

ARTICLES

Stromatolite reef from the Early Archaean era of Australia

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The 3,430-million-year-old Strelley Pool Chert (SPC) (Pilbara Craton, Australia) is a sedimentary rock formation containing laminated structures of probable biological origin (stromatolites). Determining the biogenicity of such ancient fossils is the subject of ongoing debate. However, many obstacles to interpretation of the fossils are overcome in the SPC because of the broad extent, excellent preservation and morphological variety of its stromatolitic outcrops—which provide comprehensive palaeontological information on a scale exceeding other rocks of such age. Here we present a multi-kilometre-scale palaeontological and palaeoenvironmental study of the SPC, in which we identify seven stromatolite morphotypes—many previously undiscovered—in different parts of a peritidal carbonate platform. We undertake the first morphotype-specific analysis of the structures within their palaeoenvironment and refute contemporary abiogenic hypotheses for their formation. Finally, we argue that the diversity, complexity and environmental associations of the stromatolites describe patterns that—in similar settings throughout Earth’s history—reflect the presence of organisms.

The oldest identifiable fossil assemblages from the Earth’s early biosphere are crucial to our understanding of the origins of life on our planet and, by analogy, how and where we might find traces of extinct primitive life on other planets and moons. The SPC’s widespread, well-preserved and morphologically diverse stromatolitic outcrops offer unique, ecosystem-scale insights to such questions. The formation was described almost three decades ago as a partly evaporitic, shallow-water succession containing conical structures of possible microbial origin (stromatolites)^{1,2}. However, subsequent research indicated that abiogenesis could not be excluded³. More convincing evidence of microbial sedimentation was later found in a small outcrop of well-preserved conical stromatolites at the ‘Trendall Locality’⁴. Complex morphological attributes were cited as compelling evidence for biogenesis. However, a subsequent study at another location argued that the complexity of the Trendall stromatolites was rare in the formation⁵. Those authors interpreted a hydrothermal environment of deposition for the SPC and described the ‘stromatolite’ laminae as isopachous, suggesting that the structures were abiotic hydrothermal precipitates. Another study cited detrital sedimentary structures and seawater rare-earth-element (REE) chemistry of carbonate in the Trendall area as evidence that stromatolite accretion occurred by microbial trapping and binding of grains in a marine environment⁶. However, mathematical models show that abiotic marine cementation of detritus can also produce stromatolite-like structures^{7,8}. Thus, the origin of the SPC stromatolites remains ambiguous because of contrasting observations of stromatolite morphology drawn from disparate localities and diverging environmental interpretations.

To address this conundrum we investigated stromatolite morphologies against the backdrop of their palaeoenvironmental setting, across more than 10 km of relatively continuous outcrop where the formation is best preserved (Supplementary Fig. S1). For simplicity we adopt the term ‘stromatolite’ (a term implying biogenesis⁹) but acknowledge the as yet unproven biogenicity. Here we show that

seven separate stromatolite facies arose in different environments and developmental stages of an isolated peritidal carbonate platform during transgression of previously emergent crust. We argue that the SPC is most plausibly interpreted as a fossil microbial carbonate platform on the following grounds: first, the palaeoenvironmental setting; second, combined attributes of the stromatolites; third, stromatolite distribution within the palaeoenvironment; and last, similarity with younger microbially mediated peritidal carbonates.

Stratigraphy and facies

The SPC is a sedimentary rock succession deposited unconformably over at least 3.43-Gyr-old volcanic/sedimentary rocks and overlain by 3.350–3.315-Gyr-old volcanic rocks^{10,11}. The succession is subdivided in the study area into four members (Supplementary Fig. S2). The basal member (M1) is a thin, discontinuous jasper/chert boulder conglomerate layer. Member 2 (M2) is a layer of laminated stromatolitic carbonate/chert about 10–20 m thick, subdivided into three beds. Member 3 (M3) consists of bedded black chert, and member 4 (M4) is a silicified fining-upward clastic/volcaniclastic unit. To the south, M2–M4 merge into a succession of laminated chert more than 70 m thick with a thin basal layer of wavy laminated chert.

