Available online at www.sciencedirect.com
ScienceDirect
Precambrian Research 158 (2007) 198–227
Precambrian Research
www.elsevier.com/locate/precamres

3.43 billion-year-old stromatolite reef from the Pilbara Craton of Western Australia: Ecosystem-scale insights to early life on Earth

Abigail C. Allwood [a,b,*], Malcolm R. Walter [a], Ian W. Burch [a,b], Balz S. Kamber [c]

[a] *Australian Centre for Astrobiology, Department of Earth & Planetary Sciences, Macquarie University, Herring Road, NSW 2109, Australia*
[b] *NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91024, United States*
[c] *Department of Earth Sciences, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ont. P3E 2C6, Canada*

Received 19 January 2007; received in revised form 3 April 2007; accepted 28 April 2007

Abstract

The 3.43 billion-year-old Strelley Pool Chert, Pilbara Craton, Western Australia, contains compelling evidence of Early Archaean life in the form of kilometre-sized remnants of an ancient stromatolitic carbonate platform. Reviewing and building on earlier studies, we examine the fossilized remains of the platform to seek ecosystem-scale insights to Earth's early biosphere, examining the evidence for biosedimentation, and the importance and effect of different environmental processes on biological activity.

Both vertical and lateral trends show that stromatolite abundance and diversity are greatest in the area interpreted as an isolated, partially restricted, peritidal marine carbonate platform, or reef, where there is virtually no trace of hydrothermal or terrigenous clastic input. In contrast, stromatolites are poorly developed or absent among hydrothermal, volcaniclastic or terrigenous clastic sedimentary facies, and are absent in deeper marine settings that are laterally equivalent to shallow marine stromatolitic facies. Hydrothermal veins, some of which were previously interpreted as vents that exhaled fluids from which the stromatolitic structures precipitated, are shown to postdate the stromatolites. On the platform, stromatolite facies associations varied between different palaeoenvironments, but some stromatolite types occurred across different palaeoenvironments, highlighting the combined influence of biological and environmental processes on stromatolite formation. The regional distribution of stromatolites in the palaeoenvironment suggests a biological response to variations in water depth, sediment influx and hydrothermal activity with stromatolite formation favoured by relatively 'normal' shallow marine environments with low clastic/chemical sedimentation rates and no direct input from high temperature hydrothermal systems. The lithology, structure and fabrics of the stromatolites, and their close association with abundant evaporite crystal pseudomorphs, indicate that evaporitic precipitation was probably the dominant non-biological process that contributed to stromatolite formation. The study supports a biological interpretation for the origin of the stromatolites, and reveals compelling evidence for the conditions that favoured biological activity on the early Earth and formation of macroscopic biosignatures that could be preserved for most of Earth's history.
© 2007 Elsevier B.V. All rights reserved.

Keywords: Stromatolites; Microbialites; Morphology; Biogenic; Reef; Carbonate platform; Rocky shoreline; Evaporites; Early Archaean; Pilbara; Strelley Pool Chert; Kelly Group; North Pole Dome; Panorama Greenstone Belt; Dolomite; Carbonate; Chert; Rare earth elements

1. Introduction

Knowing when Earthly life emerged, and the environmental conditions that nurtured life as it arose, is fundamental to understanding the origins of life on our planet; and perhaps by analogy, its potential existence

* Corresponding author at: NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91024, United States.
Tel.: +1 626 393 4275.
E-mail address: Abigail.C.Allwood@jpl.nasa.gov (A.C. Allwood).

0301-9268/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.precamres.2007.04.013

on other planets or moons we explore. Scientists have long sought to answer such questions through theory, examination of the early fossil record and experimentation. Hypotheses for the timing of life's emergence vary significantly (Moorbath, 2005 and references therein) and hinge upon the search for increasingly older biosignatures in the rock record. As for the conditions that nurtured early life, a popular hypothesis is that the first organisms on Earth arose under hydrothermal conditions similar to modern mid-ocean ridge hydrothermal vents (e.g. Corliss et al., 1981)—an hypothesis supported by the observation that the universal tree of life appears to be rooted in hyperthermophilic (high temperature) organisms. Significantly, this has stimulated the notion of looking for similar settings elsewhere in the solar system as possible habitats for life. An alternative hypothesis is that emergent life would have favoured less extreme conditions and lower temperatures, and proponents of that hypothesis question whether hydrothermal conditions are necessary or even favourable for the emergence of life (e.g. Bada and Lazcano, 2002 and references therein).

The debate seems likely to remain unresolved unless we can find and study physical fossil remnants that encapsulate evidence of earliest life and the environment in which it flourished. However, the very identification of fossils from the early geologic record has in itself been challenging and contentious, let alone identifying the associated paleoenvironment. Although putative fossil evidence of life – including microfossils, stromatolites (laminated sedimentary structures of probable microbial origin) and chemical biosignatures – has been traced back to almost 3.5 Ga (Walsh, 1972; Lowe, 1980, 1983; Walter et al., 1980; Awramik et al., 1983; Walsh and Lowe, 1985; Byerly et al., 1986; Schopf and Packer, 1987; Schopf, 1993; Hofmann et al., 1999; Hofmann, 2000; Ueno et al., 2001; Van Kranendonk et al., 2003; Tice and Lowe, 2004; Schopf, 2006; Westall et al., 2001, 2006; Westall and Southam, 2006), there has been long-standing debate about whether any of the Early Archaean 'fossils' are in fact biogenic (e.g. Lowe, 1992, 1994; Brasier et al., 2002, 2004, 2005, 2006; Grotzinger and Knoll, 1999; or Hofmann et al., 1999 with Lindsay et al., 2003a,b). In fact, Moorbath (2005) pointed out that there is 'no consensus' among scientists for life's existence prior to 1.9 Ga (e.g. compare Brasier et al., 2002, 2005, 2006 with Schopf, 2006). The lack of consensus centres on challenges that exist largely because key outcrops are typically structurally deformed, chemically altered and have limited lateral continuity. Furthermore, any putative morphological or chemical biosignatures that have been detected are commonly rendered inconclusive due to ambiguities attributed to the associated hydrothermal palaeoenvironments most are found in (e.g. Lindsay et al., 2005; Brasier et al., 2006). Importantly, using the fossil record to elucidate the very origin of life is predicated on the assumption that the origin of life has been preserved in the fossil record. Probability rules against this, as most of the Archaean geologic record has been obliterated through time, and what is left has been subjected to extensive alteration that would likely veil something so subtle from our eyes. The real potential of the fossil record to inform our understanding of earliest life may necessarily lie elsewhere—or else*when*: that is, *after* the moment of life's origin, when life has gained a firmer hold and left a more significant mark on its surrounds.

Fossil remnants that explore this potential were documented in a previous paper (Allwood et al., 2006a,b), in which it was proposed that large scale, well preserved sections of an Early Archaean stromatolite reef occur in 10 km-long outcrops of the 3.43 Ga Strelley Pool Chert, Pilbara Craton, Western Australia. The stromatolites of the Strelley Pool Chert are the most visible, widespread, morphologically diverse and well-preserved of the purported Early Archaean fossils, which makes them ideal candidates for resolving questions about Earth's early biosphere. The Strelley Pool Chert realizes the potential of the early fossil record to: (1) disclose the nature of Earth's biosphere in its early (if not earliest) stages; (2) set *minimum* ages of biological milestones, such as the beginning of life, the emergence of biodiversity and development of different capabilities; and (3) reveal the type of conditions that enabled life not just to emerge, but to gain sufficient foothold to leave a lasting and highly visible signature on its surrounds. This latter point is crucial for astrobiology, for if we want to know whether life once flourished even briefly on Mars or any other rocky planet or moon, the terrestrial fossil record is our only analog to gauge where to look and what to look for: that is to determine the conditions that enable life to flourish and leave a lasting, detectable impression, and to understand how to recognize the traces life might leave in such settings.

Building on the previous study by Allwood et al. (2006a,b), here we scrutinize the spatial and temporal associations between different stromatolite types in the Strelley Pool Chert; associations between stromatolites and palaeoenvironmental conditions at broad and local scales; and the role of different processes that could feasibly have contributed to stromatolite formation in the Strelley Pool Chert. The data constrain the origin of the stromatolites, underscore the probable role of biology, identify major non-biological processes that contributed to stromatolite formation, and reveal important infor-

mation about the nature of the biota that flourished during deposition of the Strelley Pool Chert. In addition, the study demonstrates the merits of a context-oriented palaeontological approach, which increases the validity of criteria that may be of limited value if examined individually.

2. Geologic setting

The Strelley Pool Chert is a clastic and chemical sedimentary rock formation deposited during a ca. 80 million year period from 3.43 to 3.35 Ga on the Pilbara Craton. The Strelley Pool Chert today forms outcrops that span the East Pilbara Granite – Greenstone Terrane, which is the ancient nucleus of the Pilbara Craton (Fig. 1). The East Pilbara Granite – Greenstone Terrane is a ~200 km-wide region comprising volcanosedimentary rocks (the Pilbara Supergroup) deposited between 3.51 and 3.0 Ga, variably metamorphosed to approximately greenschist facies and folded into curved, synclinal belts between 35 and 120 km-diameter ca. 3.57–2.85 Ga granitoid complexes (Van Kranendonk, 2001). The Pilbara Supergroup is a ca. 35 km-thick succession of volcanosedimentary rocks and is one of the best-preserved and most complete Early to Late Archaean successions on Earth (Van Kranendonk, 2001; Van Kranendonk et al., 2002, 2006). The five stratigraphic subdivisions currently recognized within the Pilbara Supergroup are, in ascending stratigraphic order: the ca. 3.52 Ga Coonterunah Group; the 3.52–3.43 Ga Warrawoona Group, the 3.43–3.31 Ga

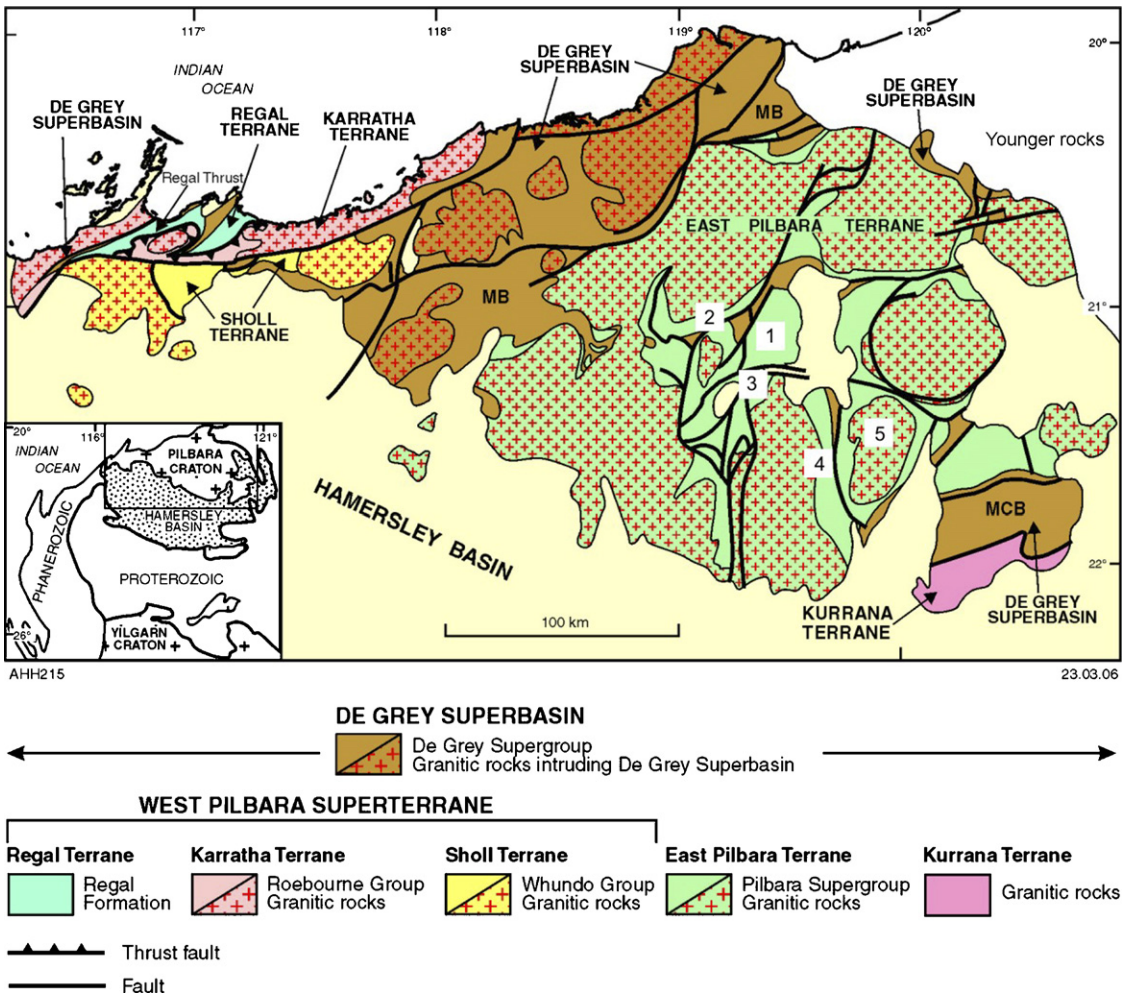

Fig. 1. Geological map of the Pilbara Craton, showing major structural elements and location of the North Pole Dome (Modified from Van Kranendonk et al., 2006). MCB = Mosquito Creek Basin, MB = Mallina Basin. Numbers represent areas containing Strelley Pool Chert outcrops examined in the present study. 1 = East Strelley Greenstone Belt, 2 = Panorama Greenstone Belt, 3 = Shaw Gorge area, 4 = Coongan Greenstone Belt, and 5 = McPhee Dome, surrounded by Kelly Greenstone Belt. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

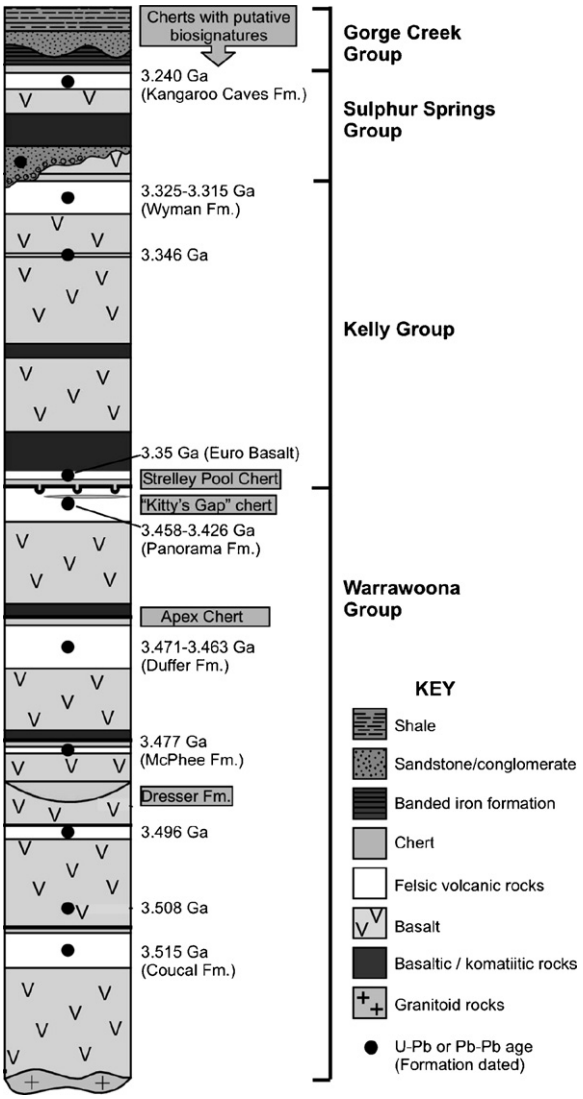

Fig. 2. Generalised stratigraphic column of the Pilbara Supergroup, showing putative fossil-bearing chert formations, age constraints from SHRIMP data (black dots) and distribution of the stratigraphic record through time (at left). Modified from (Van Kranendonk et al., 2006). Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

Kelly Group, the ca. 3.25–3.23 Ga Sulfur Springs Group and the ca. 3.23–3.0 Ga Gorge Creek Group (Fig. 2; Van Kranendonk et al., 2006).

The excellent preservation and exposure of possible fossil-bearing sedimentary rocks in the Pilbara Supergroup has drawn significant palaeobiological interest. Putative Early Archaean fossils have been found in at least four separate chert formations in the lower Pilbara Supergroup, from oldest to youngest they are: stromatolites and microfossils of the 3.49 Ga Dresser Formation (Walter et al., 1980; Ueno et al., 2001); microfossils of two ca. 3.46 Ga cherts in the Apex Basalt (Awramik et al., 1983; Schopf and Packer, 1987; Schopf, 1993); microfossils of the 3.43 Ga "Kittys Gap Chert" in the Panorama Formation (Westall et al., 2006); and stromatolites of the 3.43 Ga Strelley Pool Chert (Fig. 2) (Lowe, 1980, 1983; Hofmann et al., 1999; Van Kranendonk et al., 2003; Allwood et al., 2004a,b, 2005a,b, 2006a).

