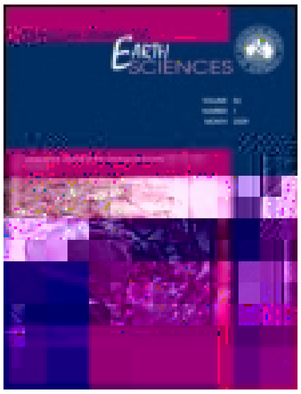

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Archean tufted microbial mats and the Great Oxidation Event: new insights into an ancient problem

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The macroscopic fossil record of the Archean consists solely of stromatolites and other microbialites, which seldom offer compelling clues to the identities of the organisms that formed them. Tufted microbial mats are an exception because their formation is known to require a suite of morphological and behavioural characteristics from which the behavioural and biological affinities of early microbialite-constructing microbes can be inferred. Here, the oldest yet reported convincing fossil tufted microbial mats are described and discussed in the context of other ancient and modern examples. Significantly, cyanobacteria dominate all known modern occurrences and may also have been the builders of ancient examples, the oldest of which predate by several hundred million years the earliest convincing cyanobacterial microfossils and most geochemical evidence for an oxygenated atmosphere.

KEY WORDS: Archean, microbialite, stromatolite, Tumbiana Formation, tufted microbial mats, Australia.

INTRODUCTION

Archean Microbialites

The macroscopic fossil record of early life on Earth is composed solely of microbialites. Almost all little-metamorphosed Proterozoic limestones, dolomites and magnesites contain stromatolites (Walter et al. 1992),

Table 1 Location and characteristics of some modern tufted microbial mats.

Location	Description and primary constituents	Environment	References
Bahamas	Pinnacles, columns and tufts. Filamentous cyanobacteria Lyngbya and Scytonema.	Seasonal hypersaline lake	Monty (1972)
Shark Bay, Western Australia	Straight parallel ridges, straight ridged reticulate patterns, tufts and pinnacles up to 2 cm high. Filamentous cyanobacteria Lyngbya aestuarii and 'Pseudophormidium.'	Hypersaline embayment	Davies (1970); Golubic (1976); this study
Yellowstone National Park	Silicified ridges and cm-scale cones linked by regularly occurring interconnecting laminae. Filamentous cyanobacterium Phormidium tenue.	Hydrothermal springs	Walter et al. (1976); Petroff et al. (2010)
Laguna Mormona, Baja California, Mexico	1 cm high tufts. Straight and sinuous ridges, rings and columns. Filamentous cyanobacteria, primarily L. aestuarii with a secondary component of Oscillatoria sp., Microcoleus chthonoplastes and Spirulina.	Evaporate-flat/salt-marsh	Horodyski (1977)
Trucial Coast, Middle East	<6 cm high tufts Filamentous cyanobacteria M. chthonoplastes and L. aestuarii	Coastal sabka	Park (1977)
Laguna Guerrero Negro, Mexico	1 cm high tufts Filamentous cyanobacterium L. aestuarii	Hypersaline	

previous geochemical proxies for atmospheric oxygen, and sets the date at which appreciable quantities of oxygen began to accumulate in the atmosphere at around 2.45 Ga (Farquhar & Wing 2003). The evolution of oxygenic photosynthesis in cyanobacteria is widely considered to have been the cause of this event, termed the Great Oxidation Event, or GOE (Holland 2002), yet some paleobiologists see evidence for the presence of cyanobacteria as far back as ca 3.5 Ga—in excess of one billion years prior to the GOE (Schopf & Packer 1987; Schopf 1993), and many see what they regard as convincing evidence for the presence of cyanobacteria at ca 2.7 Ga—some 270 million years earlier than the abrupt change in the MIF-S isotope record (eg. Schopf & Walter 1983; Walter 1983; Buick 1992; Brocks et al. 1999; Summons et al. 1999; Waldbauer et al. 2009). The existence of, and reason for, such a delay is the subject of many recent publications and considerable debate. Proposed mechanisms include a change in the redox state of volcanic gases (Kump et al. 2001), a relatively sudden switch between two stable equilibrium states (Goldblatt et al. 2006), a decrease in levels of atmospheric methane (Zahnle et al. 2006; Konhauser et al. 2009) and increased nutrient flux to the oceans (Campbell & Allen 2008). The alternative hypothesis is that oxygenic photosynthesis evolved immediately prior to the GOE (Kopp et al. 2005). The discovery of tufted microbial mats reported here from the 2.72 Ga (Blake et al. 2004) Tumbiana Formation adds to the body of evidence suggesting that the ancestors of today's oxygen-producing cyanobacteria had evolved by ca 2.7 Ga.