We identify six different stromatolite types in M2, consisting of pseudocolumnar structures composed of, and linked by, rhythmic chert/dolomite laminae. A seventh stromatolite facies occurs in M3 and is composed of laminated ironstone in chert. The SPC records evolving environments that controlled stromatolite development laterally and through time, from an initial transgressive rocky coast setting (M1); to rapid development of an isolated, southward-deepening peritidal stromatolitic carbonate platform during continued transgression (M2); and finally, resumption of hydrothermal activity, volcanism and clastic sedimentation in a southward-subsiding basin (M3–M4).

The interpretation of M1 as a rocky shoreline deposit hinges on the following: first, the wide but laterally discontinuous distribution of

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boulders; second, rounded, clast-supported fabric, indicating energetic deposition; third, correlation between clast and substrate lithologies, indicating minimal clast transport; fourth, stratigraphic position over an unconformity; fifth, substrate-dependent lateral transition from clustered and isolated large boulders on headland-type 'wave-cut' platforms to embayment beach-type conglomerates; sixth, the presence of palaeo-cliffs, fissures and cavities in the substrate (namely seacliffs and other shoreline erosion features); and last, soft mud intraclasts and desiccation cracks associated with local mudstone substrate, similar to weathering features in Holocene mudstones exposed in modern intertidal zones¹² (Supplementary Information).

At the M1 upper contact, laminated carbonates of M2 encrust the M1 boulders, 'cementing' many in precarious positions. Carbonate intraclasts occur locally within the upper part of M1, and a single layer of isolated chert boulders occurs locally about 80 cm above the contact (Supplementary Figs S4–S6). Thus, the contact is transitional, demonstrating depositional continuity from M1 to M2 and implying a shallow-water depositional setting for M2. Significantly, the contact marks a sudden change from very coarse terrigenous clastic sediment to finely laminated dolomite-chert virtually free of terrigenous sediment. The rapid switch is difficult to account for in a non-marine setting and is most plausibly explained by sudden drowning of an isolated low-relief landmass by a shallow sea. A marine environment for M2 is confirmed by the primary seawater REE patterns of the dolomite and chert (Supplementary Information). More specifically, a peritidal marine carbonate platform environment is indicated by a suite of interrelated observations (described below) on the facies associations and architecture of M2.

As is characteristic of peritidal carbonates¹³, M2 records a series of minor regressions within an overarching trend of rising sea level. The three regressive cycles are recorded as three stacked beds (Supplementary Figs S2 and S6) capped by locally eroded layers of evaporite crystal pseudomorphs. Each bed has a deeper-water facies association—and different stromatolites—in comparison with the bed below.

Bed 1 of M2 (first regressive cycle) is characterized by rapid lateral facies and thickness variations controlled by underlying topography. Where bed 1 overlies conglomerate on chert substrate, laminated carbonate encrusts the boulders and forms striking, upward-expanding, domical-laminated pseudocolumns. Where M1 conglomerate is absent, non-encrusting domical pseudocolumns occur. These 'encrusting and domical laminites' (stromatolite facies 1; Fig. 1) pass laterally to flat or irregular laminated and fenestral carbonate, notably where the underlying rocks are bedded conglomerate over mudstone (that is, a probable drowned embayment/low area). 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. 1), or flat laminite, with scattered evaporite crystal casts and intraclast conglomerates (storm and tidal channel deposits)—a characteristic intertidal to supratidal carbonate facies association¹³. 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, particularly in the northern area (Supplementary Figs S6 and S13), coupled with the trend of decreasing bedform amplitude and increasing evaporite deposition, indicate shoaling conditions through the deposition of bed 1.