The Strelley Pool Chert was previously mapped as part of the Warrawoona Group, but is now designated as the basal unit of the Kelly Group, deposited over a regional unconformity at the top of the Warrawoona Group (Buick et al., 1995; Van Kranendonk, 2000; Van Kranendonk et al., 2002, 2006). The maximum age of the Strelley Pool Chert is constrained by zircon dates in the underlying Panorama Formation (DiMarco and Lowe, 1989), which is composed of felsic volcaniclastic rocks dated at 3.459–3.426 Ga (Van Kranendonk et al., 2002). The maximum age limit is constrained by zircon populations dated at 3.346–3.363 Ga in a silicified felsic tuff within the Euro Basalt (Nelson, 2001), which locally conformably overlies the Strelley Pool Chert.

The Strelley Pool Chert crops out in several greenstone belts across the East Pilbara Granite – Greenstone Terrane, with the main outcrops occurring (from west to east) in: (1) the Strelley Pool area, which contains the type section at Strelley Pool (Lowe, 1981; Lowe, 1983; Lindsay et al., 2005); (2) the Panorama Greenstone Belt, which contains the "Trendall Locality" (Hofmann et al., 1999); (3) the Shaw Gorge area, to the south of the Panorama Greenstone Belt; (4) the Coongan Greenstone Belt south of Marble Bar township; and (5) the Kelly Greenstone Belt around the McPhee Dome, southeast of Marble Bar. The present study focuses on a 10 km-long stretch of ridge-top outcrops of the Strelley Pool Chert in the Panorama Greenstone Belt (Fig. 3).

The Strelley Pool Chert is typically recognizable by the presence of a ca. 5–20 m-thick unit of laminated chert with wavy stromatolitic or pseudostromatolitic structures ("member 2" of Allwood et al., 2006a,b). In the areas where that unit is absent, the Strelley Pool Chert is typically recognizable as a unit of layered or laminated cherty rocks, stratigraphically sandwiched between heavily altered, pre-Kelly Group volcanics below and relatively unaltered Euro Basalt above.

In most areas the Strelley Pool Chert has undergone moderate to extensive silicification. The Panorama Greenstone Belt, however, contains some exceptional outcrops that have not been heavily silicified. The Panorama Greenstone Belt consists of lower Pilbara Supergroup rocks encircling and dipping steeply away from a small granitoid complex known as the North Pole Dome, dated at 3.459 Ga (Thorpe et al., 1992). The

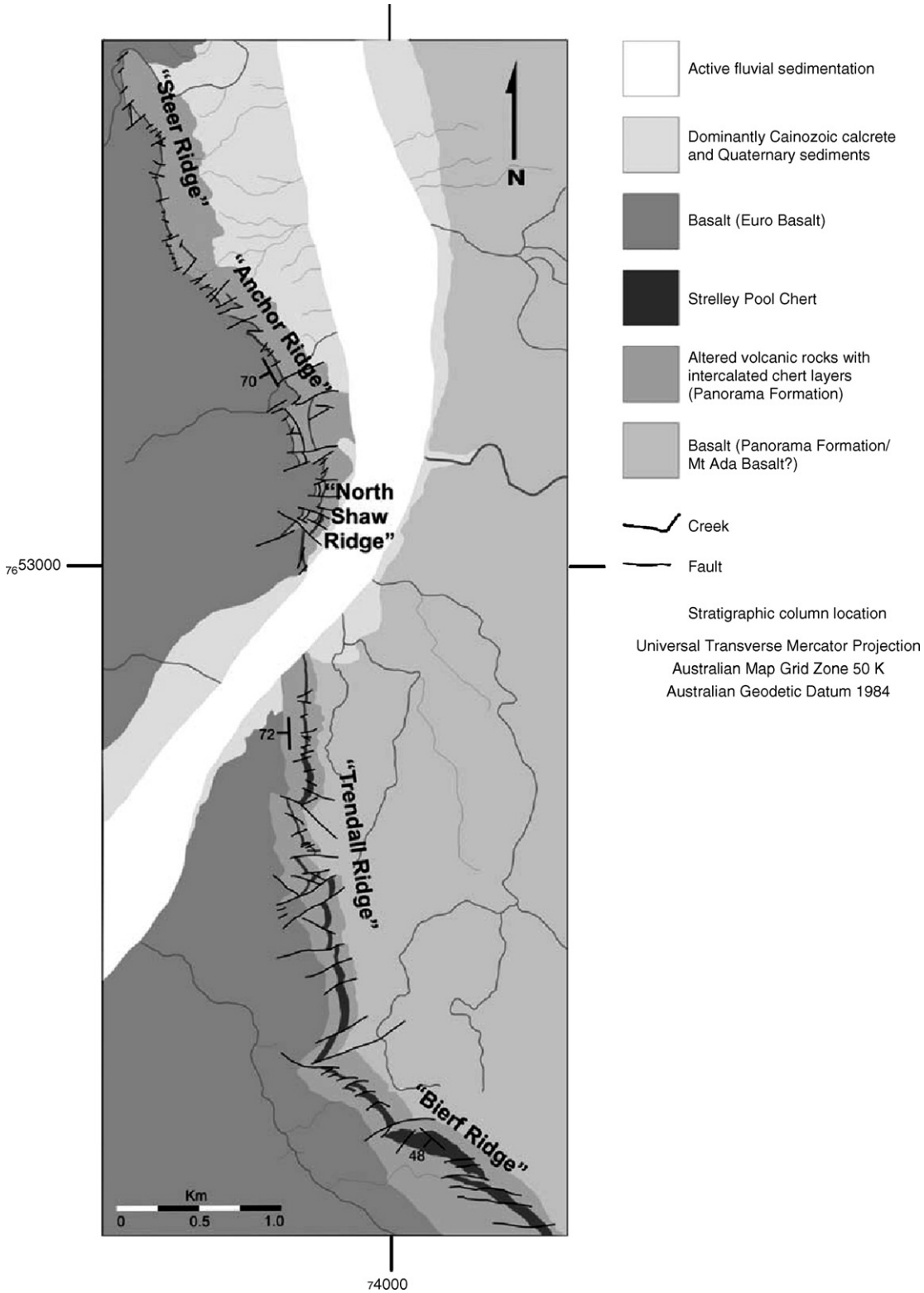

Fig. 3. Geological map of the Strelley Pool Chert in the main study area in the southwest North Pole Dome. Faults shown represent only those that cross cut the Strelley Pool Chert. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

Strelley Pool Chert occurs along two arcuate series of outcrops on the northeastern and southwestern flanks of the dome. The southwestern outcrops, which are the focus of the present study, contain abundant laminated dolomite and chert, which is considered to be little altered from the primary lithology (Allwood et al., 2006a). The outcrops in that area are also characterized by greater abundance, preservation and diversity of stromatolites compared to other parts of the formation.

In the studied outcrops, the Strelley Pool Chert dips approximately 35–90° and forms high ridges that stand above the surrounding basalts. Near the top of the ridges the strata are viewed in near-cross section. Stratigraphic thickness of the Strelley Pool Chert in the study area varies from 1 m to more than 400 m, but is typically about 30 m. Towards the northern end of the outcrops, the formation thins, pinches out and reappears before being truncated by a major fault system (Allwood et al., 2007). Towards the southeast, thickness increases to over 100 m and at the southernmost end the formation is offset by a major fault from correlative east–west trending outcrops further east where the formation is more than 400 m thick.

3. Stromatolite biogenicity

The term "stromatolite" is taken here to imply a biological or probable biological origin (Hofmann, 1973; Awramik et al., 1976; Awramik and Grey, 2005). However, proving a biological origin for stromatolites can be extremely difficult (Awramik and Grey, 2005). The biogenicity of stromatolites and microfossils in the lower Pilbara Supergroup has been questioned (e.g. Lowe, 1992, 1994; Brasier et al., 2002, 2004, 2006) and criteria for the interpretation of such ancient fossils have come under intense scrutiny. Methods that were applied in previous interpretations have been deemed insufficiently rigorous (e.g. Brasier et al., 2006), and the search for new methods and criteria has been fuelled by astrobiology and the need to unequivocally recognize true biosignatures in the search for life on other planets.

Interpreting the origin of stromatolites, or stromatolite-like structures, can be approached in a variety of ways, including: (1) experimental replication of stromatolite accretion in the laboratory comparing biological and abiological processes (e.g. Macintyre et al., 2000); (2) comparison with predetermined criteria for biogenicity (e.g. Buick et al., 1981 and Walter, 1983); (3) mathematical modelling of stromatolite morphogenesis (e.g. Grotzinger and Rothmann, 1996; Bachelor et al., 2000; Jogi and Runnegar, 2005); (4) deconvolution of morphological and other attributes using basic principals (e.g. Hofmann, 1994); and (5) morphologic comparisons with similar structures from the younger geologic record and present day (e.g. Hofmann et al., 1999).

There have been doubts about the validity or significance of using morphologic criteria for the assessment of biogenicity because of the possibility that biological accretion produces shapes indistinguishable from those produced by abiological accretion (e.g. Grotzinger and Rothmann, 1996; Brasier et al., 2005). Awramik and Grey (2005) point out that doubts about using morphologic criteria have seemingly increased in the wake of mathematical modeling experiments in which some common 'biogenic' stromatolite shapes (e.g. columns, domes, branching structures) were theoretically replicated through abiotic accretion (e.g. Grotzinger and Rothmann, 1996). Stromatolites consequently seem to have lost 'status' in the search for unequivocal biosignatures. A pertinent case example is the Strelley Pool Chert: Lindsay et al. (2005) proposed that the Strelley Pool Chert is a hydrothermal exhalite precipitated from fluids derived from chert/carbonate feeder veins in the underlying rocks. They determined that the mineralogical and carbon isotopic composition of the vein fill and Strelley Pool Chert strata are similar, and proposed that the stratiform deposits, including stromatolitic layers, were precipitated from fluids exhaled from the veins. Lindsay et al. (2003a,b, 2005) suggested that the Strelley Pool Chert stromatolites were unlikely to reveal any evidence of life, even if they were biogenic, because any biological aspects of the morphology would be overwhelmed by the influence of abiotic hydrothermal precipitation, which they proposed was a pervasive influence throughout deposition of the Strelley Pool Chert. This view highlights the need to constrain palaeoenvironmental processes during stromatolite formation, but also fundamentally reflects the emerging view that stromatolite morphologies may be better used as 'environmental dipsticks' (Grotzinger and Knoll, 1999) than signals of life.

An additional dimension in the interpretation of Early Archaean fossils was proposed by Brasier et al. (2004, 2005, 2006), who argued that the biological hypothesis for genesis of Early Archaean or alien fossil-like structures cannot be accepted until the "null hypothesis" (that the structures in question are abiogenic) has been rejected. The idea therein would be to introduce some impartiality and absoluteness to such important palaeontological investigations. However, the null hypothesis is typically used for statistical research, where a null hypothesis (e.g. that a drug has no effect) is given priority, or accepted, over alternative hypotheses until the

evidence against it is sufficiently strong. The method is arguably impartial because the investigators predetermine what constitutes 'sufficiently strong' evidence *before* the experiment is conducted (although the impartiality is limited because it is selected by the investigator). In effect the approach establishes a baseline normalcy. In palaeontology, however, the investigators must already have some clue about the result because the experiment has already been performed in the geologic past: the 'measurement' (the possible fossil) already exists and its character has already been identified, or at least postulated as something to look for. Therefore the determination of criteria is not entirely impartial and in any case calls upon conventional palaeontological approaches for fossil interpretation. This does not compare with the decision to accept, for example, a predetermined black and white figure of 78 positive results out of 100 as sufficiently strong evidence for a positive result. Rather, the baseline normalcy of the null hypothesis in the search for early life may have workers invoking increasingly abnormal combinations of circumstances, perhaps existing only in the theoretical realm, in favour of rejecting the null hypothesis. If the hypothesis lies far in the theoretical realm, then it is impossible to determine the tests that will allow it to be accepted or rejected. If an hypothesis cannot be tested then it is not a valid scientific hypothesis. Thus, the incorporation of such hypotheses is not so much adopting an impartial baseline, as developing an implausible bias.

Therefore, 'conventional' palaeontological principals must in any case apply to investigation of Early Archaean fossils. Attempting to use the null hypothesis may be unconstructive. We therefore propose that the palaeontological approaches described earlier in this section can be applied constructively to stromatolite interpretation. In the present study, we further demonstrate that the criterion of stromatolite morphology, if studied in spatial and temporal context in the palaeoenvironment, is a valid and powerful criterion for the analysis of stromatolite genesis. That is, if palaeoenvironmental aspects such as spatial relationships, conditions and processes are woven into the analysis, then a range of stromatolite features *including morphology* take on greater validity and importance as criteria to use in the assessment of stromatolite genesis.

Whereas Allwood et al. (2006a) focused on establishing a biological origin for the Strelley Pool Chert stromatolites mainly on the basis of the inherent stromatolites characteristics such as morphology, fabrics and compositional variations, with overarching reference to the palaeoenvironmental constraints; herein we examine the palaeoenvironmental aspects in more detail. As highlighted above, this is crucial for constraining the processes of stromatolite formation.

4. Stromatolites and palaeoenvironments

Having reviewed the regional geology of the Strelley Pool Chert, considered the fundamental premises and value of different approaches in Early Archaean stromatolite palaeontology, and summarized the evidence for Strelley Pool Chert stromatolite biogenicity established by Allwood et al. (2006a), we now consider Strelley Pool Chert stromatolites in context, and how they might contribute to the original questions of when Earthly life emerged and the environmental conditions that nurtured it. To do this, the palaeoenvironments of the Strelley Pool Chert and the arrangement and character of stromatolites within that context are now examined in more detail.

The Strelley Pool Chert in the southern Panorama Greenstone Belt is a four-part transgressive succession represented by four subunits or 'members' (Fig. 4) deposited in the following broad environments (from base to top): rocky shoreline (member 1); isolated peritidal stromatolite/evaporite platform (member 2); mixed marine/hydrothermal (member 3); and deep water hydrothermal + distal volcaniclastic (member 4), with lateral gradation of the entire succession to deeper water environments in the south (Allwood et al., 2006a and below). A nearly continuous depositional history is recorded from the youngest of the underlying rock units through the stromatolitic layers of the Strelley Pool Chert, so the entire succession can be examined to gain insights to the changing environmental conditions before, during and after the formation of stromatolites. The various stromatolite morphologies described in this section are based on discrete morphologies (Fig. 5), consistently and regularly repeated at a given location, and also at temporally and/or palaeogeographically separate locations within the study area. For detailed descriptions of stromatolites refer to Allwood et al. (2006a) Supplementary Information.

4.1. Underlying rocks, lower contact

Rock types immediately beneath the Strelley Pool Chert, and the amount of time represented at the contact, vary significantly along strike in the study area. The rock units are discussed in detail here because lateral variability in the underlying rocks appears to have played an important role during deposition of the Strelley Pool Chert, owing to the dissimilar weathering resistance of the different rocks types and the resulting topographic

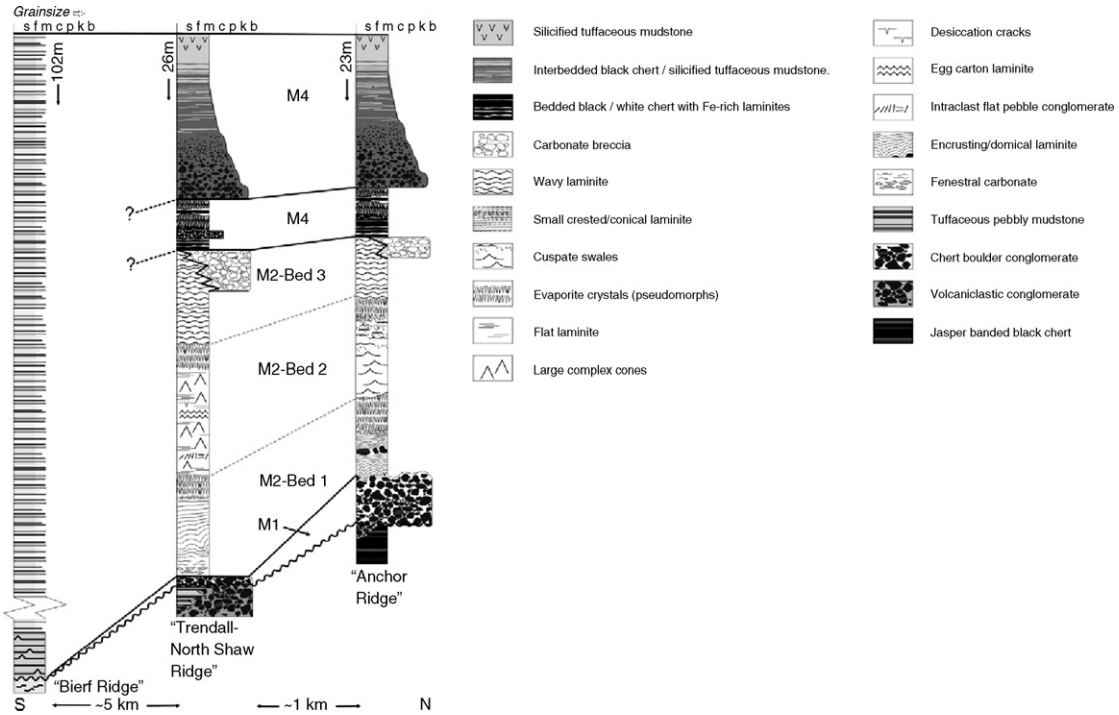

Fig. 4. Correlation of stratigraphic columns representing the southern, central and northern study area. Grainsize scale: s = silt–sand, f = fine sand, m = medium sand, c = coarse sand, p = pebble, k = cobble, b = boulder. M1, M2, M3, M4 = member 1, 2, 3, 4.

relief that they created (Allwood et al., 2006a), both at local and regional scales. Moreover, the alteration features at the contact and the nature of the youngest rocks below the contact provide significant insights to the environment of deposition leading up to the onset of stromatolite formation.