TUMBIANA FORMATION

Geological Setting

The ca 2.72 Ga Tumbiana Formation is part of the Fortescue Group, a succession of flood basalts, volcaniclastic, siliciclastic and carbonate sedimentary rocks lying unconformably upon an early Archean greenstone-granitoid basement in the Pilbara Craton of Western Australia (Figure 2). The group was deposited in lacustrine, fluvial and marine environments during the Neoarchean, when the basement was part of an emergent landmass in a continental rift setting (Thorne & Trendall 2001; Blake et al. 2004; Bolhar & Van Kranendonk 2007). Four Fortescue Group sub-basins have been recognised: the southern sub-basin55.1(an)-654.3(eaD[(the)7908.1Mcarlde)7589.2Bhar

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cross-stratification reported by Packer (1990) and Sakurai et al. (2005) (these observations have not been confirmed and appear to be misidentifications of trough cross-stratification). The presence of tufted microbial mats favours neither interpretation—modern examples are known from marine, lacustrine and hydrothermal pool environments (Logan et al. 1974; Walter et al. 1976; Love et al. 1983).

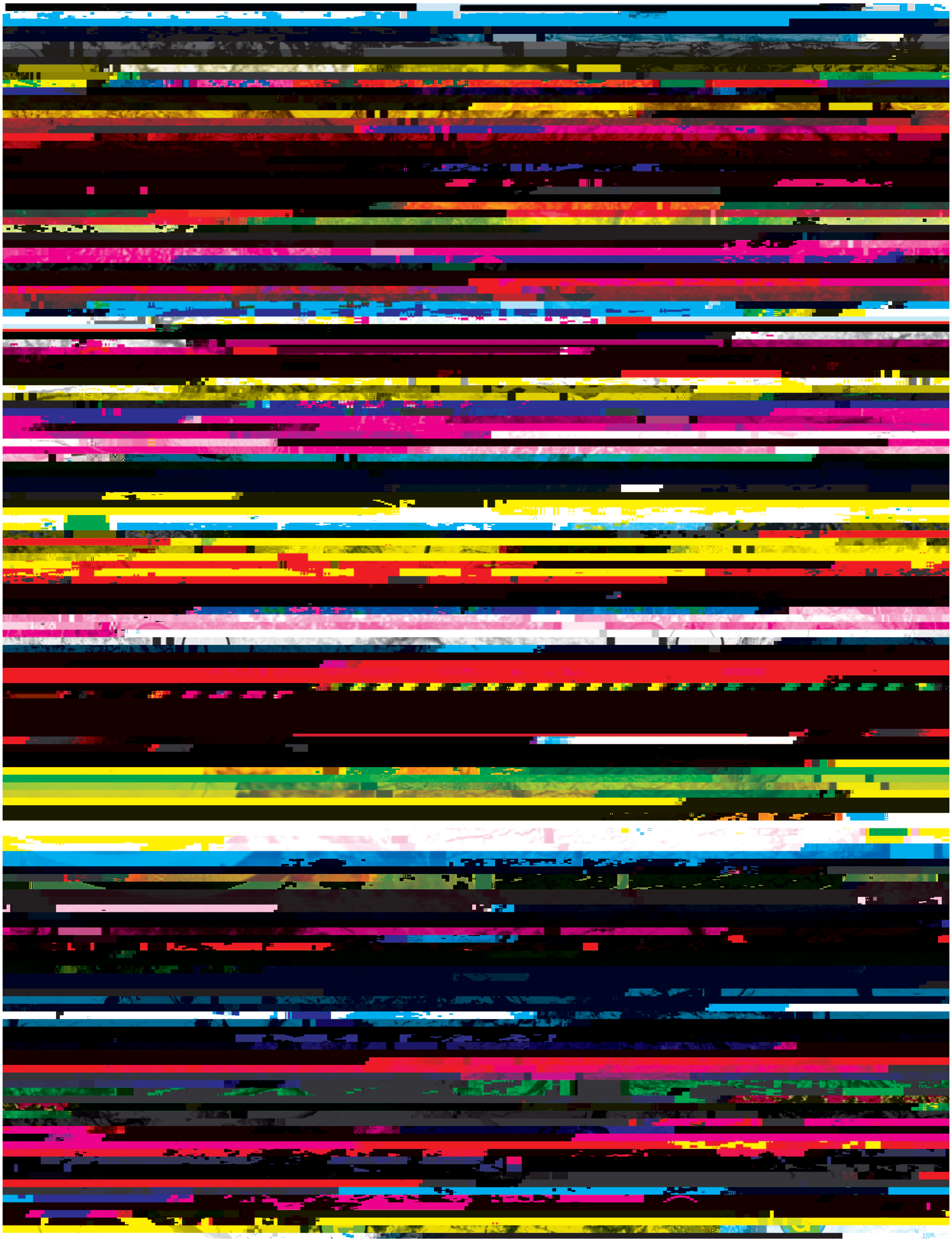

Figure 3 Microbialites of the Tumbiana Formation. (a) Thin-section photomicrograph showing the internal structure of reticulate ridges shown in Figure 4d. Note filamentous palimpsest fabrics and fenestrae in the apical zone. Scale bar = 1 mm. (b) Vertical outcrop section through coniformly laminated columns connected by regularly occurring inter-column laminae. (c) Large Domical stromatolite underlying b. (d) Plan view of coniformly laminated columns terminating in ridges. (e) Partially silicified coniformly laminated column showing lamination in outcrop.

