P.J. (1997) Emplacement of a large igneous province as a possible cause of banded iron formation 2.45 billion years ago. *Nature* 385, 55–58.

Bettenay, L.F., Bickle, M.J., Boulter, C.A., Groves, D.I., Morant, P., Blake, T.S., and James, B.A. (1981) Evolution of the Shaw Batholith—an Archaean granitoid-gneiss dome in the eastern Pilbara, Western Australia. In *Special Publication 7: The Archaean*, edited by J.E. Glover and D.I. Groves, Geological Society of Western Australia, Perth, pp. 361–372.

Blake, T.S. and Barley, M.E. (1992) Tectonic evolution of the Late Archaean to Early Proterozoic Mount Bruce Megasequence Set, Western Australia. *Tectonics* 11, 1415–1425.

Blake, T.S. and Groves, D.I. (1987) Continental rifting and the Archaean-Proterozoic transition. *Geology* 15, 229–232.

Brasier, M.D. and Lindsay, J.F. (1998) A billion years of environmental stability and the emergence of eukaryotes: new data from Northern Australia. *Geology* 26, 555–558.

Brasier, M.D., Green, O.R., Jephcoat, A.P., Kleppe, A.K., Van Kranendonk, M.J., Lindsay, J.F., Steele, A., and Grassineau, N.V. (2002) Questioning the evidence for Earth's oldest fossils. *Nature* 416, 76–81.

Brauhart, C. (1999) Regional alteration systems associated with Archaean volcanogenic massive sulphide deposits at Panorama, Pilbara, Western Australia [Ph.D. Thesis], University of Western Australia, Perth.

Brauhart, C., Groves, D.I., and Morant, P. (1998) Regional alteration systems associated with volcanogenic massive sulfide mineralization at Panorama, Pilbara, Western Australia. *Econ. Geol.* 93, 292–302.

Brocks, J., Logan, G.A., Buick, R., and Summons, R.E. (1999) Archean molecular fossils and the early rise of eukaryotes. *Science* 285, 1033–1036.

Buick, R., Dunlop, J.S.R., and Groves, D.I. (1981) Stromatolite recognition in ancient rocks: an appraisal of irregular laminated structures in an early Archaean chert-barite unit from North Pole, Western Australia. *Alcheringa* 5, 161–181.

Buick, R., Des Marais, D.J., and Knoll, A.H. (1995a) Stable isotope compositions of carbonates from the Mesoproterozoic Bangemall Group, northwestern Australia. *Chem. Geol.* 123, 153–171.

Buick, R., Thornett, J.R., McNaughton, N.J., Smith, J.B., Barley, M.E., and Savage, M. (1995b) Record of emergent continental crust ~3.5 billion years ago in the Pilbara Craton of Australia. *Nature* 375, 574–577.

Buick, R., Rasmussen, B., and Krapez, B. (1998) Archaean oil: evidence for extensive hydrocarbon generation and migration 2.5–3.5 Ga. *Am. Assoc. Petroleum Geol. Bull.* 82, 50–69.

Chan, M. (1998) Sedimentology and structure of three small congolmeratic basins in the Lalla Rookh-Western Shaw structural corridor, Pilbara Craton, Western Australia [B.Sc. Honours Thesis], University of Western Australia, Perth.

Cullers, R.L., DiMarco, M.J., Lowe, D.R., and Stone, J. (1993) Geochemistry of a silicified, felsic volcaniclastic suite from the Early Archaean Panorama Formation, Pilbara Block, Western Australia—an evaluation of depositional and post-depositional processes with special emphasis on the rare-Earth elements. *Precambrian Res.* 60, 99–116.

Darwin, F., ed. (1888) *The Life and Letters of Charles Darwin, Vol. 3*, John Murray, London.

de Wit, M.J. (1998) On Archaean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precambrian Geol.* 91, 181–226.

Drummond, B.J. (1981) Crustal structure of the Precambrian terrains of northwest Australia from seismic refraction data. *BMR J. Geol. Geophys.* 6, 123–135.