In most areas, particularly in the southern study area, the Strelley Pool Chert lies in nonconformable contact over a suite of light green altered volcanic rocks, or 'palaeoalterite' (Mayer, 1997). The palaeoalterite consists of basaltic rocks that have been extensively altered to clay minerals, with local carbonatization and iron enrichment. A foliated to highly schistose fabric largely obscures primary fabrics and structures of the rock, although remnant lapilli and pillow lava structures are visible locally. The volcanic rocks from which the palaeoalterite formed are the oldest rocks subcropping the Strelley Pool Chert in the study area, and the stratiform nature of their alteration suggests the cause was Early Archaean weathering (Allwood et al., 2006a). The zone of alteration beneath the Strelley Pool Chert extends across the East Strelley, Coongan and Kelly Greenstone belts and in the Shaw Gorge area south of the Panorama Greenstone Belt. Almost everywhere the underlying rock type is pale greenish altered volcanic or volcaniclastic rock.

In the study area, in contrast to other areas, two additional units are locally preserved beneath the unconformity, stratigraphically above the altered volcanics. The first is a jasper-banded black chert unit that attains maximum thickness of ∼14 m, on "Anchor Ridge" (Allwood et al., 2007). Clasts of the jasper-banded black chert occur in overlying conglomerates at the base of the Strelley Pool Chert, indicating that jasper formation pre-dates Strelley Pool Chert deposition and is not a product of younger weathering. The relative abundances of rare earth elements (REE) in the black chert indicate a primary hydrothermal origin (Allwood et al., 2006a).

In just three localities in the study area, a third rock type underlies the Strelley Pool Chert. This latter rock unit consists of thinly bedded, grey-green, pebble to boulder-bearing, tuffaceous mudstones (Fig. 6) and flow banded pebbly tuff. The tuffaceous mudstone overlies and therefore postdates the palaeoalterite. The mudstone unit was not observed overlying hydrothermal jasper-banded black chert, but does contain clasts of the jasper-banded black chert, indicating it was deposited after the jasper-banded black chert as no other sources for such clasts could be identified. The mudstone is therefore the youngest unit beneath the Strelley Pool Chert. Moreover, the presence of soft intraclasts of the mud-

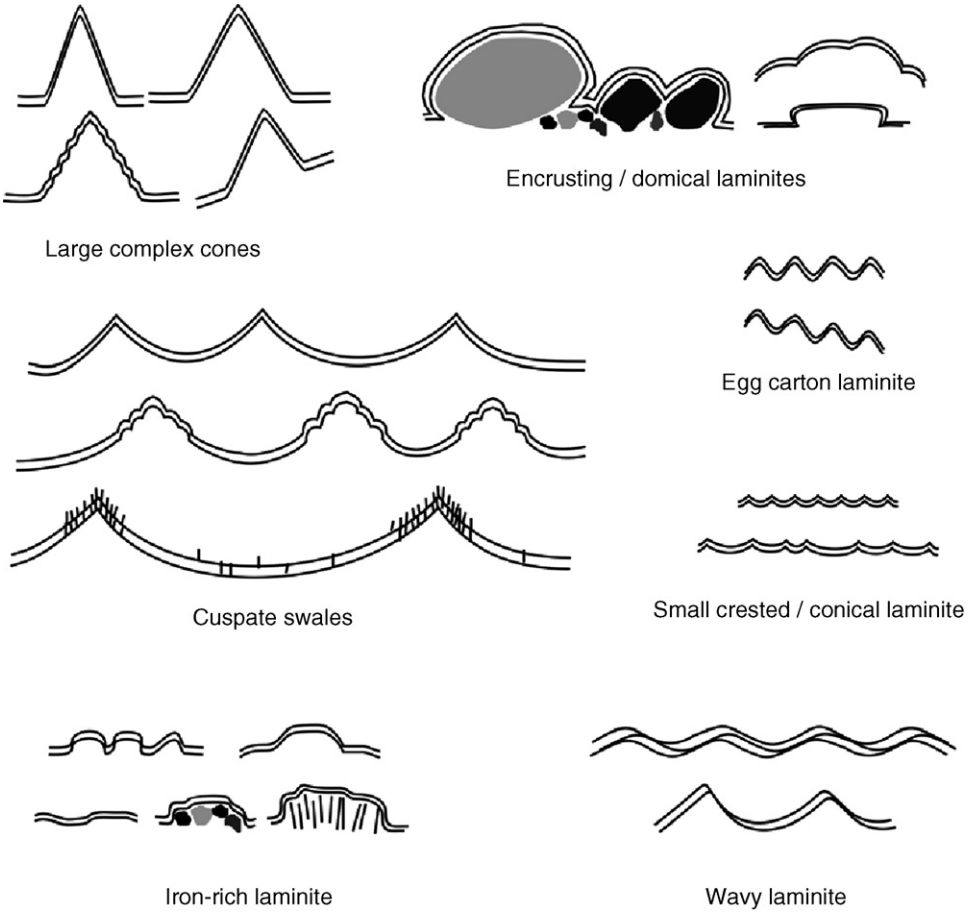

Fig. 5. Typical profile view of lamina shapes of the seven stromatolite facies of the Strelley Pool Chert. Scales vary (see text).

stone in the basal conglomerate of the Strelley Pool Chert (Fig. 6) indicates that the mudstones were not fully lithified when deposition of the Strelley Pool Chert began. The softness of the mudstone is indicated by the presence of jellybean-shaped and wasp-waisted clasts, and mudstone stringers trailing from some clasts.

Several alteration features – interpreted as by-products of Early Archaean weathering and erosion – occur at the upper contact of the mudstone. In particular, there are zones of local 'bleaching' where the uppermost layers of the mudstone are almost white, grading down to grey-green over a stratigraphic depth of around one metre. In many places the uppermost layers are also cross cut by carbonate-filled, downward-tapering cracks, bedding-plane parallel cracks, and larger fissures and cavities filled with carbonate matrix-supported chert gravel conglomerate (Fig. 7). Those features are also most prominent at the upper contact and decrease downward over a stratigraphic depth of around one metre. The assemblage of sediment-filled crack networks, fissures, cavities, potholes and soft mud intraclasts closely resembles features developed on modern coastlines where partially lithified mudstone substrates are weathered in the intertidal zone. One example occurs at Formby Point, northwest England, where intertidal weathering processes create desiccation crack networks, shallow erosional features and local mud intraclast deposits over semi-lithified late Holocene (up to 5900-year-old) mudstones (Knight, 2005). This suggests the alteration features observed at the base of the Strelley Pool Chert were caused by Early Archaean surface weathering of semi-lithified mudstones—indicating that only a short period of time passed between deposition of the mudstones (which belong to the 3.43 Ga Panorama Formation) and onset of Strelley Pool Chert deposition. The preservation of 'pockets' of semi-lithified mudstone, which would be relatively susceptible to erosion in a shoreline environment, suggests the mudstones were rapidly buried and that the transition from one set of environmental conditions to the next was very rapid.

Fig. 6. Cut slab (cross section detail view) showing basal contact of the Strelley Pool Chert: upper half of the picture is member 1 conglomerate and lower half is thinly bedded tuffaceous pebbly mudstone (dark layer is a bedding-parallel fissure that was filled with carbonate). Note soft mudstone intraclasts in the overlying conglomerate (arrow). Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

Fig. 8. Cross section outcrop of jasper-banded black chert palaeo cliff (sea cliff), overlain by carbonate (member 2/bed 1). Bedding dips steeply to the right of the picture: angle of stadia rod shows palaeovertical direction. Rock type to the left of dotted line is chert, to the right is carbonate (member 2). Boulders of member 1 conglomerate rest on the platform on the stratigraphically higher side of the palaeocliff about 20 m along strike. Stadia increments = 20 cm. Reprinted with permission, Geological Survey of Western Australia Record (Allwood et al., 2007), 2007.

The chert, being resistant to weathering, formed highs that were onlapped by the Strelley Pool Chert. In at least one location, the chert formed a ca. 2 m high cliff (Fig. 8). The mudstone, on the other hand, correlates with lower areas that manifested as embayments on the transgressive shoreline. The underlying rocks also locally contain black chert veins ranging from centimeters to a few metres across. Some of the veins terminate within the volcanic rocks and cherts, and many cross cut the underlying rocks and continue up into the Strelley Pool Chert and beyond. None of the veins terminate within the mudstone. This indicates the sequence of events was: (1) emplacement of volcanic rocks and possibly some black chert veins; (2) deposition of jasper-banded black chert and emplacement of veins; (3) erosion and probable weathering alteration of the volcanic rock (and chert) and deposition of the mudstone with chert and volcanic clasts; (4) erosion (and probable weathering alteration) of the volcanic rocks, chert and mudstone;

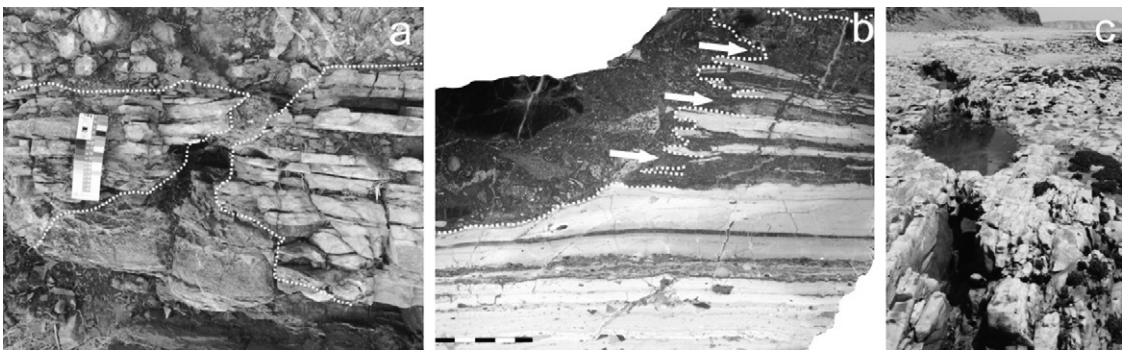

Fig. 7. (a and b) Erosional features at the base of the Strelley Pool Chert: white dotted lines mark the base of member 1. (a) Outcrop showing cross section view of a fissure leading down to a small cavity in the tuffaceous mudstone substrate beneath member 1. The majority of clasts in the overlying conglomerate are tuffaceous mudstone: compare with this figure and Fig. 9, where conglomerate containing dominantly jasper-banded chert boulders overlies a jasper-banded chert substrate. Scale card is 18 cm long. (b) Cut slab showing a portion of a pothole scour (top left quarter of slab) and carbonate infill along parted bedding planes in the pale mudstone substrate (white arrows). Scale increments = 1 cm. (c) Erosional potholes and fissures in mudstone – similar to features shown in A and B – formed in the intertidal zone on a wave cut platform on the modern California coast. Pothole is ~60 cm across (photo by A. Allwood). Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

(5) commencement of Strelley Pool Chert deposition (with clasts of chert, volcanic rock and mudstone) while the mudstone was still soft, with marine and subaerial weathering of the mudstone and other underlying rocks; and (6) much later, emplacement of more chert veins. Therefore, significant environmental changes immediately preceding Strelley Pool Chert deposition included cessation of volcanism, last stages of erosion and weathering of the exposed landmass, and drowning of the weathered, eroded landmass. The presence of remnant topography on the underlying landmass would have been a significant influence upon the development of local and regional palaeoenvironments and sedimentary facies, particularly during the earliest stages of Strelley Pool Chert deposition.

4.2. Member 1: transgressive shoreline sets the stage for stromatolites

Strelley Pool Chert deposition commenced as soon as relative sea level rise began to submerge the exposed surface, creating a series of transgressive coastal sedimentary environments. The first sediments deposited were laterally extensive conglomerates (member 1) that formed in rocky coastal environments (Allwood et al., 2006a). The lateral association of facies in member 1 is closely comparable with along-strike variations typical of modern rocky shorelines (e.g. Oak, 1984; Johnson, 1992; Felton, 2002), with large, scattered boulders accumulated on high energy wave-cut platforms in headland areas formed over the more resistant substrates (chert), and pebble/cobble/boulder beach deposits accumulated in embayments formed by the less-resistant substrates (mudstone). The beach conglomerates show graded bedding, whereas headland conglomerates tend to consist of isolated and clustered boulders. Moreover, the intertidal zone weathering features that occur at the contact with mudstone substrates, described above, further supports the hypothesis that member 1 was deposited on a shoreline (Allwood et al., 2006a). Deposition of the conglomerate was probably diachronous, following the march of the transgressing coastline.

Modern rocky shorelines that provide an excellent analogue for member 1 occur on the southern and southwestern margins of Australia; for example, at Cape Leeuwin on the southwestern tip of the continent (Fig. 9). The key similarity lies in the low relief and slow erosion rates of the coast and hinterland, which contrast with the typically steep relief and rapid erosion of most modern rocky coasts (Trenhaile, 2002). As a result, terrigenous sediment influx to the shoreline is minimal, so that shoreline deposits are almost entirely derived from *in situ* marine erosion of the coastal bedrock. The lack of allochthonous sediment in member 1 is explained by such an analogue. Comparison with the coastline at Cape Leeuwin also shows that it is probable that relief of the Strelley Pool Chert basal unconformity was limited to metre-scale features such as the palaeo cliff in Fig. 8, and that transport of the boulders in the shoreline environment probably occurred entirely through marine processes. That is, absence of evidence for a steep slope nearby does not pose a problem for the hypothesis: in modern wave-cut platforms on the Hawaiian coast, boulders weighing up to 90 tonnes were not delivered to the platform by down-slope transport, but were in fact eroded by marine processes from a submerged cliff at the seaward edge of the platform and emplaced on the platform during storms. In addition, *in situ* erosion and deposition of boulders and cobbles on the platform is found to be an ongoing process, with clasts liberated by marine and subaerial weathering along pre-existing fractures in the bedrock (Noormets et al., 2002). The low relief of the Cape Leeuwin and Hawaiian analogues therefore provides a reasonable explanation for observations in member 1 of the Strelley Pool Chert.

Fig. 9. The rocky shore and wave cut platform at Cape Leeuwin, Western Australia, which provides a modern analogue for member 1 of the Strelley Pool Chert. At Cape Leeuwin, the conglomerate boulders are derived from the underlying granulite and constitute virtually 100% of the sediment deposited on the platform. The boulders are scattered or clustered in small groups across the platform. Topographic relief along the shoreline is low (metre-scale) and there is no cliff or steep slope behind the wave-cut platform. The boulders are derived from *in situ* erosion of the platform and possibly a submerged seaward edge (photo by A. Allwood). Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

The low relief of the underlying landmass in the Strelley Pool Chert resulted in very rapid drowning and onset of shallow marine conditions with no siliciclastic sedi-

ment influx. As soon as the last high area was completely drowned and clastic sedimentation ceased, carbonate sediments of member 2 began to encrust and cement the shoreline conglomerates in place. The rapid onset of carbonate deposition enabled preservation of many of the coastal features that might otherwise have been eroded away during transgression. The presence of the relatively resistant chert substrate and onlapping relationship of the Strelley Pool Chert suggests the study area represents a relatively high area in palaeotopographic terms that: (1) was the last area to be submerged during relative sea level rise; and (2) consequently, was shallower than other areas at the point in time when the landmass finally became completely submerged and significant clastic sedimentation ceased (Allwood et al., 2006a).

Although no stromatolites are observed in member 1, the first member 2 stromatolites began forming locally while member 1 was still being deposited in some parts—this is suggested by the presence of carbonate intraclasts (i.e. derived from the first member 2 facies, which included encrusting/domical stromatolites) within the member 1 conglomerates, and local interbedding of the member 1–member 2 contact (Allwood et al., 2006a,b).

Chert veins cut across member 1 locally, but none terminate within the unit. Several examples occur on the southern end of "North Shaw Ridge", where veins of black, grey and white chert cut across the conglomerate. The boundaries of the veins are locally diffuse, resulting in an irregular chert replacement of the conglomerate matrix in parts. However, there are no places where the chert has the architecture or internal fabric of bedded, surface-deposited sediment.