Bed 2 of M2 displays less pronounced, broader-scale facies variations than bed 1, reflecting continued carbonate build-up, transgression and topographic infill. The facies association consists of four different types of stromatolites—'egg-carton laminites' and 'large complex cones' (LCC) in the central to southern area; and in the north, large 'cusped swales' grading up to 'small crested/conical

laminites' (Fig. 1)—intercalated with flat laminite and edgewise intraclast conglomerates (storm/tidal channel deposits). The flat laminite displays low-angle downlap, cross-lamination, scours, intraclast microconglomerates and graded lamination, indicating the deposition of granular sediment. Rare desiccation cracks and structures resembling blister mats or desiccated microbial mats in the northern area indicate intermittent exposure (Supplementary Information). That facies association is typical of intermittently exposed, intertidal to lower supratidal carbonates¹³. As with bed 1, shoaling is reflected in an up-section trend of decreasing bedform amplitudes, increasing abundance of evaporites and a widespread, locally eroded capping evaporite layer. However, erosion features are less prominent than in bed 1, indicating that regression was less pronounced at the end of the second regressive cycle.

Bed 3 of M2 is a relatively uniform, extensive layer of 'wavy laminites'—a typical subtidal carbonate facies¹³—with abundant laminar onlap indicating possible loose sediment deposition in water continuously agitated by waves and currents. 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 (Supplementary Information). Local breccia deposits containing boulders of the underlying carbonate facies indicate erosion at the end of the third regressive cycle.

M3, which sharply overlies M2, is a layer of bedded carbonaceous chert about 1–3 m thick with thin white quartz bands, silicified pebble conglomerates and rare silicified evaporite beds. Thin, continuous, bumpy/wavy layers of laminated ironstone (stromatolite facies 7; Fig. 1) occur at irregular stratigraphic intervals through the chert (Supplementary Information). These observations indicate possible shallow, silica-depositing and clastic sediment-depositing, partially restricted conditions.

M4 is a clastic sediment succession of variable thickness, deposited in subsiding fault blocks and fining upwards from conglomerate to bedded, silicified tuffaceous mudstone. The presence of black chert veins terminating in zones of phreatomagmatic brecciation in the tuffaceous mudstone, as well as hydrothermal REE signatures of the breccia matrix, vein and bedded cherts, indicate the onset of hydrothermal activity during the deposition of M4 (Supplementary Information).

In the far south, the SPC thickens to more than 70 m and consists almost entirely of flat laminated black/grey chert with carbonate silt (Supplementary Figs S2 and S14). Only a thin layer (less than 2 m thick) of wavy laminite occurs near the base, locally overlying chert conglomerate (M1). Convolute laminae (namely slump folds; Supplementary Fig. S15) indicate deposition on a slope dipping approximately south. The laminites are interpreted as platform slope deposits: the basal wavy laminite and the lower laminite succession probably correspond to M2, as indicated by the abundant carbonate silt; the remaining section is interpreted as the equivalent of M3–M4.

On the basis of observations in the four members, we propose that the SPC stromatolites formed on an isolated, transgressive peritidal carbonate platform that developed on a drowned landmass as soon as erosion surfaces and rocky coastal deposits became submerged and clastic influx ceased. Evidence for periodic restriction and exposure increases northward, reflecting the on-platform direction. Southward facies trends confirm basinward deepening to the south. Abundant intraclast conglomerates, scours and ripped-up laminites in M2 in the Trendall area indicates that a platform margin may have absorbed high wave energy there at times. Onset of stromatolite development coincided with the end of siliciclastic sediment influx, and the end of stromatolite formation coincided with the resumption of siliciclastic sedimentation, hydrothermal activity and volcanism. The stromatolites were spatially restricted to shallow-water areas.