Dunlop, J.S.R., Muir, M., Milne, V.A., and Groves, D.I. (1978) A new microfossil assemblage from the Archaean of Western Australia. *Nature* 274, 676–678.

Dutkiewicz, A., Rasmussen, B., and Buick, R. (1998) Oil preserved in fluid inclusions in Archaean sandstones. *Nature* 395, 885–888.

Fedo, C.M. and Whitehouse, M.J. (2002) Metasomatic origin of quartz-pyroxene rock, Akilia, Greenland, and implications for Earth's earliest life. *Science* 296, 1448–1452.

Gee, R.D. and Grey, K. (1993) *Report 41: Proterozoic Rocks on the Glengarry 1:250 000 Sheet—Stratigraphy, Structure and Stromatolite Biostratigraphy*, Geological Survey of Western Australia, Perth.

Glikson, A.Y. and Hickman, A.H. (1981a) Chemical stratigraphy and petrogenesis of Archaean basic-ultrabasic volcanic units, eastern Pilbara Block, Western Australia. In *Special Publication 7: Archaean Geology*, edited by J.E. Groves and D.I. Groves, Geological Society of Western Australia, Perth, pp. 287–300.

Glikson, A.Y. and Hickman, A.H. (1981b) *Record 1981/36: Geochemistry of Archaean Volcanic Successions, Eastern Pilbara Block, Western Australia*, Australian Bureau of Mineral Resources, Canberra.

Glikson, A.Y., Davy, R., and Hickman, A.H. (1991) *Record 1991/46: Trace Metal Distribution Patterns in Basalts, Pilbara Craton, Western Australia, with Stratigraphic-Geochemical Implications*, Australian Bureau of Mineral Resources, Canberra.

Groves, D.I., Dunlop, J.S.R., and Buick, R. (1981) An early habitat of life. *Sci. Am.* 245, 64–73.

Harvey, R.P. and Schutt, J.W. (1998) Meteorite recovery and reconnaissance in the Allan Hills-David Glacier and Darwin Glacier regions, 1996–1997. *Antarctic J. U. S.* 32, 25–27.

Hickman, A.H. (1975) *Annual Report 1974: Precambrian Structural Geology of Part of the Pilbara Region*, Geological Survey of Western Australia, Perth, pp. 68–73.

Hickman, A.H. (1983) *Bulletin 127: Geology of the Pilbara Block and Its Environs*, Geological Survey of Western Australia, Perth.

Hickman, A.H. (1984) Archaean diapirism in the Pilbara Block, Western Australia. In *Precambrian Tectonics Illustrated*, edited by A. Kroner and R. Greiling, E.

Schweizerbart'sche Verlagbuchhandlung, Stuttgart, pp. 113–127.

Hickman, A.H. and Lipple, S.H. (1978) *1:250 000 Geological Series: Marble Bar, W.A. Sheet SF 50-8*, 2nd edit., Geological Survey of Western Australia, Perth.

Hill, R.M. (1997) Stratigraphy structure and alteration of hanging wall sedimentary rocks at the Sulphur Springs volcanogenic massive sulfide (VMS) prospect, east Pilbara Craton [Ph.D. Thesis], University of Western Australia, Perth.

Hofmann, H.J., Grey, K., Hickman, A.H., and Thorpe, R. (1999) Origin of 3.45 Ga coniform stromatolites in the Warrawoona Group, Western Australia. *Geol. Soc. Am. Bull.* 3, 1256–1262.

Horowitz, R.C. (1982) Geological history of the early Proterozoic Paraburdoo hinge zone, Western Australia. *Precambrian Res.* 19, 191–200.

Knoll, A.H. and Canfield, D.E. (1998) Isotopic inferences on early ecosystems. In *The Paleontological Society Papers 4: Isotopic Paleobiology and Paleoecology*, edited by R.D. Norris and R.M. Corfield, The Paleontological Society, Lawrence, KS, pp. 212–243.