4.3. Member 2: isolated peritidal stromatolite/evaporite platform

4.3.1. Overview

Member 2 of the Strelley Pool Chert consists of three stacked beds (Fig. 4), each with a complex association of laminated dolomite-chert rocks with laterally and vertically intercalated stromatolite, evaporite crystal pseudomorph, flat pebble conglomerate, fenestrae, breccia and flat laminite facies. The beds are capped by distinctive, laterally extensive, locally eroded layers of evaporite crystal pseudomorphs, which act as stratigraphic markers across the study area.

Six different types of stromatolites occur in member 2. Different beds and parts of the platform were characterized by different sedimentary facies and different associations of stromatolites (Allwood et al., 2006a). Some stromatolite types occur in more than one palaeoenvironmental setting, as described in the following sections.

The vertical facies assemblage in each bed of member 2 depicts shoaling conditions, but each bed also records slightly deeper water conditions than the bed beneath. This vertical sequence is interpreted to represent a series of minor regressions within an overarching transgression. There is also an area-wide lateral trend in water depth that is particularly evident at the upper contacts of bed 1 and 2. Upward-diminishing lateral facies variations and thickness changes – related to palaeotopography – indicate that progressive topographic infill was also a significant control on sedimentation. Thus, the facies associations and architecture during deposition of member 2 point to three overarching environmental influences during stromatolite formation: (1) relative sea level cycling; (2) lateral variation in water depth; (3) diminishing effects of underlying topography through continued deposition.

Important insights to the environment of deposition are also found at the basal contact of member 2, where several features indicate a close temporal and spatial relationship – but contrasting nature – between member 1 and member 2 depositional environments. Firstly, member 1 boulders are encrusted by laminated carbonate with many literally 'cemented' in precarious positions (Fig. 10), which indicates the boulders were rapidly stabilized by carbonate after they came to rest. Secondly, carbonate intraclasts occur locally within the upper part of member 1 (Fig. 11), indicating that carbonate deposition had already commenced in some areas

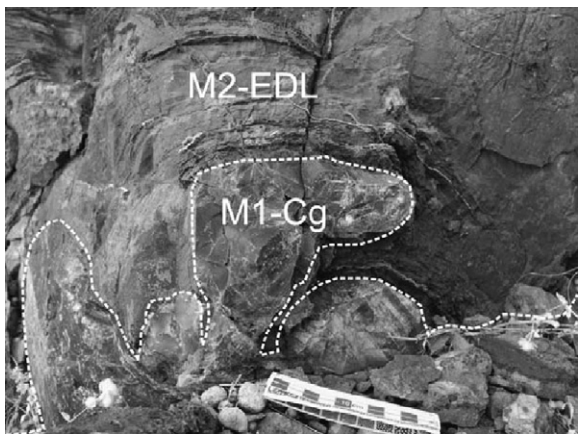

Fig. 10. Contact between member 1 chert boulder conglomerate (member 1-Cg: lower section) and encrusting/domical laminites of member 2 (member 2-EDL: brown rock in upper section). The laminated carbonate encrusted precariously perched boulders, so that the contact (dotted white line) has extremely sharp, sinuous, even locally overhanging relief. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

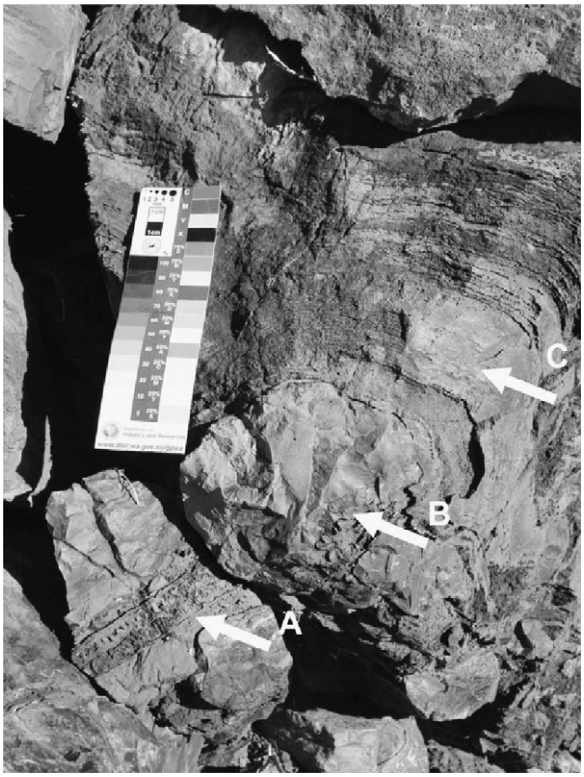

Fig. 11. Outcrop showing upper part of member 1 conglomerate with encrusting/domical laminites at base of member 2 on "Anchor Ridge". Arrow "A" points to a carbonate intraclast in the conglomerate, arrow "B" points to a chert boulder, arrow "C" points to encrusting/domical laminites. Scale card increments = 1 cm. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

before conglomerate deposition had ceased in others. Finally, the contact is locally interbedded, with a layer of isolated chert boulders locally in the lowest part of member 2. These three observations show that the member 1–member 2 contact is transitional; that there was no significant break in deposition from member 1 to member 2; and that member 2's environment of deposition could not have been far removed (in terms of water depth) from the shoreline setting of member 1 (Allwood et al., 2006a).

Evidence for a shallow marine interpretation hinges upon four interrelated observations. Firstly, the observed continuous deposition through drowning of the shoreline environment suggests a shallow subaqueous environment as the natural successor in a transgressive sequence. Secondly, a marine environment for member 2 is confirmed by the primary seawater Rare Earth Element (REE) patterns of the dolomite and chert, which represent a complex suite of geochemical processes not readily replicated by any other means other than deposition in a marine environment (Allwood et al., 2006a). Thirdly, the three beds within member 2 are not only bounded by shoreline facies at the base, but are also separated by erosional surfaces between each bed, providing further evidence that water depths in the area were never very deep. A marine environment of deposition (i.e. as opposed to a shallow lake environment) is further supported by the fact that the contact marks a sudden change from very coarse terrigenous clastic sediment (member 1 conglomerate) to finely laminated dolomite-chert virtually free of terrigenous sediment. The complete and sudden cessation of clastic sedimentation suggests that the erosional source was suddenly and completely submerged, as when rising sealevel finally drowns an isolated, low-relief landmass. The observation is difficult to explain in a non-marine setting – such as a lake, where some vestige of terrigenous influx should remain – and is most plausibly explained by the drowning of a landmass that had low enough relief to be rapidly submerged. Therefore, given that a non-marine setting is excluded, it is reasonable to propose that member 2 was deposited in a shallow marine environment (Allwood et al., 2006a).

Finally, the facies associations and their vertical arrangement also indicate a shallow marine environment, or more specifically—a peritidal marine carbonate depositional environment. Interpretation of a peritidal environment is made on the basis of a number of associated observations and their arrangement within a vertical sequence (Flugel, 2004). The interpretation of member 2 of the Strelley Pool Chert as a peritidal carbonate deposit hinges upon several interrelated lines of evidence. Firstly, the observations described above preclude a non-marine interpretation. Secondly, the facies are arranged into three stacked regressive cycles in an overall transgressive succession, which is characteristic of peritidal carbonate sequences (Flugel, 2004). Thirdly, member 2 is composed entirely of facies associations that are moderately to strongly characteristic of peritidal carbonates. For example, fine scale lamination is a very common feature of peritidal carbonates, typically with fine grainsize variations and often occurring in association with fenestral pores—both of which are observed in member 2. The association of flat laminite, wrinkly laminite and fenestrae is also characteristic, and – notably – the distribution of those facies is thought to be linked to the distribution of microbial mats in the intertidal zone. Some of the strongest indicators of a peritidal setting are features associated with local subaerial exposure, desiccation and evaporite solution. In the Strelley Pool Chert those are present in the form of desiccation cracks in flat laminite, local erosion surfaces, evaporite solution cavities and solution collapse breccias in member 2. Lastly,

there are no sedimentary facies within member 2 that are inconsistent with a peritidal setting. Moreover, while each of the facies may occur in other depositional environments, the association of facies as a whole and their vertical arrangement into regressive cycles in a transgressive succession is not generally associated with any other setting (Allwood et al., 2006a).

4.3.2. Chert veins

Some of the chert veins identified in the rocks below the Strelley Pool Chert extend up through member 2. Examination of cross cutting relationships between the chert vein fill and bedded facies of member 2 shows that all the hydrothermal vein complexes cross cut and post-date member 2. Locally, the chert that occurs in the veins also extends laterally within member 2, but in every case the chert cut across, displaced or replaced the primary sedimentary rock. Examples occur on every ridge in the study area, where black chert veins cut across member 2 at low to high angles to bedding. At the Trendall Locality (Hofmann et al., 1999), in particular, a black chert sill cuts across the upper layers of member 2, giving the appearance of chert bedding. However, along strike the sill can be seen to turn gently and cut across bedding.

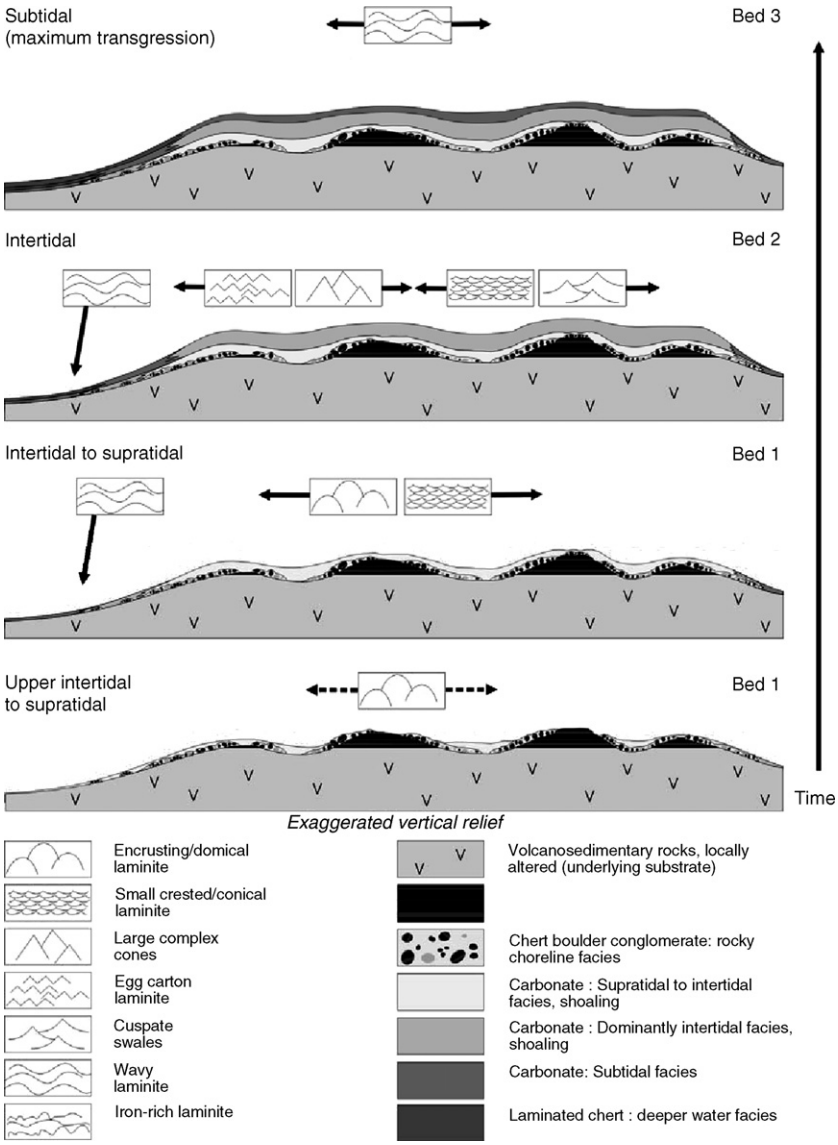

Fig. 12. Schematic interpretation showing cross section view of Strelley Pool Chert members 1 and 2 deposition through time (base to top) in the study area. The lowest panel represents member 1 and initial stages of member 2. The top three panels represent member 2 beds 1, 2 and 3, respectively, during formation of the stromatolite facies (evaporite depositional stages at the end of each regressive cycle not shown).

4.3.3. Bed 1 stromatolites in the first regressive cycle

Bed 1 (first regressive cycle; Fig. 12) shows rapid lateral facies and thickness variations controlled by metre-scale topographic relief at the basal unconformity and over the large boulders of member 1. The lateral facies variations in the lower part of the bed are as follows: Where bed 1 overlies bedded conglomerate over mudstone (that is, a drowned embayment/low area) flat or irregular laminated and fenestral carbonate were deposited. Where bed 1 overlies conglomerate on chert substrate, laminated carbonate encrusts the boulders and forms striking, upward-expanding, domical-laminated pseudocolumns. Where member 1 conglomerate is absent, non-encrusting domical pseudocolumns occur. These 'encrusting and domical laminites' are stromatolite facies #1 (Fig. 13). The encrusting/domical laminites consist of decimetre to metre-sized domical laminae with cuspate margins stacked atop one another to form pseudocolumns. Laminae are continuous between the decimetre to metre-high pseudocolumns. The pseudocolumns commonly touch at their margins, although in some instances pseudocolumns are separated by areas of flat lamination The laminar morphology is – in some instances – derived from an underlying boulder that has been encrusted. The encrusting/domical laminites are syndepositional structures, as evidenced by their encrusting and infilling habit, as well as the observation that crystal splays that grew in the cusps of some developing domes were themselves subsequently encrusted.

Fig. 13. Encrusting/domical laminites. (a) Three-dimensional reconstruction. Scale bar is approximately 5 cm. (b) Outcrop showing encrusting structure in cross section over member 1 conglomerate (Anchor Ridge). Large boulder in (b) measures approximately 20 cm from top to base. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

The amplitude of individual encrusting/domical laminae indicates minimum water depths of about 1 m in the lower part of bed 1. The upper layers of bed 1 mark a gradual infilling of topography and transition to centimetre-scale 'small crested/conical laminites' (stromatolite facies 2; Fig. 14), or flat laminite, with scattered evaporite crystal casts and storm/tidal channel conglomerates. In the northern area the transition to evaporite crystal deposition is more gradual than in the south: in the north, the size and abundance of crystals increases upwards over the last metre or so of the bed, whereas in the south the transition from laminites and stromatolites to crystal beds is sharp. Bed 1 is capped throughout the area by a 0.5–1.8-m-thick layer of evaporite crystal pseudomorphs, indicating regression and widespread restricted circulation. Local erosion surfaces, solution cavities and collapse breccia (karst) at the upper contact, coupled with the trend of decreasing bed form amplitude and increasing evaporite deposition, indicate shoaling conditions through the deposition of bed 1. Significantly, the erosion surfaces at the top of the bed are more laterally extensive, and cut down more sharply and deeply in the northern outcrops compared to the south. Moreover, solution collapse breccias and solution cavities are common and pronounced at the top of the bed along "Steer Ridge" and "Anchor Ridge" but are rare to the south, along "North Shaw Ridge" and "Trendall Ridge". Those factors indicate that water depths were greater in the south compared to the north.

Member 2 bed 1 represents the earliest stages of transgression (Fig. 12). The association of fenestrae, flat laminites, stromatolites and flat pebble intraclast conglomerates in bed 1 is typical of intertidal to supratidal carbonate deposits and is consistent with deposition

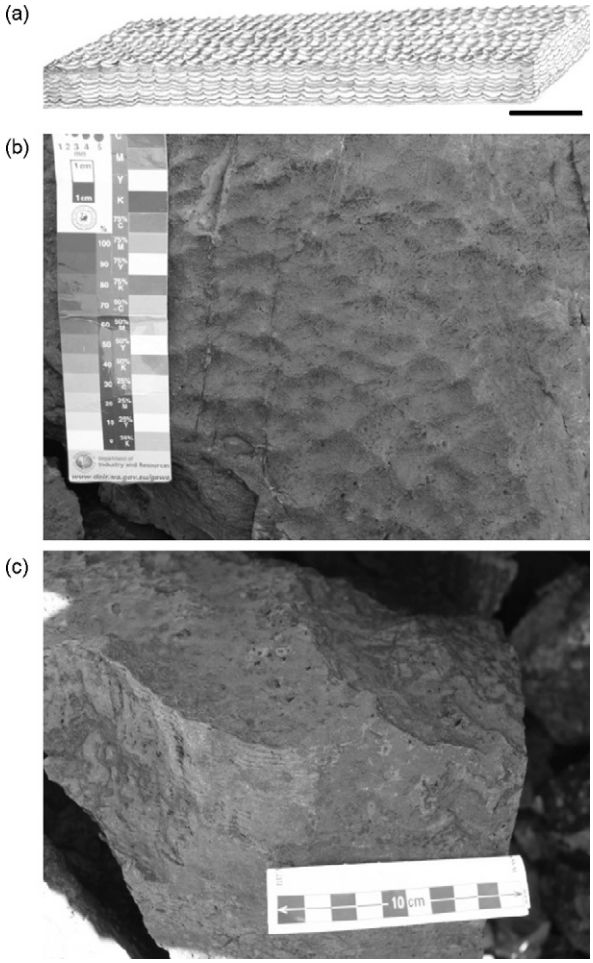

Fig. 14. Small conical/crested laminites. (a) Three-dimensional reconstruction. Scale bar is ∼5 cm. (b) Outcrop at Anchor Ridge looking down on a bedding plane from above, showing small, partially linked, pointed peaks. (c) Three-dimensional outcrop exposure showing a crested ridge-like example. Small holes are evaporite crystal moulds. Scale card increments = 1 cm. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

over shoreline deposits. Thus, bed 1 is interpreted as representing a suite of intertidal to supratidal environments formed on the newly-submerged landmass, with the topographic relief of the landmass creating small lateral variations in water depth. The types of environments would probably have included partially restricted to interconnected shallow pools and embayments, tidal flats and shallow platforms. Wave and current energy may have been locally or intermittently high at the margins of the platform(s), or during storm events. In those environments, encrusting/domical laminites, which constitute the first type of stromatolite that formed on the platform, emerged immediately and persisted during deposition of bed 1.