Origin of stromatolites

This study introduces new evidence relevant to the debate about the

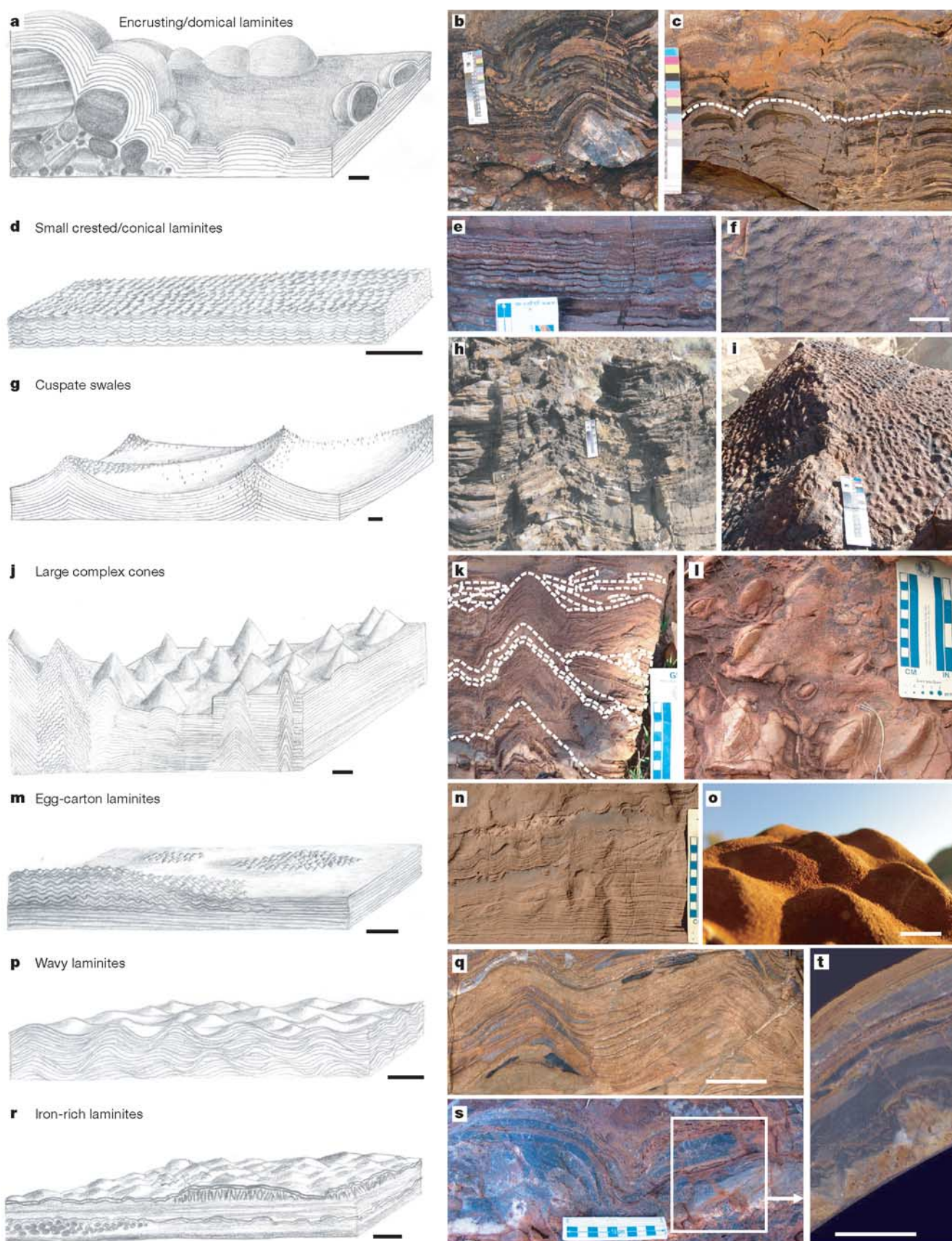


Figure 1 | Stromatolite facies of the Strelley Pool Chert, showing reconstructed three-dimensional views and outcrop photographs. **a–c**, ‘Encrusting/domical laminites’; **d–f**, ‘small crested/conical laminites’; **g–i**, ‘cuspate swales’; **j–l**, ‘large complex cones’ (dashed lines in **k** trace lamina shape and show outlines of intraclast conglomerate piled against the cone at

two levels). **m–o**, ‘Egg-carton laminites’; **p, q**, ‘wavy laminites’; **r–t**, ‘iron-rich laminites’ (**t** is a cut slab). The scale card in **b, h** and **i** is 18 cm. The scale card increments in **c, e, k, l, n** and **s** are 1 cm. The scale bar in **o** is about 1 cm. The scale bars in the remaining pictures are about 5 cm.

biogenicity of SPC stromatolites. Not one but seven stromatolite types occur, each with distinct morphological attributes (Fig. 1, Supplementary Fig. S16 and Supplementary Tables S1–S8) and distribution. All have syndepositional origins and possess geometries that are inconsistent with purely mechanical deposition (Supplementary Information). The palaeoenvironmental context does not support a general interpretation of the stromatolites as abiogenic hydrothermal precipitates⁵. Indeed, the identification of multiple stromatolite facies with distinct attributes means that no generalized abiogenic interpretation can be applied without differentiating between attributes of individual facies. Finally, the wealth of information contained in the seven facies introduces a degree of complexity not previously considered in growth models for such stromatolites^{7,14,15}. These factors provide significant impetus for a re-examination of the SPC stromatolites by facies type and as facies associations within the palaeoenvironmental framework.