Krapez, B. (1984) Sedimentation in a small, fault-bounded basin—Lalla Rookh Sandstone, East Pilbara Block. In *Publication 9: Archaean and Proterozoic Basins of the Pilbara, Western Australia—Evolution and Mineralization Potential*, edited by J.R. Muhling, D.I. Groves, and T.S. Blake, University of Western Australia, Geology Department and University Extension, Perth, pp. 89–110.

Krapez, B. (1996) Sequence-stratigraphic concepts applied to the identification of basin-filling rhythms in Precambrian successions. *Aust. J. Earth Sci.* 43, 355–380.

Lindsay, J.F. and Brasier, M.D. (2000) A carbon isotope reference curve for c.1700 to 1575 Ma, Macarthur and Mount Isa Basins, northern Australia. *Precambrian Res.* 99, 271–308.

Lindsay, J.F. and Brasier, M.D. (2002a) Did global tectonics drive early biosphere evolution? Carbon isotope record from 2.6 to 1.9 Ga carbonates of Western Australian basins. *Precambrian Res.* 114, 1–34.

Lindsay, J.F. and Brasier, M.D. (2002b) A comment on tectonics and the future of terrestrial life—reply. *Precambrian Res.* 118, 293–295.

Lindsay, J.F., Kennard, J.M., and Southgate, P.N. (1993) Application of sequence stratigraphy in an intracratonic setting, Amadeus Basin, central Australia. In *Special Publication 18: Sequence Stratigraphy and Facies Associations*, edited by H.W. Posamentier, C.P. Summerhayes, B.U. Haq, and G.P. Allen, International Association of Sedimentologists, Blackwell, Oxford, pp. 605–631.

Lindsay, J.F., Brasier, M.D., McLaughlin, N., Green, O.R., Fogel, M., McNamara, K.M., and Steele, A. (2003a) The Archaean: crucible of creation or cauldron of crud, data from Western Australia [abstract]. *Astrobiology* 2, 455–456.

Lindsay, J.F., Brasier, M.D., McLaughlin, N., Green, O.R., Fogel, M., McNamara, K.M., Steele, A., and Mertzman, S.A. (2003b) Abiotic Earth—establishing a baseline for earliest life, data from the Archean of Western Australia [abstract 1137]. In *Lunar and Planetary Science Conference XXXIV* [book on CD-ROM], Lunar and Planetary Institute, Houston.

Lowe, D.R. (1980) Stromatolites 3,400–Myr old from the Archaean of Western Australia. *Nature* 284, 441–443.

Lowe, D.R. (1983) Restricted shallow-water sedimentation of early Archaean stromatolitic and evaporitic strata of the Strelley Pool Chert, Pilbara Block, Western Australia. *Precambrian Res.* 19, 239–283.

Lowe, D.R. (1994) Abiological origin of described stromatolites older than 3.2 Ga. *Geology* 22, 387–390.

Lowe, D.R. (1995) Abiological origin of described stromatolites older than 3.2 Ga. *Geology* 23, 191–192.

McKay, D.S., Gibson, E.K., Thomas-Keprta, K.L., Vali, H., Romanek, C.S., Clemett, S.J., Chillier, X.D.F., Maechling, C.R., and Zare, R.N. (1996) Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001. *Science* 273, 942–930.

McNaughton, N.J., Compston, W., and Barley, M.E. (1993) Constraints on the age of the Warrawoona Group, eastern Pilbara Block, Western Australia. *Precambrian Res.* 60, 69–98.

Morant, P. (1998) Panorama zinc-copper deposits. In *Monograph 22: Geology of Australia and Papua New Guinean Mineral Deposits*, edited by D.A. Berkman and D.H. MacKenzie, Australian Institute of Mining and Metallurgy, Melbourne, pp. 287–292.

Murray, C.G., Schreiber, E., and Walker, R.N. (1989) Regional geological interpretation of a digital coloured residual Bouguer gravity image of eastern Australia with a wavelength cut-off of 250 km. *Aust. J. Earth Sci.* 36, 423–449.