At least the initial formation of encrusting/domical laminites in the nearshore rocky coastline environment would have occurred in high energy conditions. Yet two important observations arise. Firstly, the encrusting/domical laminites are found in bed 1 of member 2 through most of the study area, including all outcrops where the basal conglomerate is present. Where the encrusting/domical laminites are absent, flat to irregular laminated and fenestral carbonate occur instead. Therefore, the encrusting/domical laminites formed at the same time as irregular laminated and fenestral carbonate facies were forming nearby, indicating that some kind of localized set of processes were operating in the same palaeoenvironment to produce different carbonate facies, similar to the way the distribution of microbial mats affects local facies development in modern peritidal carbonates (Flugel, 2004). Secondly, the formation of delicate crystal fans (evidently at the surface—as they are draped by overlying laminae) among the stratigraphically higher parts of encrusting/domical laminate columns indicates that the same stromatolite facies continued to form in low energy, restricted evaporitic settings toward the latter stages of the depositional cycle. Therefore, the one stromatolite type persisted through different environment conditions, suggesting that the form of those stromatolites does not reflect only external, environmental influences. The processes that controlled the accretion of the encrusting/domical laminites persisted through accretion of scores of alternating chert and carbonate laminae, through decreasing water depths, and presumably through other environmental changes resulting from varying water depths, such as wave energy and brine concentration.

The encrusting/domical laminites could not have formed by purely chemical precipitation, as the laminae are at least partially composed of granular sediment (Fig. 15). The presence of the grains on the steep to overhanging slopes indicates there was likely a microbial mat to trap and bind grains—or to form grains *in situ*. Mineral precipitates could have occurred as sticky, grain-trapping gels, although the formation of stromatolites by such means has never been observed or demonstrated. The persistent rhythmic deposition of thin, even chert and carbonate gel laminae that form cuspate-edge domes—soft enough for grains to sink into but not so soft as to lose the laminar shape or to slide off the overhanging slopes, all in a high energy marine environment, is improbable. Accretion of the sediment into domical laminae is more plausibly interpreted as a biogenic feature, shared by known stromatolite taxa such as *Colonnella* (Komar et al., 1965) and *Conusella* (Golovanov, 1970) The exact combination of processes that formed such structures

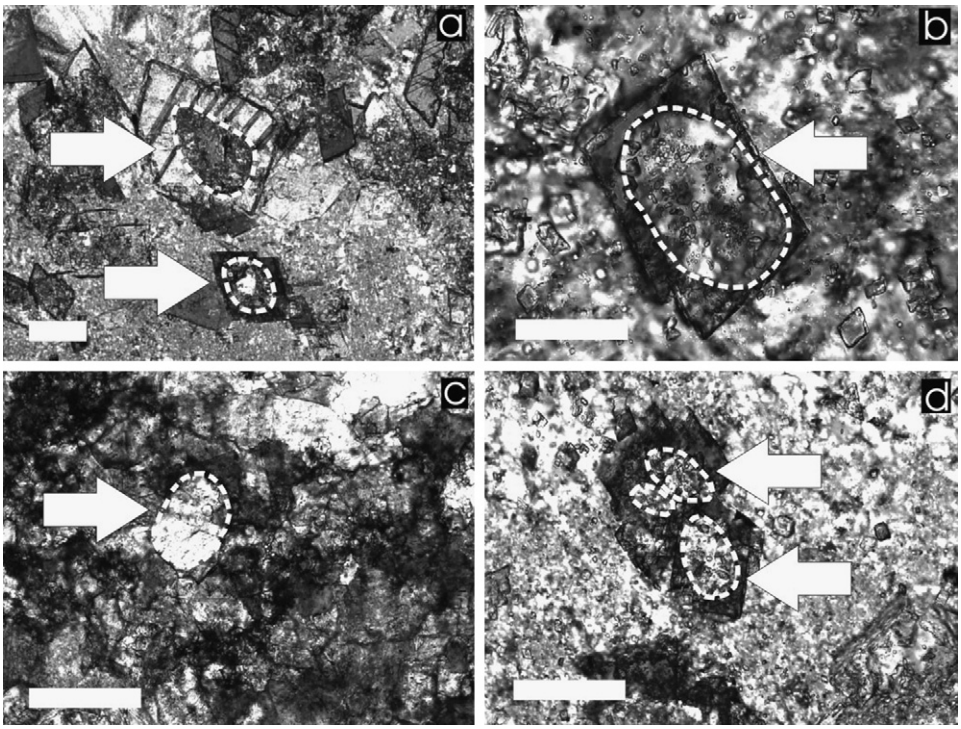

Fig. 15. Thin section photomicrographs showing remnants of rounded grains in four different laminations in "encrusting/domical laminites" from "North Shaw Ridge". White arrows in (a), (b) and (d) point to rounded cores representing the original sedimentary grains (white dashed lines) inside rhombic dolomite crystal overgrowths. (c) Rounded carbonate grain (arrow) floating in a chert/dolomite matrix. The preservation of grains in this sample is attributed to local silicification that did obliterate primary fabrics. Scale = 100 μm. Cross-polarized light. Image originally published by Nature Publishing Group, 2006.

is uncertain, but the presence of evaporite crystal pseudomorphs in the cusps of some cuspate swales along "Anchor Ridge" indicates that chemical precipitation was occurring at the time and therefore could have played an important role in formation of the stromatolites.

Small crested/conical laminites formed locally at the same time as encrusting/domical laminites and became increasingly common toward the latter stages of the bed 1 regressive cycle. This facies consists of centimetre-scale rounded, conical or cuspate bumps and ridges that are repeated and inherited through successive laminae. The margins of the domes, cones and bumps are gradational, with laminae passing smoothly into adjacent areas of flat lamination. Spacing between bumps and ridges is regular to slightly irregular, and the bumps and ridges have approximately uniform size and shape within a given bed and outcrop (Allwood et al., 2006a). The wavy to wrinkly, locally conical or bumpy morphology of the small crested/conical laminites does not by itself preclude an abiological origin. However, such lamina shapes – especially wrinkly laminae – are characteristic of microbialites in a variety of subaqueous environments throughout the geologic record (e.g. *Cyathotes phorbadicia*; Vlasov, 1977). In peritidal carbonate settings the distribution of wrinkly laminites among flat laminated and fenestral carbonate (a characteristic association found in bed 1) is closely linked to the distribution of microbial mats (Flugel, 2004).

4.3.4. Bed 2: stromatolites in the second regressive cycle

Bed 2 of member 2 displays less pronounced, broader-scale facies variations than bed 1, reflecting continued carbonate build-up, transgression and topographic infill (Fig. 12). However, the local erosion surfaces at the top of bed 1 created new decimetre-scale topography that was infilled during bed 2 deposition. This is particularly evident in some outcrops along "Anchor Ridge". The presence of rare desiccation cracks and structures resembling blister mats (or desiccated microbial mats) indicates the sediment was intermittently exposed. As with bed 1, shoaling is reflected in an up-section trend of decreasing bedform amplitudes, increasing abundance of evaporite crystal pseudomorphs and a widespread, locally eroded capping evaporite layer. However, erosion features are less prominent than in bed 1, indicating

that the water was generally deeper at the end of the second regressive cycle compared to the first. Bed 2 is also similar to bed 1 inasmuch as evidence of shoaling, subaerial exposure and erosion is more pronounced in the north compared to the south. Thus, water depths remained greater in the southern part of the study area compared to the north. During deposition of bed 2 the platform had less topographic relief, instead showing only the more general trend from intertidal/supratidal depths in the northern area, to intertidal/subtidal depths in the central area and subtidal depths in the south.

The facies association in bed 2 consists of four different stromatolites intercalated with flat laminite and storm/tidal channel edgewise intraclast conglomerates: a facies association that is typical of an intermittently exposed, intertidal to lower supratidal carbonate setting. The occurrence of storm/tidal channel intraclast flat pebble conglomerates and breccias is highest in the central area, along southern "North Shaw Ridge" and "Trendall Ridge", whereas the northern outcrops have few scour channels with intraclast breccias but instead have rare desiccation cracks and evaporite solution collapse breccias. Those features suggest that the central study area was a platform margin setting with slightly deeper water and higher energy conditions, while the northern study area represents an on-platform setting with restricted circulation and intermittent local exposure (Allwood et al., 2006a,b).

The most complex and diverse stromatolite facies associations developed across the platform during the first part of bed 2 deposition (Fig. 12), prior to the onset of massive evaporite crystal formation. Four types of stromatolites occur, namely: (1) 'egg-carton laminites' (Fig. 16); (2) 'large complex cones' (LCC; Fig. 17); (3) large 'cuspate swales' (Fig. 18) and (4) 'small crested/conical laminites'(Fig. 14).

In the central part of the study area, mainly along southern "North Shaw Ridge" and "Trendall Ridge" in the platform margin setting, the stromatolite-sedimentary facies association consists of LCC stromatolites and egg carton stromatolites distributed heterogeneously among flat laminite with common scour channels and intraclast breccias (storm and tidal channel deposits). The LCC stromatolites are laminated, laterally linked conical pseudocolumnar structures up to 1.2 m in stratigraphic height with synoptic relief of individual cones around 5–20 cm. Allwood et al. (2006a,b) showed that the LCC structures cannot have formed by post-depositional deformation processes such as tectonic folding or soft-sediment slumping, or by early diagenetic deformation processes such as dewatering or expansion and buckling of sheet cements, or by unmediated mechanical deposition of loose sediment or purely chemical precipitation. Essentially, it was argued that an implausible combination of proceses was required to form the LCC structures without biological mediation.

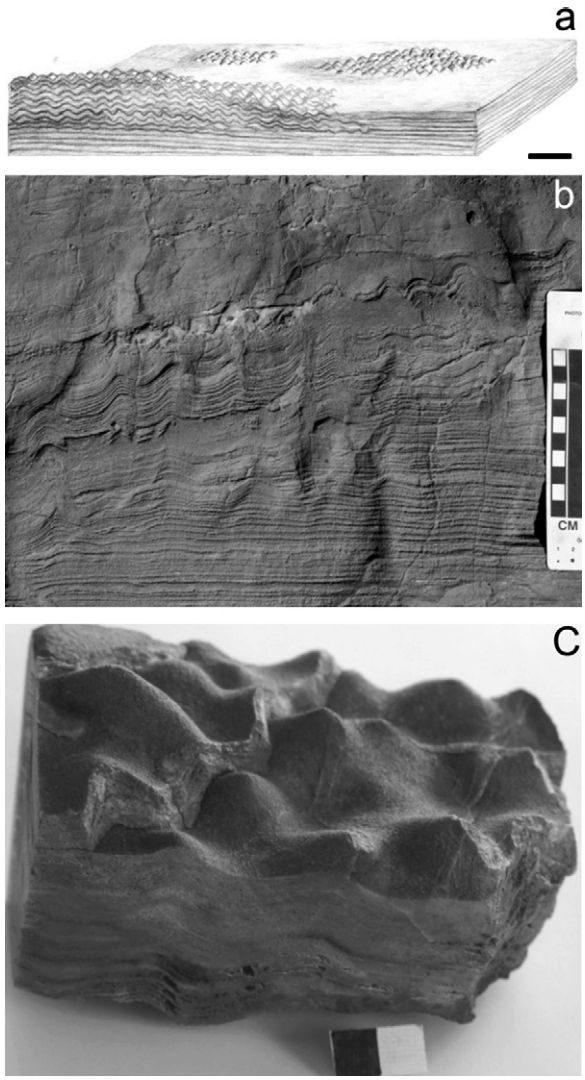

Fig. 16. Egg carton laminites. (a) Three-dimensional reconstruction. Scale bar is ~5 cm. (b) Outcrop at 'North Shaw Ridge' showing structures in cross section. (c) Cut slab showing regular, close spacing of small cones with rounded bases. Scale increments in (c) = 1 cm. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

The egg carton laminites are similar to some of the smaller LCC stromatolites, but are distinguished from the latter by their: (1) typically smaller size (synoptic relief ~1–3 cm); (2) occurrence in contiguous, laterally linked 'runs' of similar-sized structures, in some instances collectively mounding upward in bioherm-like geometry; and (3) lower height of the pseudocolumns

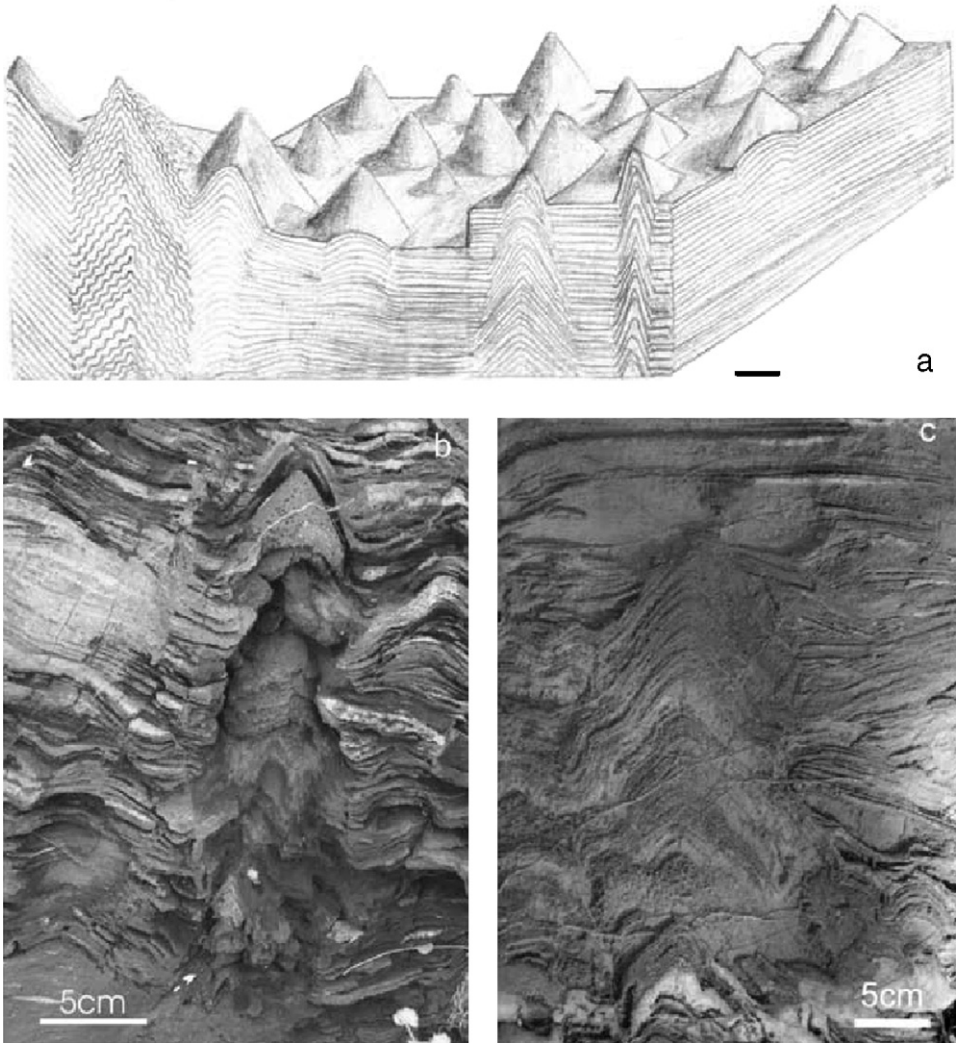

Fig. 17. Large complex cone stromatolite facies. (a) Three-dimensional reconstruction. Scale bar is ∼5 cm. (b) Conical pseudocolumn in outcrop ('Trendall Ridge'), where the cones stand out in weathered relief. (c) Conical pseudocolumn in outcrop 'North Shaw Ridge' where the structure is seen in cross section approximately through the central vertical axis. Note cobble-sized carbonate intraclasts stacked against the right hand side of the cones. Images originally published by Nature Publishing Group. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

(∼3 cm)—falling well short of the decimetre to metre-scale heights of the LCC structures. The similar size and spacing of the cones in each series gives them the appearance of an egg carton. Allwood et al. (2006a) argued against a non-biological interpretation for the egg carton stromatolites on similar grounds as for the LCC stromatolites.