We first examine the LCC stromatolites—which include previously described ‘Trendall Locality’ structures⁴—and consider whether they are more plausibly explained as biogenic or abiogenic (chemically precipitated) accretionary structures. In a purely chemical sedimentary regime it is first difficult to explain why laminae took on a specific and strongly inherited conical shape at certain heterogeneously spaced points, whereas everywhere else they remained relatively flat. Uneven spacing can occur in abiogenic accretionary structures, according to theoretical models^{7,8}, but not in combination with the particular conical morphology of the LCC structures⁸. Purported abiogenic structures with conical laminae have been described from the geological record—but they differ in morphology from the LCCs owing to the surface-normal growth and isopachous geometry of the crystalline layers, which produce pseudocolumns with upward-diverging margins¹⁶ (Supplementary Fig. S19). Previous studies proposed that SPC stromatolite laminae are isopachous and are therefore chemically precipitated⁵. However, our measurements show that the laminae are not isopachous. They thin on the cone slopes by the exact amount that ensures that the vertical ‘depth’ of the laminae is consistent throughout, the cone dimensions are inherited through successive layers, and a palaeovertical, parallel-sided pseudocolumn is formed (Supplementary Fig. S18). Isopachous or any laminar geometry other than that measured will alter the cone size and/or shape through successive layers (Supplementary Fig. S19). Thus, the palaeovertical conical pseudocolumn is a structure requiring specific, vertically directed accretion^{8,14}; it has no known abiogenic analogue or model⁸. Palaeovertical growth is echoed in the vertical alignment of LCC pseudocolumns on palaeoslopes¹⁰ (Supplementary Fig. S20) and is most plausibly explained—and demonstrated in modern conical stromatolites¹⁷—as the product of upward-migrating microbial colonies at the sediment/water interface.

In addition to geometric arguments for biogenesis, textural differences between cone and interspace laminae indicate that unique, localized sedimentary processes may have prevailed on the cones. In contrast with cone laminae, interspace laminae have graded fabrics and onlapping or infilling geometries. They also have more variable thickness and measurably different fabric—on average 45% are tangentially truncated, in comparison with less than 5% on the cones (Supplementary Information). That indicates a dominantly mechanical deposition of grains in the interspaces and a different combination of processes and/or sediment types on the cones, most plausibly explained by microbial influence (for example, trapping and binding and/or intra-mat mineral precipitation) at the cone surfaces.

Finally, a significant trace chemical signature detected in the LCC structures that is only known to occur in biosediments is the 250-fold enrichment of REE in carbonate laminae relative to chert laminae (Supplementary Fig. S22). Previous geochemical studies have indicated that microbial carbonates have REE concentrations consistently 200–300-fold higher than their syndepositional and early diagenetic abiotic counterparts^{18–20}.

Thus, the LCC structures have geometric, textural and chemical attributes that provide compelling evidence for biogenesis, and have no natural or experimental abiogenic analogue. The LCC structures are most plausibly explained as biosedimentary structures that resemble younger conical stromatolites of widely accepted biogenicity, such as *Conophyton*²¹ and related forms.