Nelson, D.R. (1997) *Record 1997/2: Compilation of SHRIMP U-Pb Zircon Geochronology Data, 1996*, Geological Survey of Western Australia, Perth.

Nelson, D.R. (1998) *Record 1998/2: Compilation of SHRIMP U-Pb Zircon Geochronology Data, 1997*, Geological Survey of Western Australia, Perth.

Nelson, D.R. (1999) *Record 1999/2: Compilation of Geochronology Data, 1998*, Geological Survey of Western Australia, Perth.

Nelson, D.R. (2000) *Record 2000/2: Compilation of Geochronology Data, 1999*, Geological Survey of Western Australia, Perth.

Nelson, D.R. (2001) *Record 2001/2: Compilation of Geochronology Data, 2000*, Geological Survey of Western Australia, Perth.

Nijman, W., de Bruijne, K.C.H., and Valkering, M.E. (1998) Growth fault control of early Archaean cherts, barite mounds and chert-barite veins, North Pole Dome, eastern Pilbara, Western Australia. *Precambrian Res.* 88, 25–52.

Occhipinti, S.A., Grey, K., Pirajno, F., Adamides, N.G., Bagas, L., Dawes, P., and Le Blanc Smith, G. (1997) *Record 1997/3: Stratigraphic Revision of Palaeoproterozoic Rocks of the Yerrida, Bryah and Padbury Basins (Former Glengarry Basin)*, Geological Survey of Western Australia, Perth.

Occhipinti, S.A., Swager, C.P., and Pirajno, F. (1998) Structural-metamorphic evolution of the Palaeoproterozoic Bryah and Padbury Groups during the Capricorn orogeny, Western Australia. *Precambrian Res.* 90, 141–158.

Pavlov, A.A. and Kasting, J.F. (2002) Mass-independent fractionation of sulfur isotopes in Archean sediments: strong evidence for an anoxic Archean atmosphere. *Astrobiology* 2, 27–41.

Pirajno, F. and Adamides, N.G. (2000) *Report 60: Geology and Mineralisation of the Palaeoproterozoic Yerrida Basin, Western Australia*, Geological Survey of Western Australia, Perth.

Pirajno, F., Occhipinti, S.A., and Swager, C.P. (1998) Geology and tectonic evolution of the Palaeoproterozoic Bryah, Padbury and Yerrida Basins (formerly Glengarry Basin), Western Australia: implications for the history of the south-central Capricorn Orogen. *Precambrian Res.* 90, 119–140.

Plumb, K.A. (1991) New Precambrian time scale. *Episodes* 14, 139–140.

Pope, M.C. and Grotzinger, J.P. (2000) Controls on fabric development and morphology of tufa and stromatolites, uppermost Pethei Group (1.8 Ga), Great Slave Lake, Northwest Canada. In *Special Publication 67: Carbonate Sedimentation and Diagenesis in the Evolving Precambrian World*, edited by N.P. James and J.P. Grotzinger, SEPM, Tulsa, OK, pp. 103–121.

Rasmussen, B. (2000) Filamentous microfossils in a 3,240–million-year-old volcanogenic massive sulphide deposit. *Nature* 405, 676–679.

Rasmussen, B. and Buick, R. (2000) Oily old ores: evidence for hydrothermal petroleum generation in an Archaean volcanogenic massive sulfide deposit. *Geology* 28, 731–734.

Rogers, J.J.W. and Santosh, M. (2002) Configuration of Columbia, a Mesoproterozoic continent. *Gondwana Res.* 5, 5–22.

Rutland, R.W.R. (1976) Orogenic evolution of Australia. *Earth-Sci. Rev.* 12, 161–196.

Schopf, J.W. (1992) Paleobiology of the Archean. In *The Proterozoic Biosphere: A Multidisciplinary Study*, edited by J.W. Schopf and C. Klein, Cambridge University Press, Cambridge, UK, pp. 25–39.