The LCC and egg carton stromatolites occur within metres or in some cases decimetres of each other, and in many cases formed contemporaneously, as indicated through correlation of laminae between the different stromatolites. This indicates that the processes controlling the formation of each stromatolite type were occurring in close proximity in the palaeoenvironment. Therefore it is not possible, for example, to invoke different current intensities to explain different accretionary characteristics.

The contact between the stromatolite-flat laminite facies association and the evaporite layer is relatively sharp, although some crystal casts appear in the upper parts of the stromatolite-flat laminite facies association and there is no evidence of erosion beneath the evaporite layer. Those features at the contact between stromatolite and evaporite facies associations indicate

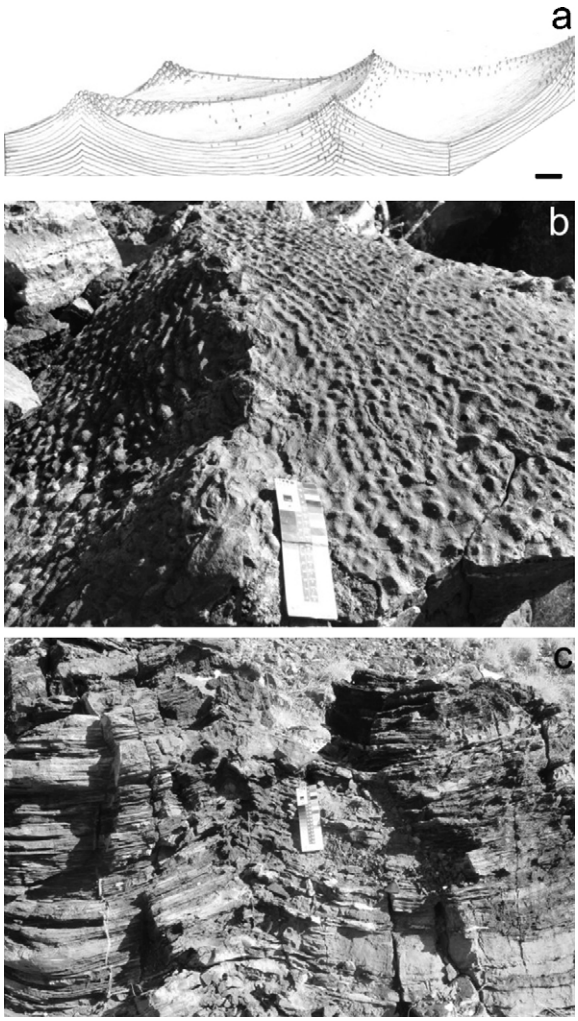

Fig. 18. Cuspate swale stromatolite facies. (a) Three-dimensional reconstruction. Scale bar is ∼5 cm. (b) Outcrop view looking down and along a bedding plane exposure, showing crest and adorning bumps. Scale card = 18 cm. (c) Outcrop showing a cuspate swale in cross section, with crystal casts and small bumps around the axial zone. Scale card = 18 cm. (b and c) Taken at 'Anchor Ridge'. (a and b) Originally published by Nature Publishing Group. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

that deposition was essentially continuous between the two.

In the northern outcrops (on-platform, intertidal to supratidal, low energy environment) cuspate swales were the dominant type of stromatolite, but were closely intercalated (at metre scales) with LCC stromatolites, egg carton laminites, small crested/conical laminites, flat laminites, scattered evaporite crystal pseudomorphs and rare storm/tidal channel intraclast conglomerates. The cuspate swale stromatolites show the most variety of form and the greatest degree of morphological

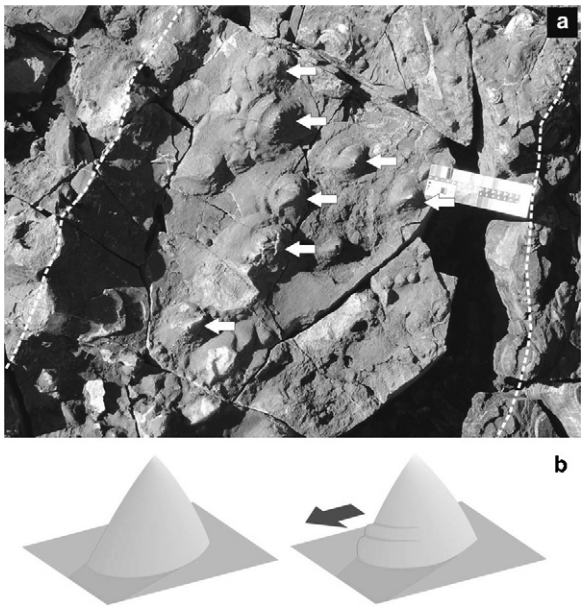

Fig. 19. "Slumped" cones on a cuspate swale structure (arrows point to each cone). (a) Overhead bedding plane view of the cuspate swale with medium sized cones (6–10 cm diameter). White dotted lines show the ridge crests of the cuspate swale. Each of the cones has a bulge on the left hand side, suggesting the cones slumped to the left. Scale card = 20 cm. (b) Schematic diagram illustrating how the bulges could have formed by lateral movement of soft but cohesive cones. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

complexity of all the stromatolite facies in the Strelley Pool Chert. In cross section the cuspate swales consist of cuspate peaks with concave-upward slopes, linked by broad (∼1–2 m wide × ∼30 cm-deep) troughs. There are no column margins: the laminar fabric continues across the troughs between each peak. In bedding plane view, the structures consist of an irregular, decimetre- to metre-scale network of crested, saddle-shaped ridges. Centimetre scale cones and bumps, or evaporite crystal pseudomorphs commonly occur at the ridge intersections and rarely in the shallow troughs between the ridges. In one bedding plane outcrop of a cuspate swale, a number of large (8–10 cm-high) cones with arcuate bulges on their sides occur on the flanks of the structures (Fig. 19). The large cones are spaced along the ridges and in the troughs alongside some clusters of smaller closely spaced cones. Every large cone on the surface has a semi-circular bulge around its base on the northern side. The appearance and uniform vergence of the bulges suggests they were formed by soft-sediment flexure of the laminae during downhill slumping, as illustrated in Fig. 19. The presence of slump-like bulges suggests the structures had flexible, microbially-bound laminae rather than rigid crystalline laminae. The bulges are unlikely to have

formed by preferential accretion on one side of the cones due to some unidirectional environmental process such as currents, as the small cones on the same surface do not show any preferential build-up. The smaller cones probably lacked sufficient mass to cause lamina flexure during downhill movement.

The three-dimensional mesostructure of the cuspate swales is similar to the Proterozoic stromatolite *Thesaurus pyramoides* (Vlasov, 1977). *Thesaurus* has slightly steeper slopes and marginally closer ridge spacing (∼20–40 cm) than the cuspate swales, but demonstrates microbially-influenced development of the complex ridge-cusp-cone geometry of the cuspate swales. Some variants of *Siren pyelodes* (Vlasov, 1977) also have similar mesoscopic features to the cuspate swales, notably including small adorning cones at the crests, which are remarkably similar to the cones that adorn the crests of the cuspate swales.

As in bed 2 in the central study area, the different types of stromatolites occur within metres, decimetres or even centimetres of each other, implying that the processes that formed each facies co-existed in such proximity in the palaeoenvironment. This observation of stromatolite morphologies and their relationships in the palaeoenvironment is most reasonably explained by biological input to stromatolite formation. As with the more southerly (platform margin equivalent) parts of bed 2, a close relationship between stromatolites and evaporites suggests evaporitic mineral precipitation also controlled stromatolite formation. In contrast to the central area outcrops, the contact between the stromatolite facies association in the lower part of the bed and the evaporites facies association in the upper part is gradational. That is, evaporite crystal psuedomorphs gradually increase in abundance up-section through the bed. This suggest that brine concentration increased and evaporitic crystal precipitation commenced earlier (but perhaps more gradually) in that area and that stromatolites continued to form while the evaporite crystals were growing at the surface or in the subsurface. At least some of the crystals grew at the surface, as indicated by the draping geometry of overlying laminae.

4.3.5. Bed 3: stromatolites in the third regressive cycle

Bed 3 of member 2 is relatively uniform in thickness, reflecting the infilled topography, and contains 'wavy laminite' facies (Figs. 12 and 20) throughout. The wavy laminites that characterize bed 3 are a typical subtidal carbonate facies. The cross section geometry of the wavy laminae ranges from low-amplitude, undulose waves (locally similar in appearance to climbing ripples) to angular chevrons, with vertical to inclined axes. Bedding plane exposures show most structures have geometry ranging from cones to very elongate cones to short, sinuous ridges with sharp to rounded peaks. Typical synoptic relief of the cones or waves is 3–8 cm and the typical wavelength between crests is 5–15 cm. In many instances the wavy laminites would be difficult to distinguish from abiogenic sedimentary structures such as climbing ripples, particularly in profile view. However, the structures are commonly cone-shaped with slopes up to about 50° above horizontal, indicating possible accretionary mediation and prompting their classification as stromatolite facies #6. The wavy laminites show abundant laminar onlap, indicating that they could not have formed solely through mineral precipitation, and that they formed at least partially through loose sediment deposition in water agitated by waves and currents. A stromatolite bearing close resemblance is *Irregularia* (Korolyuk, 1960), a stratiform stromatolite that occurs in biostromes of similar dimension and geometry to bed 3 of M2. *Irregularia* – like the wavy laminites, and unlike purely mechanically-deposited structures such as ripples – has irregular undulating laminae, erect to inclined axes, highly variable lamina shape and slopes that are commonly steeper than the angle of repose for loose sediment. The wavy laminites of the Strelley Pool Chert also bear comparison with microbially-bound current

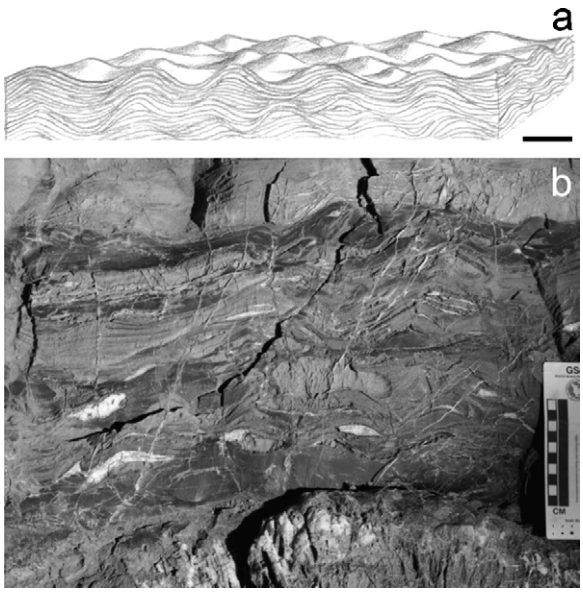

Fig. 20. Wavy laminite stromatolite facies. (a) Three-dimensional reconstruction. Scale bar is ∼5 cm. (b) Outcrop at 'North Shaw Ridge' showing structures in cross section, partially replaced by black chert and overlying a bed of evaporite crystal pseudomorphs. Images originally published by Nature Publishing Group. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

and wave ripples, which are known from modern and ancient environments.

The lack of evaporite crystals in bed 3 compared to bed 1 and 2 suggests that brine concentration did not reach the same level as the earlier two beds during the last regressive cycle on the platform, so that massive evaporite deposition did not occur. This conclusion is consistent with continued relative sea level rise and increased seawater circulation across the platform.

At the top of bed 3 there are local intraclast breccia deposits containing boulders of the underlying laminated chert-carbonate facies, indicating local erosion at the end of the third regressive cycle. The breccia is angular and moderately to poorly sorted, shows rapid lateral transitions in grainsize and occurs in two or three laterally restricted, southward-thickening wedges or lens-shaped deposits in the central study area. The architecture and internal characteristics of the breccia are similar to a reef talus, and differ from the solution collapse breccias in the lower parts of member 2. Given that the breccia wedges/lenses occur at the point south of which the Strelley Pool Chert succession begins to thicken greatly due to growth normal faulting, the breccia could represent the activation/reactivation of those faults and erosion of the upthrown blocks. The presence of the intraclast breccia and the absence of evaporite crystal beds reinforces this postulation: if the area had transitioned through regression and the brine concentration sequence, deposition of the associated minerals would be expected. The absence of these indicates catastrophic, rapid exposure of areas to erosion, such as through tectonism.

4.4. Southern succession: off-platform facies

South of "Trendall Ridge", the Strelley Pool Chert thickens to more than 70 m and consists almost entirely of flat laminated black/grey chert with carbonate silt (Fig. 21). Only a thin layer (less than 2 m thick) of wavy laminite occurs near the base, locally overlying chert conglomerate (member 1). The absence of any indications of current or wave activity indicates deposition in deep water, below wave base. The presence of rare convolute laminae (namely slump folds; Fig. 22) indicates deposition on a slope dipping approximately south (Allwood et al., 2007). The basal part of the southern laminites contains abundant carbonate silt-sized grains in a chert matrix petrographically similar in thin section to some of the more finely layered black and white banded cherts of member 3 on "Trendall Ridge" and further north. Those factors suggest that at least the basal parts of the southern succession are the distal equivalents of member 2 and member 3 (i.e. platform slope deposits), with the upper part of the succession equating only to member 4 (implying a condensed section for member 3 and parts of member 2).

Fig. 21. Laminated grey, black and white chert that constitutes most of the Strelley Pool Chert succession in the southern study area (photograph taken at the southeastern end of 'Bierf Ridge'). Scale card is 18 cm long. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

An even thicker succession (up to 400 m) of flat, rhythmically laminated black/grey/white chert and fine silicified sand/silt occurs on the next series of Strelley Pool Chert outcrops 2–5 km southeast of the study area, and on south-southwest-trending ridges approximately 10 km to the south (Shaw Gorge area). The laminites in all those areas also show soft sediment deformation structures that verge approximately to the south/southeast (Fig. 23). Combined with the trend of decreasing grainsize to the south/southeast, this con-

Fig. 22. Left (south)-verging slump fold in laminated grey, black and white chert in the southern study area (photograph taken at the southern end of 'Bierf Ridge'). Scale card increments = 1 cm. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

Fig. 23. South-verging slump fold in flat laminites of the Strelley Pool Chert approximately 10 km to the south of the study area. South is to the right of the picture. Scale card increments = 1 cm.

firms that during deposition of the Strelley Pool Chert the basinward direction in the area was south to southeast.

4.5. Members 3 and 4: post-platform stromatolites and other facies

Member 3 marks a transition from isolated peritidal evaporitic carbonate platform to a mixed marine-hydrothermal environment with rapid silica deposition. The onset of hydrothermal activity marked a dramatic change and significant reduction in stromatolite development. The hydrothermal/marine cherts of member 3 contain a possible stromatolitic facies – the iron-rich laminites (stromatolite facies #7; Fig. 24) – which are compositionally and morphologically dissimilar to any of the member 2 stromatolites. While the laminar morphology of the iron-rich laminites may not preclude an abiologic origin, the concentration of elements such as iron in sedimentary laminae is commonly attributed to microbial metabolism (Flugel, 2004). Iron-rich crusts may also form abiotically at transgressive submarine hardgrounds through extremely slow chemical precipitation in the absence of sediment influx. However, that interpretation is inconsistent in the case of the Strelley Pool Chert due to the presence of many pebble conglomerate beds (many of which have channel infill geometry) and accumulations of detritus between the iron-rich pseudocolumns, indicating a shallow environment and high sedimentation rates through member 3. If the iron-rich laminites were not formed biologically, some mechanism for episodic rapid abiotic chemical precipitation of iron laminae would be required, including some means of forming laminae with domical and pseudocolumnar shapes.