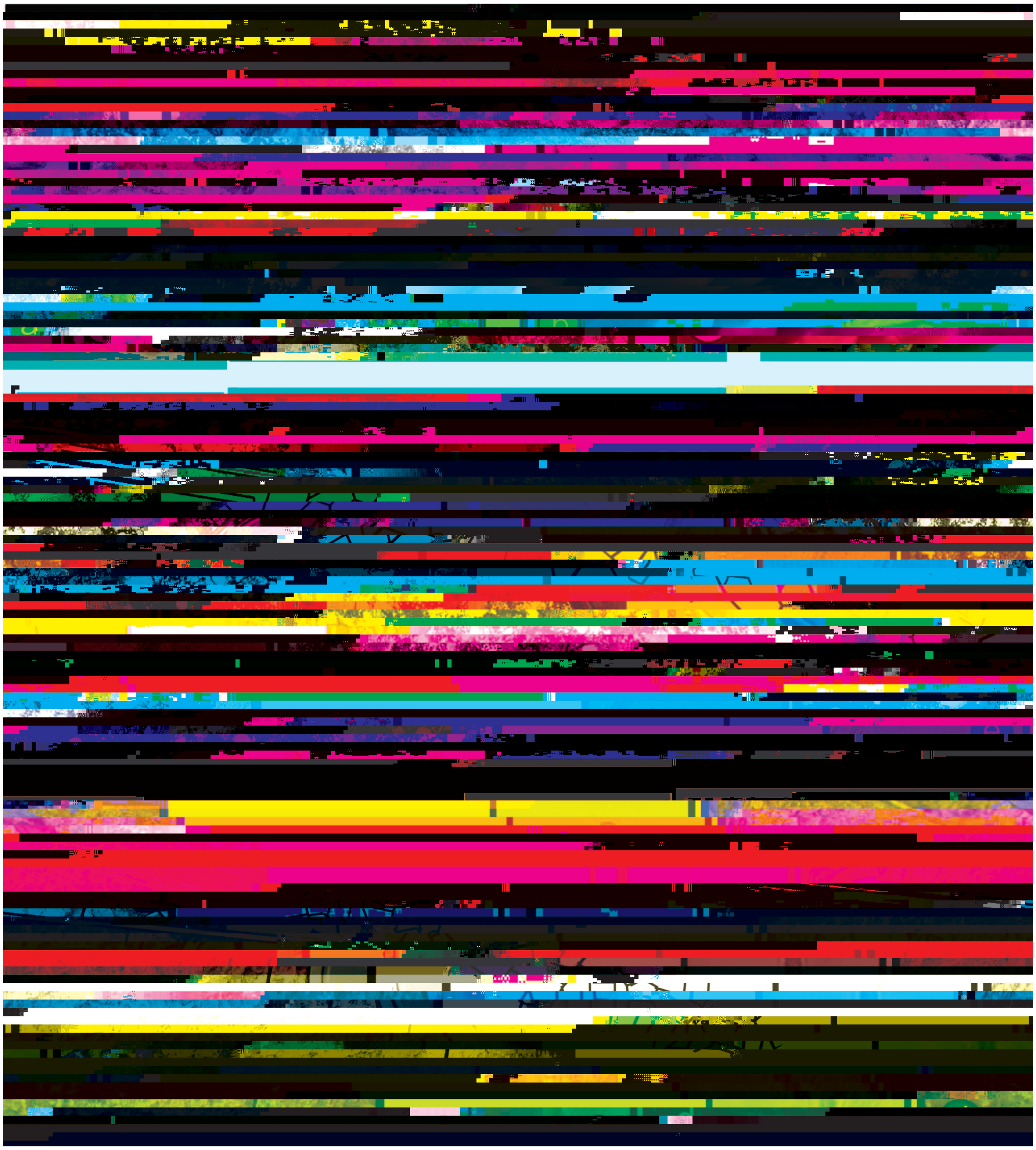

Figure 4 Modern tufted microbial mats of Shark Bay, Western Australia. (a) Contact between pustular microbial mat comprised mostly of unicellular cyanobacteria (right) and reticulate tufted microbial mat (left) comprising mostly motile filamentous cyanobacteria. Mechanical pencil for scale. (b) Section of tufted microbial mat showing vertical relief of coniform structures and underlying endobenthic mats. Photo credit: J. Coffey. (c) Reticulate ridges in tufted microbial mat at Carbla Point, Shark Bay, Western Australia. (d) Reticulate ridges of the Tumbiana Formation. (e) Lyngbya aestuarii filament—the primary constituent of Shark Bay tufted microbial mats. Scale bar = 100 μm. (f) 'Pseudophormidium' filament—this cyanobacterium also occurs in Shark Bay tufted microbial mat structures. Scale bar = 10 μm.

carbonate, with rare tabular crystals of carbonate, shards of volcanic glass (now chert) and other detrital grains occurring within coniform laminae and in the surrounding laminated and unlaminated sediments. Sub-mm euhedral crystal pseudomorphs, of what appear to be goethite after pyrite, occur along bedding planes.

DISCUSSION

Modern tufted microbial mats

Modern tufted microbial mats are restricted to a handful of 'extreme' environments, including hypersaline

Bosak et al. (2010) describe the preservation of gas explanation fails to account for several important structures from the ca 1.2 Ga Stoer Group of Scotland as fossilised tufted microbial mats. The tufts have been heavily distorted by post-burial compaction, and microstructure is not preserved, but other explanations for the features seem unlikely.

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