Schopf, J.W. (1993) Microfossils of the early Archaean Apex chert: new evidence of the antiquity of life. *Science* 260, 640–646.

Schopf, J.W. (1999) *The Cradle of Life*, Princeton University Press, Princeton, NJ.

Schopf, J.W. and Packer, B.M. (1987) Early Archean (3.3 billion to 3.5 billion-year-old) microfossils from Warrawoona Group, Australia. *Science* 237, 70–73.

Schopf, J.W. and Walter, M.R. (1983) Archaean microfossils: new evidence of ancient microbes. In *Earth's Earliest Biosphere—Its Origin and Evolution*, edited by J.W. Schopf, Princeton University Press, Princeton, NJ, pp. 214–239.

Schopf, J.W., Kudryavtsev, A.B., Agresti, D.G., Wdowiak, T.J., and Czaja, A.D. (2002) Laser-Raman imagery of Earth's earliest fossils. *Nature* 416, 73–76.

Shaw, R.D., Wellman, P., Gunn, P., Whitaker, A.J., Tarlowski, C., and Morse, M. (1996) *Record 1996/30: Guide to Using the Australian Crustal Elements Map*, Australian Geological Survey Organisation, Canberra.

Simonson, B.M. and Hassler, S.W. (1996) Was the deposition of large Precambrian iron formations linked to major marine transgressions. *J. Geol.* 104, 665–676.

Simonson, B.M. and Hassler, S.W. (1997) Revised correlations in the early Precambrian Hamersley Basin based on a horizon of resedimented impact spherules. *Aust. J. Earth Sci.* 44, 37–48.

Simonson, B.M., Hassler, S.W., and Schubel, K.A. (1993a) Lithology and proposed revision in stratigraphic nomenclature of the Wittenoom Formation (Dolomite) and overlying formations, Hamersley Group, Western Australia. In *Report 34: Professional Papers*, Geological Survey of Western Australia, Perth, pp. 65–79.

Simonson, B.M., Schubel, K.A., and Hassler, S.W. (1993b) Carbonate sedimentology of the early Precambrian Hamersley Group of Western Australia. *Precambrian Res.* 60, 287–335.

Summons, R.E., Jahnke, L.L., Hope, J.M., and Logan, G.A. (1999) 2–Methylhopanoids as biomarkers for cyanobacterial oxygenic photosynthesis. *Nature* 400, 554–557.

Thorne, A.M. and Seymour, D.D. (1991) *Bulletin 139: Geology of the Ashburton Basin*, Geological Survey of Western Australia, Perth.

Thorpe, R.I., Hickman, A.H., Davis, D.W., Mortensen, J.K., and Trendall, A.F. (1992) U-Pb zircon geochronology of Archaean felsic units in the Marble Bar region, Pilbara Craton, Western Australia. *Precambrian Res.* 56, 169–189.

Trendall, A.F. (1983) The Hamersley Basin. In *Iron-Formations: Facts and Problems*, edited by A.F. Trendall and R.C. Morris, Elsevier, Amsterdam, pp. 69–129.

Trendall, A.F. (1990) Hamersley Basin. In *Memoir 3: Geology and Mineral Resources of Western Australia*, Geological Survey of West Australia, Perth, pp. 163–190.

Trendall, A.F., Nelson, D.R., de Laeter, J.R., and Hassler, S.W. (1998) Precise zircon U-Pb ages from the Marra Mamba Iron Formation and the Wittenoom Formation, Hamersley Group, Western Australia. *Aust. J. Earth Sci.* 45, 137–142.

Tyler, I.M. and Thorne, A.M. (1990) The northern margin of the Capricorn Orogen, Western Australia—an example of an early Proterozoic collision zone. *J. Struct. Geol.* 12, 685–701.

Van Kranendonk, M.J. (1998) Litho-tectonic and structural map components of the North Shaw 1:100,000 sheet, Archaean Pilbara Craton. In *Annual Review 1997*, Geological Survey of Western Australia, Perth, pp. 63–70.