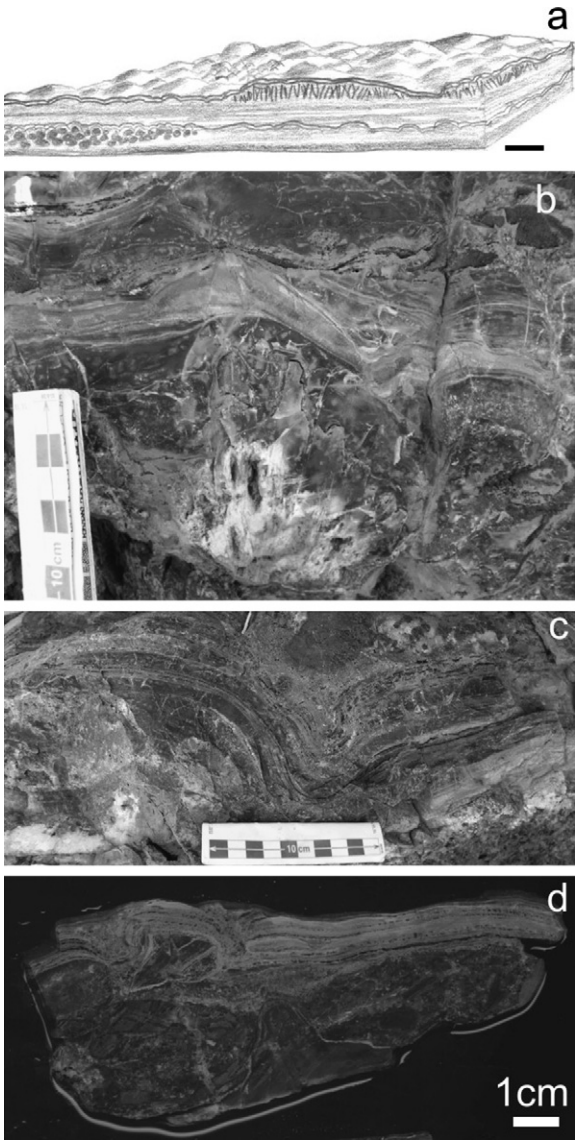

Fig. 24. Iron-rich laminite stromatolite facies. (a) Three-dimensional reconstruction. Scale bar is ~5 cm. (b) Outcrop at 'Trendall Ridge' showing cross section view of laminites over silicified crystal splay. (c) Outcrop also at 'Trendall Ridge' showing cross section view of a domical laminite with a cuspate margin. (d) Cut slab of sample from 'Trendall Ridge' showing laminite encrusting a layer of chert conglomerate. Images (a and c) originally published by Nature Publishing Group. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

The final stage (member 4) of Strelley Pool Chert deposition involved rapid siliciclastic sediment influx in subsiding fault blocks. Syndepositional growth faulting is indicated by the changing bedding orientation vertically through the succession, and the lateral thickening and thinning of the succession along the ridges and across the study area. Although syndepositional faults

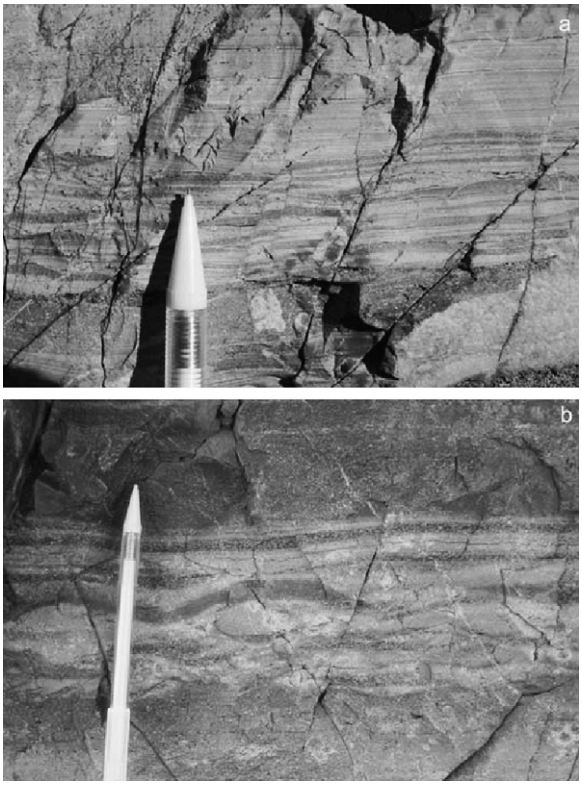

Fig. 25. Silicified tuffaceous mudstone/sandstone and black chert, member 4, 'North Shaw Ridge'. (a) Graded, laminated and thinly bedded layers with some subtle cross lamination. (b) Layer of mudstone showing convolute or possible buoyancy structures. Pencil is 7 mm wide. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

were not positively identified among the myriad of post-depositional faults, deposition in subsiding synclines is a less plausible explanation due to the absence of concomitant onlapped anticlines.

The basin subsided more rapidly to the south, as indicated by the thicker succession in that area. The lower part of member 4 consists of bedded chert boulder conglomerates with rare carbonate clasts. The conglomerates fine upwards to sandstones and then siltstones, with increasing amounts of grey-green ash and interbeds of black chert (Fig. 25). The uppermost parts of member 4 consists of interbedded black chert and tuffaceous mudstone, with common areas of phreatomagmatic breccia (Allwood et al., 2006a; Fig. 26). The tuffaceous mudstone beds are very fine grained, well sorted, and show graded bedding, indicating that the ash had undergone some water transport and sorting. The interbedded chert represents chemical sediment precipitated directly from hydrothermal fluids probably sourced from the suite of black chert veins terminating in the beds and in zones of phreatomagmatic breccia, but also contains

Fig. 26. Angular puzzle-fit mudstone breccia in black chert matrix, upper layer of member 4, 'North Shaw Ridge'. Reprinted with permission, Geological Survey of Western Australia, Record 2007-11.

allochthonous detrital material including organic matter and lithic clasts deposited from the water column (Allwood et al., 2006b).

The depositional environment of member 4 is interpreted as a transgressive subaqueous setting with increasing volcanic and hydrothermal input, and decreasing terrigenous clastic sediment input through time. The presence of rare cross beds, sand and silt layers in the upper parts of the bed indicates that – even as transgression continued – there were periods of higher water energy and coarser sediment influx: that is, deposition occurred above storm wave base and within the influence of a distal terrigenous sediment source.

There are no stromatolites in member 4, but the organic matter preserved in the chert could contain the remains of planktonic organisms. Thus, although microbes did not form mats or films that influenced the formation of localized accretionary structures in that area, they may have existed in the water column or in other environments nearby.

4.6. Chert veins: the regional picture

Chert veins similar to those identified in the study area also occur in the Strelley, Coongan, Kelly and other parts of the Panorama Greenstone Belts. In all cases examined, the veins cut across members 1 and 2 (where present). Some terminate in member 3 or 4, or their equivalent, and some continue into the overlying Euro Basalt. Where veins terminate in the upper parts of the Strelley Pool Chert, large zones of phreatomagmatic breccia with chert matrix are observed, indicating near-subsurface emplacement of chert. The breccia zones are commonly surrounded or overlain by bedded chert deposits. The

observations indicate temporal dissociation between the hydrothermal deposits and stromatolitic deposits.

The regional dissociation between stromatolites and hydrothermal activity is reinforced by geochemistry and facies analysis. The stromatolitic deposits have trace element chemistry very different to that of the vein cherts and cherts of members 3 and 4. On the one hand, members 3, 4 and vein cherts have trace element chemistry suggesting derivation from hydrothermal fluids. On the other hand, the member 2 cherts and carbonates have chemistry indicating a seawater origin (Allwood et al., 2006a). It is extremely difficult to explain such contrasting trace element compositions if the bedded cherts and carbonates both came from exhalative fluids from which the vein fills precipitated.

5. Stromatolite formation processes and favouring conditions

5.1. Hydrothermal processes

Members 1 and 2 of the Strelley Pool Chert are preceded and followed by hydrothermally-influenced sedimentary environments. However, the weight of evidence presented herein shows that during their formation there was no direct input from hydrothermal systems.

The hydrothermal interpretation of Lindsay et al. (2005) discusses the similar isotopic and mineralogic compositions of bedded Strelley Pool Chert strata and vein complexes beneath the Strelley Pool Chert, which, it was suggested, indicated that the beds of the Strelley Pool and vein fills were both precipitated from hydrothermal fluids that moved upwards through the veins. However, a detailed outcrop and regional survey has shown that the stromatolitic strata of the Strelley Pool Chert are not contemporaneous with the chert veins. The isotopic compositions identified by Lindsay et al. (2005) may not be unique to the Strelley Pool Chert veins and beds, and the mineralogic compositions are not unique. Therefore, they may not be diagnostic of a common, hydrothermal origin. Moreover, members 1 and 2 lack the vent-centred, apron-like geometry, and the proximal-distal hydrothermal facies associations and architecture that would be expected if they had been exhaled from hydrothermal vents. Thus, there are hydrothermally influenced sediments in the upper beds of the Strelley Pool Chert, but the stromatolitic deposits are not directly associated with them and do not exhibit characteristics to suggest they are hydrothermal vent deposits.

This interpretation has important ramifications for our understanding of early life: both in terms of interpreting the evidence for life's existence, and interpreting the conditions that may have helped early biota to flourish and to form ecosystems that left a large, visible signature. In particular, the palaeoenvironmental context described herein prohibits interpretation of the stromatolites as abiotic hydrothermal non-biological precipitates, and provides scope for a combination of shallow marine, evaporitic and biologically influenced processes.

5.2. Marine, evaporitic and biological processes

The processes that contributed to stromatolite formation in the Strelley Pool Chert must have arisen within the shallow marine/evaporitic palaeoenvironmental conditions described herein. The stromatolites formed on an isolated peritidal marine carbonate platform with periodic evaporitic conditions and little or no terrigenous sediment influx or direct hydrothermal input. In that environment, combinations of mechanical (granular) sediment deposition, chemical (marine/evaporitic) precipitation and biological (grain trapping/binding and induced mineral precipitation) would have been possible.

Allwood et al. (2006a) proposed that the Strelley Pool Chert stromatolites cannot all have formed by purely mechanical or purely chemical deposition, and that whatever processes formed the stromatolites, they were likely to have been mediated by biological activity in order to produce the observed stromatolite characteristics. The present study yields further evidence to support that interpretation.

Firstly, there are many instances in the Strelley Pool Chert where, within a given palaeoenvironmental setting, different types of stromatolites accreted in close proximity to one another. Particularly in bed 2 of member 2, up to four different stromatolite types formed simultaneously and different stromatolite types accreted close together, in some instances just centimetres away from one another. Such close proximity implies that the structures accreted in essentially the same palaeoenvironment at the metre to centimetre scale. Such rapid lateral variations are not readily explained in a basin where sediments are deposited only through physical and chemical processes, without microbial mediation.

The localisation of accretion processes parallels the different laminar fabrics between stromatolites and surrounding laminae (Allwood et al., 2006a). Such variation of stromatolite accretion processes within a non-varying palaeoenvironment indicates biological contribution to the formation of different stromatolite morphologies. Each palaeoenvironment within the Strelley Pool Chert peritidal carbonate platform is defined by a different

stromatolite-facies association (Allwood et al., 2006a), which implies environmental control on the development of stromatolite facies *associations*. However, the formation of different stromatolite morphologies within a single palaeoenvironment facies strongly suggests biological control on morphogenesis of *individual stromatolite types*. This not only provides compelling evidence that life existed in the Early Archaean, but also supports the notion that stromatolite morphology in general is affected by biology as well as environmental processes. Most importantly, it provides strong evidence that there was diversity among any of the following: (1) microbial species that mediated accretion of the stromatolites; (2) the make up of stromatolite-building microbial communities; (3) the activities carried out by or influenced by the stromatolite-forming communities. A combination of the above would be the most likely.

The spatial restriction of the biosignatures (stromatolites) to shallow water areas, and their decreasing abundance and eventual disappearance toward the deeper parts of the basin is a strong indicator of ecological control (Brasier et al., 2006). The spatial and temporal correlation between stromatolites and shallow marine/evaporitic facies suggests that stromatolite formation was favoured by such conditions. Organisms may have preferred the higher levels of sunlight or other environmental variations occurring near the air–water interface (such as changes in water composition, temperature and dissolved gases). The vertical growth of stromatolites (Allwood et al., 2006a,b) further suggests that biological response to sunlight could have been a significant controlling factor in the distribution and character of stromatolites, and that the microbial reef community probably included phototrophic/phototactic organisms.

The close proximity of stromatolites and evaporitic deposits implies evaporitic precipitation contributed strongly to stromatolite formation. The pattern of stromatolites grading stratigraphically upwards to evaporites is similar to patterns in many younger regressive evaporitic settings wherein microbial organisms flourish during the earlier stages of the basin evolution when the brines are more dilute: as evaporation continues and the brines become more concentrated, organisms are overwhelmed by rapid evaporite crystal growth. The close association of stromatolites and evaporites in the Strelley Pool Chert demands careful scrutiny of the stromatolites to determine how much of their formation can be attributed to evaporitic mineral crust formation and how much can be attributed to microbially-mediated sedimentation. In particular, the even, continuous laminae observed in many facies throughout member 2 are consistent with evaporitic precipitation of a mineral crust. However, granular, water-sorted fabrics are also common in closely associated facies, such as wavy laminites and flat laminites (Allwood et al., 2006a), though the composition of the rocks with water-sorted fabrics is the same as the rocks with precipitated fabrics. Therefore, the one sediment type formed both mechanical and precipitated deposits in the same basin. The co-deposition of chemical and mechanical sedimentary fabrics suggests the precipitation of mineral grains in the water column, that then settled out and underwent mechanical transport and deposition, while elsewhere the same mineral phase formed crusts at the sediment-water interface or in the near subsurface, either by direct chemical processes or microbially mediated processes. In any case, it is fair to conclude that formation of the stromatolites and associated facies cannot be entirely attributed to chemical precipitation.

Importantly, the pervasive influence of evaporitic conditions through member 2 deposition implies that any organisms that contributed to formation of stromatolites had to tolerate high salinity levels. That is, any organisms that existed during stromatolite formation were probably at least moderately halophillic. This does not necessarily imply that evaporitic conditions favoured the emergence of life, nor its ability to flourish and gain a strong foothold. The mineral crusts may have played an important role in shielding microbial communities from the intense UV radiation that bathed the surface of the Early Archaean Earth (e.g. Cnossen et al., 2007). Alternatively the evaporitic mineral precipitation may have simply aided the accretion of lithified structures that could be readily preserved in the geologic record.

Significantly, larger scale temporal and palaeogeographical distribution of stromatolites in the palaeoenvironment highlights an inverse correlation between stromatolites and hydrothermal activity. Thus, while life may well have metabolised its first chemical meal at a hydrothermal vent, the volatility, chemical and temperature gradient-invoked environmental isolation, and inherent instability of hydrothermal vents may have rendered them unsuitable as a nursery within which life might gain a firm foothold on the Earth. Rapid adaption to a normal marine basin would likely provide access to a more stable set of conditions for life to prosper.

The development of a specific and unique set of conditions in the study area during deposition of the Strelley Pool Chert was dependant upon numerous factors, including: relatively high topographic location and low topographic relief, distance from terrigenous and volcanic sediment sources; distance from hydrothermal

vents; and relative sea level rise. All of these factors combined to make a shallow, isolated platform setting favourable for development of a microbial reef-type buildup.

6. Conclusions

The present study demonstrates a first principles, context-oriented approach to the interpretation of Early Archaean stromatolites. Analytical criteria that may have limited value when considered in isolation – such as stromatolite morphology – increased in value when examined within palaeoenvironmental context, and provide crucial insights to stromatolite genesis. The palaeoenvironmental context developed herein will similarly provide constraints upon the interpretation of geochemical and organical geochemical data in future investigations.

The present study further supports a biological interpretation of stromatolites in the Strelley Pool Chert (Allwood et al., 2006a). Acceptance of the biological hypothesis for genesis of the Strelley Pool Chert stromatolites requires far fewer assumptions and hypothetical entities than any currently known hypotheses involving exclusively abiotic processes. For the entire Strelley Pool Chert carbonate platform to be interpreted as abiogenic, seven different unusually balanced sets of abiological processes must have operated discretely, persistently and at times, simultaneously on the platform. Importantly, persistence of those processes throughout significant timeframes and at multiple locations would also have been required to reproduce the vertically inherited, laterally repeated stromatolite morphologies documented by Allwood et al. (2006a).

Significantly, the stromatolites of the Strelley Pool Chert show consistency among types, repetition of types in discrete locations, and particularly formation of different morphotypes concurrently in the same location. This diversity of stromatolite types in a non-varying palaeoenvironment, and the consistency of types across varying palaeoenvironments, both provide compelling evidence of biologically mediated sedimentation.

The occurrence of such a diverse array of stromatolites in the Strelley Pool Chert – each with features resembling known microbialites and none resembling any known geologic abiogenic structure – coupled with their occurrence in a transgressive carbonate platform deposit; their association with different platform environments; their persistence through different platform environments; and the absence of stromatolites in deeper water is consistent with ecologically controlled growth of a microbial reef on an isolated platform (Allwood et al., 2006a). This array of constraining factors indicates that organisms flourished on the peritidal platform, rapidly taking hold and creating a reef-like build-up in shallow waters as surfaces became submerged.

Stromatolite formation on the platform probably occurred through biomediated combinations of chemical precipitation of mineral crusts and early burial cementation, as well as mechanical sedimentation with trapping, binding and/or rapid cementation of granular sediment at the sediment/water interface. Evaporitic and/or marine precipitation was likely the major non-biological process that contributed to stromatolite formation. Precipitation or nucleation of chemical sediments could have occurred at the sediment-water interface, in the water column, and/or in the subsurface.

Evaporitic conditions may not necessarily have favoured biological activity. The correlation between the traces of life and the evaporitic deposits may simply indicate that the rapid mineral precipitation assisted in the accretion of lithified structures. That is, the combination of evaporitic mineral precipitation and microbial mediation of that process ensured preservation of a recognizable signature in the geologic record. On the other hand, evaporitic precipitation could have been a crucial ecological factor that aided biological activity itself, as the formation of thin, translucent mineral crusts over microbial communities would have provided protection from the high UV flux on the Early Archaean Earth (e.g. Cnossen et al., 2007).