The other six stromatolite facies also display attributes that indicate probable biogenesis (Supplementary Information). The encrusting/domical laminates have granular sediment in their laminae (Supplementary Fig. S17), indicating the likely presence of a microbial mat to trap and bind grains—or to form grains *in situ*—and precluding their interpretation as purely chemical precipitates. Accretion of the sediment into domical laminae is more plausibly interpreted as a biogenic feature, shared by known stromatolite taxa such as *Colonnella*²² and *Conusella*²³. The wavy laminates look similar to climbing ripples in cross section; however, the conical lamina shapes and steep slopes indicate microbial influence and are comparable with the stromatolite taxon *Irregularia*²⁴. Egg-carton laminates, like the LCC structures, are most plausibly interpreted as having been formed by biogenic processes similar to those that formed conical stromatolites such as *Conophyton*. The cusped swales are perhaps least compatible with the abiogenic hypothesis: their laminae form strongly inherited, highly complex metre-scale networks of crested ridges with concave-sided pseudo-cones at the ridge intersections and smaller cones commonly adorning the crests. To have been formed abiotically, their morphology would have required an improbable combination of physical and chemical processes, and even more improbable conditions to maintain those processes through the deposition of scores of near-identical laminae. In contrast, the biogenic hypothesis is plausible—even highly probable—given that similar morphological attributes occur in known stromatolite taxa such as *Thesaurus*²⁵. Perhaps the most significant observation relates to slumped cones on the flanks of some cusped swales: these indicate that the sediment was coherent but soft, and thus that coherence was probably provided by flexible microbial mats rather than rigid crystalline crusts (Supplementary Information). Abiogenic replication of the complex morphology, the inferred flexible but cohesive laminar rheology, morphological inheritance through metres of finely laminated sediment, inhomogeneous adornment with small cones, crystals and bumps, and repetition of the morphology over a wide area is so complex as to be implausible.

Thus, seven distinct stromatolite facies in the SPC each display suites of attributes that are readily explained by biogenesis and are present in recognized stromatolite taxa from the geological record. In contrast, to interpret each facies as abiogenic requires not only a balance of processes that is unknown and unlikely in the natural world, but also lateral and temporal persistence of those processes to reproduce the vertically inherited, laterally repeated stromatolite morphologies. Perhaps the most compelling point is that—for the entire SPC carbonate platform to be interpreted as abiogenic—not one, but seven different unusually balanced sets of abiogenic processes must have operated discretely, persistently and sometimes simultaneously on the platform.

Finally, not only do the individual and collective stromatolite morphologies indicate biogenesis, but several factors are consistent with ecologically controlled growth of a microbial reef: especially the diversity of stromatolites—each with features resembling known microbialites and none resembling any known abiogenic structure, their occurrence in a transgressive carbonate platform deposit, their association with different platform environments, and the absence of stromatolites in deeper water.

This array of constraining factors strongly indicates that organisms flourished on a broad peritidal platform 3.43 Gyr ago in the Pilbara, rapidly taking hold and creating a reef-like build-up in shallow waters as surfaces became submerged. The variety of stromatolites present indicates that the SPC may contain not only some of Earth’s earliest fossils but also a diverse fossil ‘ecosystem’, sustained by

shallow seawater free of terrigenous influx—ideal conditions for phototrophism and a consequence of the location on a drowned topographic high. Moreover, the stratigraphic position of the SPC between thick igneous and hydrothermal successions shows that, although early life may have gained a foothold much earlier in ‘extreme’ volcanic²⁶ or hydrothermal²⁷ environments, the oldest surviving 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. Perhaps in this instance, abiogenesis is the ‘extraordinary claim’ that requires extraordinary proof, whereas biogenesis offers an ordinary, plausible explanation for the nature of the SPC stromatolitic carbonate platform.

Received 9 September 2005; accepted 29 March 2006.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank M. Van Kranendonk, S. Awramik and K. Grey for discussion and reviews; A. Grieg for assistance with REE analyses; the Geological Survey of Western Australia (GSWA) and the Pilbara Regiment for field support; and the NSW Dept of Commerce Heritage Restoration Services for large sample cutting. Research was supported by Macquarie University and the M.U. Biotechnology Research Institute. A.C.A. was supported by an Australian Postgraduate Award. All samples were collected with GSWA permission.

Author Contributions A.C.A. undertook the study and wrote the paper with supervision from M.R.W. and C.P.M. I.W.B. gave field assistance, and research and writing assistance. B.K. supervised and assisted with REE analyses.

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