Van Kranendonk, M.J. (2000) *1:100,000 Geological Series Explanatory Notes: Geology of the North Shaw 1:100,000 Sheet*, Geological Survey of Western Australia, Perth.

Van Kranendonk, M.J. (2004) Volcanic degassing, hydrothermal circulation and the flourishing of life on Earth: new evidence from the c.3.46 Ga Warrawoona group, Pilbara Craton, Western Australia. *Precambrian Res.* (in press).

Van Kranendonk, M.J. and Collins, W.J. (1998) Timing and tectonic significance of Late Archaean, sinistral strike-slip deformation in the Central Pilbara Structural Corridor, Pilbara Craton, Western Australia. *Precambrian Res.* 88, 207–232.

Van Kranendonk, M.J. and Morant, P. (1998) Revised Ar-

chaean stratigraphy of the North Shaw 1:100,000 sheet, Pilbara Craton, Western Australia. In *Annual Review 1997–98*, Geological Survey of Western Australia, Perth, pp. 55–62.
Van Kranendonk, M.J., Hickman, A.H., Smithies, R.H., Nelson, D.N., and Pike, G. (2002) Geology and tectonic evolution of the Archaean Pilbara Terrain, Pilbara Craton, Western Australia. *Econ. Geol*. 97, 695–732.
Vearncombe, S. (1996) Volcanogenic massive sulfide-sulfate mineralisation at Strelley, Pilbara Craton, Western Australia [Ph.D. Thesis], University of Western Australia, Perth.
Vearncombe, S., Barley, M.E., Groves, D.I., McNaughton, N.J., Mikulki, E.J., and Vearncombe, J.R. (1995) 3.26 Ga black smoker-type mineralisation in the Strelley Belt, Pilbara Craton, Western Australia. *J. Geol. Soc. Lond*. 152, 587–590.
Vearncombe, S., Vearncombe, J.R., and Barley, M.E. (1998) Fault and stratigraphic controls on volcanogenic massive sulfide deposits in the Strelley Belt, Pilbara Craton, Western Australia. *Precambrian Res*. 88, 67–82.
Walter, M.R., ed. (1976) *Stromatolites*, Elsevier, Amsterdam.
Walter, M.R. (1983) Archaean stromatolites: evidence of Earth's oldest benthos. In *Earth's Earliest Biosphere—Its Origin and Evolution*, edited by J.W. Schopf, Princeton University Press, NJ, pp. 187–213.
Walter, M.R., Buick, R., and Dunlop, J.S.R. (1980) Stromatolites, 3400–3500 Myr old from the North Pole area, Western Australia. *Nature* 284, 443–445.
Wilhelmij, H.R. (1986) Depositional history of the middle Archaean sedimentary sequences in the Pilbara Block, Western Australia—a genetic stratigraphic analysis of the terrigenous rocks of the Pilgangoora syncline [Ph.D. Thesis], University of Western Australia, Perth.
Wilhelmij, H.R. and Dunlop, J.S.R. (1984) A genetic stratigraphic investigation of the Gorge Creek Group in the Pilgangoora Syncline. In *Publication 9: Archaean and Proterozoic Basins of the Pilbara, Western Australia—Evolution and Mineralization Potential*, edited by J.R. Muhling, D.I. Groves, and T.S. Blake, University of Western Australia, Geology Department and University Extension, Perth, pp. 68–88.
Williams, I.S. and Collins, W.J. (1990) Granite-greenstone terranes in the Pilbara Block, Australia, as coeval volcano-plutonic complexes; evidence from U-Pb zircon dating of Mount Edgar Batholith. *Earth Planet. Sci. Lett*. 97, 41–53.

Address reprint requests to:
Dr. John F. Lindsay
Lunar and Planetary Institute
3600 Bay Area Boulevard
Houston, TX 77058

E-mail: john.f.lindsay@jsc.nasa.gov