The Strelley Pool Chert stromatolites persisted through the high energy conditions of a barely submerged rocky shoreline, to subtidal marine conditions and extremely shallow conditions with increased salinity and evaporite mineral precipitation. These factors are consistent with ecological adaptation and/or environmental selection among microbial communities. The palaeoenvironmental context suggests that the reef hosted organisms that were halophillic and possibly phototrophic. Notably, however, microbial stromatolite formation was eventually overcome by evaporite crystal formation as the brines became more saline, indicating that organisms were increasingly challenged by brine concentration and mineral precipitation. The variety of stromatolites that coexisted in parts of the platform indicates that there was diversity of species, or at least diversity among the communities or activities of stromatolite-forming organisms. Thus, the Strelley Pool Chert may contain not only some of Earth's earliest fossils but also remnants of a diverse fossil 'ecosystem'.

The development and diversification of stromatolites was evidently favoured by the absence of hydrothermal activity and siliciclastic sedimentation. The inverse rela-

tionship between biological and hydrothermal activity shows that, although early life may have gained a toehold much earlier in 'extreme' volcanic (Banerjee et al., 2005) or hydrothermal (e.g. Corliss et al., 1981) environments, the oldest surviving, compelling indications of a firm foothold are associated with a rare pause in igneous and hydrothermal activity and with the onset of relatively 'normal' shallow marine conditions similar to those that have nurtured marine biodiversity throughout geological history.

The Strelley Pool Chert may not contain the very first vestiges of life on Earth, but it does contain the oldest compelling, ecosystem-scale evidence for an Early Archaean biosphere. How close to the origin of life these fossil vestiges may be is unclear, but whether life originated in a hydrothermal setting or in the type of setting encapsulated in the Strelley Pool Chert, knowledge of the conditions that enabled life to become firmly established at the Earth's surface and leave visible traces that last for billions of years will be highly relevant in the search for traces of past life elsewhere in the solar system.

Acknowledgements

The authors would like to thank the Geological Survey of Western Australia for generous field support and helpful discussions with geological staff. Thanks also to the Pilbara Regiment of the Australian Army for field support. A. Allwood supported by an Australian Postgraduate Award and NASA Postdoctoral Program fellowship during the course of the research.

References

Allwood, A., Walter, M., Marshall, C., Van Kranendonk, M., 2004a. Habit and habitat of earliest life on Earth. Int. J. Astrobiol. 3 (S1), 104.

Allwood, A.C., Walter, M.R., Marshall, C.P., Van Kranendonk, M.J., 2004b. Life at 3.4 Ga; paleobiology and paleoenvironment of the stromatolitic Strelley Pool Chert, Pilbara Craton, Western Australia. In: Abstracts with Programs—Geological Society of America, vol. 36, p. 458.

Allwood, A.C., Walter, M.R., Van Kranendonk, M.J., 2005a. Stromatolite facies of the 3.43 Ga Strelley Pool Chert: Pilbara Craton, Western Australia. Biennial Meeting of the NASA Astrobiology Institute, University of Colorado, Boulder. URL: http://nai.arc.nasa.gov/nai2005/abstracts.cfm.

Allwood, A.C., Walter, M.R., Van Kranendonk, M.J., Kamber, B.S., 2005b. Life on a transgressive rocky shoreline and carbonate platform: 3.43 Ga Strelley Pool Chert, Pilbara Craton, Western Australia. In: European Geophysical Union Annual General Meeting Abstracts.

Allwood, A.C., Walter, M.R., Kamber, B.S., Marshall, C.P., Burch, I.W., 2006a. Stromatolite reef from the Early Archaean era of Australia. Nature 441 (7094), 714–718.

Allwood, A.C., Walter, M.R., Marshall, C.P., 2006b. Raman spectroscopy reveals thermal palaeoenvironments of c.3.5 billion-year-old organic matter. J. Vib. Spectrosc. 41, 190–197.

Allwood, A.C., Burch, I.W., Walter, M.R., 2007. Stratigraphy and facies of the 3.43 Ga Strelley Pool Chert in the southwestern part of the North Pole Dome, Pilbara Craton, Western Australia. Geological Survey of Western Australia Record 2007-11.

Awramik, S.M., Grey, K., 2005. Stromatolites: biogenicity, biosignatures, and bioconfusion. In: Proceedings of SPIE, vol. 5906, p. 59060P (online).

Awramik, S.M., Margulis, L., Barghoorn, E.S., 1976. Evolutionary processes in the formation of stromatolites. In: Walter, M.R. (Ed.), Stromatolites. Elsevier, Amsterdam, pp. 149–162.

Awramik, S.M., Schopf, J.W., Walter, M.R., Weber, R., Guerrero, J.C., 1983. Filamentous fossil bacteria from the Archean of Western Australia. Precambrian Res. 20 (2–4), 357–374.

Bachelor, M.T., Burne, R.V., Henry, B.I., Watt, S.D., 2000. Deterministic KPZ model for stromatolite laminae. Phys. A 282, 126–136.

Bada, J.L., Lazcano, A., 2002. Some like it hot, but not the first biomolecules. Science 296 (5575), 1982–1983.

Banerjee, N.R., et al., 2005. A mechanism for preservation of approximately 3.5 billion-year-old microbial alteration textures in pillow basalts from the Barberton greenstone belt. Geochim. Cosmochim. Acta 69 (Suppl. 10), 37.

Brasier, M.D., Green, O.R., Jephcoat, A.P., Kleppe, A.K., Van Kranendonk, M.J., Lindsay, J.F., Steele, A., Grassineau, N.V., 2002. Questioning the evidence for Earth's oldest fossils. Nature 416 (6876), 76–81.

Brasier, M., Green, O., Lindsay, J., Steele, A., 2004. Earth's oldest (approximately 3.5 Ga) fossils and the "Early Eden hypothesis"; questioning the evidence. In: Luisi, P.L. (Ed.), Origins of Life and Evolution of the Biosphere. Kluwer Academic Publishers, Dordrecht, pp. 257–269.

Brasier, M.D., Green, O.R., Lindsay, J.F., McLoughlin, N., Steele, A., Stoakes, C., 2005. Critical testing of Earth's oldest putative fossil assemblage from the approximately 3.5 Ga Apex Chert, Chinaman Creek, Western Australia. Precambrian Res. 140 (1–2), 55–102.

Brasier, M.D., McLoughlin, N., Green, O., Wacey, D., 2006. A fresh look at the fossil evidence for Early Archaean cellular life. Philos. Trans. Roy. Soc. B 361, 887–902.

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

Buick, R., Thornett, J.R., McNaughton, N.J., Smith, J.B., Barley, M.E., Savage, M., 1995. Record of emergent continental crust approximately 3.5 billion years ago in the Pilbara Craton of Australia. Nature 375 (6532), 574–577.

Byerly, G.R., Lower, D.R., Walsh, M.M., 1986. Stromatolites from the 3300–3500-Myr Swaziland Supergroup, Barberton Mountain Land, South Africa. Nature 319 (6053), 489–491.

Cnossen, I., Sanz-Forcada, J., Favata, F., Witasse, O., Zegers, Z., Arnold, N.F., 2007. Habitat of early life: solar X-ray and UV radiation at Earth's surface 4–3.5 billion years ago. J. Geophys. Res. 112, E02008, doi:10.1029/2006JE002784.

Corliss, J.B., et al., 1981. An hypothesis concerning the relationship between submarine hot springs and the origin of life on Earth. Oceanol. Acta 4 (Suppl.), 59–69.

DiMarco, M.J., Lowe, D.R., 1989. Stratigraphy and sedimentology of an early Archean felsic volcanic sequence, eastern Pilbara Block, Western Australia, with special reference to the Duffer Formation

and implications for crustal evolution. Precambrian Res. 44 (2), 147–169.

Felton, E.A., 2002. Sedimentology of rocky shorelines. 1. A review of the problem, with analytical methods, and insights gained from the Hulopoe Gravel and the modern rocky shoreline of Lanai, Hawaii. Sediment. Geol. 152, 221–245.

Flugel, E., 2004. Microfacies of Carbonate Rocks. Springer, Berlin.

Golovanov, N.P., 1970. Upper Precambrian stromatolites of the western slope of the Anabar Uplift, Opornyy razrez verkhnedokembriyskikh otlozheniy zapadnogo sklona of Anabarskogo podnyatiya (Sbornik Statey). In: Nauchno-Ossled. Inst. Geol. Arkt., Leningrad, pp. 60–89 (in Russian).

Grotzinger, J.P., Knoll, A.H., 1999. Stromatolites in Precambrian carbonates; evolutionary mileposts or environmental dipsticks? Ann. Rev. Earth Planet. Sci. 27, 313–358.

Grotzinger, J.P., Rothmann, D.H., 1996. An abiotic model for stromatolite morphogenesis. Nature 383 (6599), 423–425.

Hofmann, H.J., 1973. Stromatolites; characteristics and utility. Earth Sci. Rev. 9, 339–373.

Hofmann, H.J., 1994. Quantitative stromatolitology. J. Palaeontol. 68, 704–709.

Hofmann, H.J., 2000. Archean stromatolites as microbial archives. In: Riding, R.E., Awramik, S.M. (Eds.), Microbial Sediments. Springer-Verlag, Berlin, Heidelberg, pp. 315–327.

Hofmann, H.J., Grey, K., Hickman, A.H., Thorpe, R.I., 1999. Origin of 3.45 Ga coniform stromatolites in Warrawoona Group, Western Australia. GSA Bull. 111 (8), 1256–1262.

Jogi, P.M., Runnegar, B., 2005. Quantitative methods for evaluating the biogenicity of fossil stromatolites. Astrobiology 5, 293.

Johnson, M.E., 1992. Studies on ancient rocky shores: A brief history and annotated bibliography. J. Coastal Res. 8, 797–812.

Knight, J., 2005. Processes of soft-sediment clast formation in the intertidal zone. Sediment. Geol. 181, 207–214.

Komar, V.P., Raaben, M.E., Semikhatov, M.A., 1965. Conophytons in the Riphean of the USSR and their stratigraphic significance, 72. Trudy Geologicheskiy Institut (Moskva), Nauka, Moscow.

Korolyuk, I.K., 1960. Lower Cambrian stromatolites of the Irkutsk, stromatolites of the lower Cambrian and proterozoic of the Irkutsk Ampitheatre. Tr. Inst. Geol. Razrab. Goryuchikhina Iskop., Akademija Nauka, 479-498 (in Russian).

Lindsay, J.F., McKay, D.S., Allen, C.C., 2003a. Earth's earliest biosphere—a proposal to develop a collection of curated Archean geologic reference materials. Astrobiology 3, 739–758.

Lindsay, J.F., Brasier, M.D., McLaughlin, N., Green, O.R., Fogel, M., McNamara, K.M., Steele, A., Mertzman, S.A., 2003b. Abiotic Earth—establishing a baseline for earliest life, data from the Archean of Western Australia. In: Proceedings of the Lunar and Planetary Science Conference XXXIV. p. 1137, Abstracts.

Lindsay, J.F., Brasier, M.D., McLaughlin, N., Green, O.R., Fogel, M., Steele, A., Mertzmann, S.A., 2005. The problem of deep carbon; an Archean paradox. Precambrian Res. 143 (1–4), 1–22.

Lowe, D.R., 1980. Stromatolites 3400–3500 Myr old from the Archean of Western Australia. Nature 284 (5755), 441–443.

Lowe, D.R., 1983. Restricted shallow-water sedimentation of early Archean stromatolitic and evaporitic strata of the Strelley Pool Chert, Pilbara Block, Western Australia. Precambrian Res. 19 (3), 239–283.

Lowe, D.R., 1992. Probable non-biological origin of pre-3.2 Ga-old "stromatolites" in the Barberton and Pilbara greenstone belts. Abstracts with Programs—Geological Society of America, Boulder, pp. 137.

Lowe, D.R., 1994. Abiological origin of described stromatolites older than 3.2 Ga. Geology 22 (5), 387–390.

Macintyre, I.G., Prufert-Bebout, L., Reid, R.P., 2000. The role of endolithic cyanobacteria in the formation of lithified laminae in Bahamian stromatolites. Sedimentology 47, 916–921.

Mayer, R., 1997. Paleoalterites and Paleosols. A.A. Balkema, Rotterdam.

Moorbath, S., 2005. Dating earliest life. Nature 434, 155.

Nelson, D.R., 2001. Compilation of geochronology data, 2000. Western Australia Geological Survey Record, 2001/2.

Noormets, R., Felton, E.A., Crook, K.A.W., 2002. Sedimentology of rocky shorelines. 2. Shoreline megaclasts on the north shore of Oahu, Hawaii-origins and history. Sediment. Geol. 150, 31–55.

Oak, H.L., 1984. The boulder beach: a fundamentally distinct sedimentary assemblage. Ann. Assoc. Am. Geogr. 74, 71–82.

Schopf, J.W., 1993. Microfossils of the early Archean Apex Chert; new evidence of the antiquity of life. Science 260 (5108), 640–646.

Schopf, J.W., 2006. Fossil evidence of Archean life. Philos. Trans. Roy. Soc. B 361, 869–885.

Schopf, J.W., Packer, B.M., 1987. Early Archean (3.3-billion to 3.5-billion-year-old) microfossils from Warrawoona Group, Australia. Science 237 (4810), 70–73.

Thorpe, R.I., Hickman, A.H., Davis, D.W., Mortensen, J.K., Trendall, A.F., 1992. U-Pb zircon geochronology of Archaean felsic units in the Marble Bar region, Pilbara Craton, Western Australia. Precambrian Res. 56 (3–4), 169–189.

Tice, M.D., Lowe, D.R., 2004. Photosynthetic microbial mats in the 3416-Myr-old ocean. Nature 431 (7008), 549–552.

Trenhaile, A.S., 2002. Rock coasts, with particular emphasis on shore platforms. Geomorphology 48, 7–22.

Ueno, Y., Isozaki, Y., Yurimoto, H., Maruyama, S., 2001. Carbon isotopic signatures of individual Archean microfossils (?) from Western Australia. Int. Geol. Rev. 43, 196–212.

Van Kranendonk, M.J., 2000. North Shaw, Western Australia, Map and Explanatory notes. Geological Survey of Western Australia, 1:100,000 Geological Series, Sheet 2755.

Van Kranendonk, M.J., 2001. Volcanic degassing, hydrothermal circulation and the flourishing of early life on Earth; new evidence from the c. 3460 Ma Warrawoona Group, Pilbara Craton, Western Australia. Earth system processes—abstracts. Geol. Soc. Am. Geol.Soc. Lond., 91–92.

Van Kranendonk, M.J., Hickman, A.H., Smithies, R.H., Nelson, D.R., Pike, G., 2002. Geology and tectonic evolution of the Archaean North Pilbara terrain, Pilbara Craton, Western Australia. Econ. Geol. 97, 695–732.

Van Kranendonk, M.J., Webb, G.E., Kamber, B.S., 2003. Geological and trace element evidence for a marine sedimentary environment of deposition and biogenicity of 3.45 Ga stromatolitic carbonates in the Pilbara Craton, and support for a reducing Archaean ocean. Geobiology 1 (2), 91–108.

Van Kranendonk, M.J., Hickman, A. H., Smithies, R. H., Williams, I. R., Bagas, L., Farrell, T., 2006. Revised lithostratigraphy of Archean supracrustal and intrusive units in the northern Pilbara Craton, Western Australia. Western Australia Geological Survey, Record 2006/15.

Vlasov, F.Y., 1977. Precambrian stromatolites from the Satkian formation, southern Urals, materials on the middle palaeozoic palaeontology of the Urals and Siberia. Uralian Branch, Academy of Sciences, Sverdlovsk, 101–124 (in Russian).

Walsh, M.M., 1972. Microfossils and possible microfossils from the early Archean Onverwacht Group, Barberton Mountain Land, South Africa. Precambrian Res. 54 (2–4), 271–293.

Walsh, M.M., Lowe, D.R., 1985. Filamentous microfossils from the 3500-Myr-old Onverwacht Group, Baberton Mountain Land, South Africa. Nature 314 (6011), 530–532.

Walter, M.R., 1983. Archean stromatolites: evidence of the Earth's earliest benthos. In: Schopf, J.W. (Ed.), Earth's Earliest Biosphere. Princeton University Press, Princeton, pp. 187–213.

Walter, M.R., Buick, R., Dunlop, J.S.R., 1980. Stromatolites 3400–3500 Myr old from the North Pole area, Western Australia. Nature 284, 443–445.

Westall, F., Southam, G., 2006. Early life on Earth. In: Benn, K. (Ed.), Archean Geodynamics and Environments. American Geophysical Union Geophysical Monograph, pp. 283–384.

Westall, F., Walsh, M.M., de Vries, S.T., Nijman, W., 2001. Fossil microbial biofilms from Early Archaean volcaniclastic sediments. In: Cassidy, K.F., Dunphy, J.M., Van Kranendonk, M.J. (Eds.), Australian Geological Survey Organisation, Report 2001/37. Australian Geological Survey Organisation, pp. 266–268.

Westall, F., de Vries, S.T., Nijman, W., Rouchon, V., Orberger, B., Pearson, V., Watson, J., Verchovsky, A., Wright, I., Rouzaud, J.-N., Marchesini, D., Anne, S., 2006. The 3.466 Ga Kitty's Gap Chert, an Early Archaean microbial ecosystem. In: Reimold, W.U., Gibson, R. (Eds.), Processes on the Early Earth. Geological Society of America Special Publication, pp. 105–131.